C6 Wheels

Final Design Report

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Statement of Disclaimer

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Abstract

This document details the C6 Wheels project being undertaken for senior design. The objective is to design and manufacture carbon fiber reinforced polymer wheels for the Cal Poly Formula Society of Automotive Engineers (FSAE) team. The wheel shells will be used on FSAE's competition vehicles. FSAE requested the wheels to improve the handling characteristics of their vehicles by reducing the unsprung and rotational mass. They have attempted carbon fiber wheels previously but have not yet run any on their vehicles. FSAE specifically proposed the design of carbon fiber shells with an aluminum center as opposed to full carbon fiber wheels on the recommendation of the 2018 attempt. C6 Wheels is responsible for designing the wheel shells—including interfacing with the aluminum centers, designing and manufacturing the mold tooling, and molding of the carbon fiber wheel shells—including any post machining. The aluminum centers are being designed and manufactured by the FSAE team.

The C6 Wheels team lost support and sponsorship from Seriforge Inc. on March 1, 2019. The team has adjusted their project scope in response. Manufacturing of the wheel mold is still the main objective but now it will be designed for pre-impregnated (pre-preg) carbon fiber instead of the Resin Transfer Molding (RTM) method. The team will proof out manufacture of a mold through machining of a female mold component and recording compaction data to be handed off to the Cal Poly FSAE club team. C6 Wheels' intention is for the club to perform the carbon fiber layup using pre-preg carbon fiber. The process of successfully creating a complex carbon layup was unrealistic for C6 Wheels to accomplish along with the task of manufacturing the wheel mold given the timing of separation from Seriforge.

1. Introduction

C6 Wheels is a team of mechanical engineering students at California Polytechnic State University, San Luis Obispo (Cal Poly): Sam Pizot, Luke Martin, Josh Warner, and Jonah Levis. The Cal Poly FSAE team is a group of students organized to design and build a racing vehicle for an annual, international, collegiate racing competition.

The FSAE team has requested the design and manufacture of carbon fiber wheels for their race vehicle. The manufacturing of carbon fiber wheels has been attempted by FSAE previously but has yet to produce useable wheels. On campus, there are multiple professors willing to consult with C6 Wheels in specific areas such as composites design, mold manufacturing, and vehicle dynamics.

This document outlines some background for the project, relevant patents and technical literature, and project objectives and planning. Additionally, this document discusses SAE requirements, engineering specifications, project boundaries, process flow, quality function deployment, and the proposed timeline.

The boundary diagram, shown in Figure 1 below, displays the perceived scope of the project. The design priorities for this project are focused on the wheel shell and wheel shell mold. The wheel hub is outside of the boundary diagram and will be handled by the FSAE team.

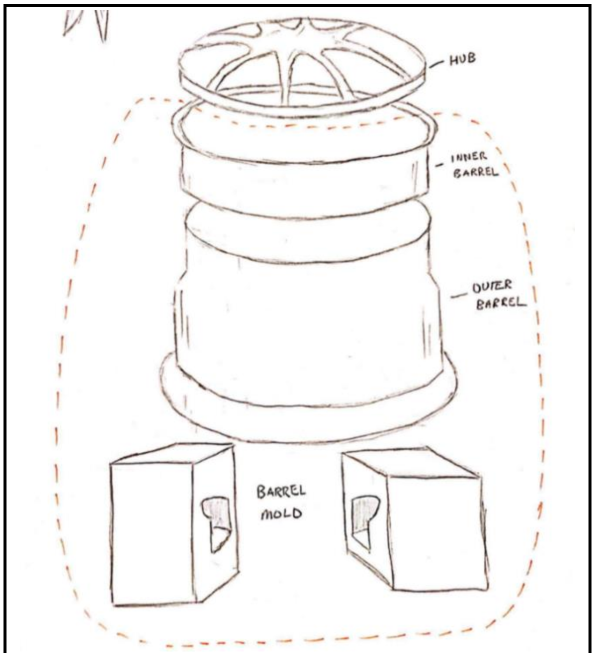


Figure 1 – Boundary diagram showing the hub (FSAE's responsibility), and the wheel shell with mold (C6 Wheels' responsibility).

2. Background

In recent decades, carbon fiber reinforced plastics have revolutionized design in the aerospace industry and have quickly become a material of choice for a variety of high-performance applications. This composite material makes use of the properties of a strong fiber embedded in a matrix, usually a thermoset polymer, such that the fiber reinforces the matrix once it is cured (heated under pressure) to produce a finished part. Compared to traditional materials like aluminum, the resulting composite possesses superior strength and stiffness pound for pound.

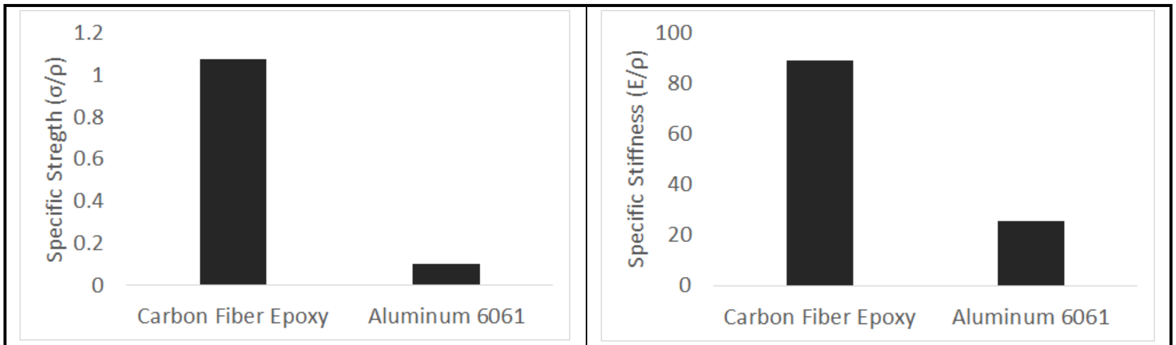


Figure 2 – Comparison of material strength to weight and stiffness to weight ratios

The automotive industry has leveraged the development of carbon fiber to produce many components, especially on racing vehicles, where weight is a primary concern. The reason for replacing traditional wheels with a carbon fiber counterpart is to decrease the unsprung and rotational mass of the car. The unsprung mass of the car corresponds with all the mass that is not mounted using the suspension, of which the wheels are a significant portion. By reducing the unsprung mass, the handling characteristics of the car improve. Similarly, decreasing the weight of the wheels will reduce their rotational inertia therefore requiring less power during acceleration and braking.

Construction of composites is an intricate process, requiring multiple steps and detailed planning. Current methods of composites manufacturing and tooling will need to be evaluated. Options include producing male molds where parts are formed on the mold and must be pulled off upon removal, or female molds, where parts are formed in the mold and must be taken out upon removal. Complicated part geometry can lead to correspondingly complicated molds. The design of the molds therefore is critical to success of the finished parts.

A significant barrier to widespread adoption of this technology is the cost, mostly due to need for skilled laborers to hand-lay fabric, or the difficulty in automating the process. Seriforge aims to automate the layup process. Their proprietary process automates stitching together three-dimensional dry parts before curing, and significantly reduces time and cost of manufacturing.

2.1 Interviews

KC Egger, the lead wheel engineer for Formula SAE, is the main point of contact on the Formula team. She is currently working on the wheel hub design in her Finite Element Analysis (FEA) class (using Abaqus). She has provided some wheel specifications and standards. The team will integrate her hub models as well as specified bolt pattern and location into the shell design.

The team will work with her and the FSAE team to simulate the loads on the wheel using Abaqus and address the necessary strength and stiffness requirements in order to validate the proposed design. The interface between the hub and the shell will require C6 wheels and KC to work together to develop the connection method and analysis. FSAE is responsible for seating the tire on the finished wheel, as well as performing FEA on the aluminum hub. C6 Wheels is responsible for performing FEA on the one-piece shell. Eventually, the team will perform physical testing of the parts with the FSAE team.

2.2 Wheel Considerations

2.2.1 Wheel Design

A previous senior project team, Reinventing the Wheel, [1] in 2017 attempted to manufacture one-piece carbon fiber wheels for the Cal Poly FSAE racing team. They experienced problems with resin flow during the curing process and were not able to release the wheel from the mold after curing. Their analysis showed that carbon spokes did not offer significant weight reduction compared with aluminum, and the team spent a significant portion of the manufacturing time laying up the complicated spoke geometry. For these reasons, Reinventing the Wheel recommends making carbon fiber wheel shells with aluminum centers. Figure 3 below shows Reinventing the Wheel's carbon fiber wheel still attached to the mold.

Figure 3 – Reinventing the Wheel's attempt to separate wheel from their mold.

Reinventing the Wheel struggled with an overly ambitious project. The complex geometry of hollow spokes, while light and stiff, is incredibly difficult to produce using composites techniques. Because all the pieces of carbon were cut and laid into the mold by hand, the lay-up process took about 80 hours. In addition, the sections of the mold forming the spoke geometry trapped the wheel in place after the resin had cured. The female portion of the mold shrank around the spokes when the metal cooled to ambient temperature.

The Ohio State University (OSU) FSAE team attempted to make carbon fiber wheel shells with aluminum centers. They were unsuccessful, breaking the carbon fiber shells at the bead seat during removal from the mold due to the aluminum mold shrinking around the cured carbon shell. The use of aluminum as the mold material was primarily driven by the use of pre-impregnated carbon fiber for the layup, which requires higher curing temperature. The use of dry fiber with resin infusion could allow for the use of other materials for the mold which could eliminate the thermal shrinkage problems after cure [2]. Due to the failure of both the Reinventing the Wheel and OSU one-piece wheel design, it is advantageous to examine relevant successful carbon fiber wheel designs to inform C6 Wheels' design process.

A University of Kansas master's thesis details the design process for a one-piece carbon fiber wheel [3]. From 2006 to 2015, the University of Kansas FSAE team ran two-piece carbon fiber wheels with aluminum centers. In 2016 they developed one-piece carbon fiber wheels with hollow spokes to further reduce weight. The process of moving from a multi-piece design to the one-piece design seems to be a feasible and prudent design path. Based on this and the recommendation of Reinventing the Wheel, making multi-piece wheels is advisable.

A small Swedish auto builder, Koennisegg, successfully constructed 13 lb, one-piece carbon fiber wheels capable of handling 280 mph. Figure 4 below shows the wheel Koenissegg manufactures. Their process includes laying carbon fiber pre-impregnated with resin by hand then using proprietary technology to set the wheel once it has been formed. Designer Christian von Koenissegg in a YouTube video explains "a negative mold is used to produce the finished, hollow, wheel" [4].

Figure 4 – Completed Koenissegg carbon fiber reinforced epoxy wheel.

Carbon Revolution is another company that produces one-piece carbon fiber wheels and theirs have been used on the new Ford Mustang Shelby GT350R. Their Australian patent 2009290123: METHOD OF MOLDING A FIBRE-REINFORCED COMPOSITE WHEEL contains a reliable method for constructing a fiber-reinforced composite wheel having integral rim and disc portions [5]. It can be used as a reference to identify key manufacturing differences associated with a multi-piece wheel including: releasability, connecting/fastening sections and a flexible polymer mold cavity element versus a traditional rigid mold element.

Dymag Performance has claimed to be the first to produce carbon fiber wheels for a commercial vehicle, the Fiskar EMotion. They have been granted a full UK patent 2541498 for their wheel shell design which implements a carbon fiber composite wheel shell and an aluminum center. Their specialty is a wheel shell which "moves the key load bearing structure of the wheel away from areas that are more exposed to impact damage" [6]. This patent can be used as a guide for transferring the tire load to the wheel shell.

Table 1 – SAE International wheel requirements [7].

Code	*Regulation*
T.1.7.1	Wheels must be 203.2 mm (8.0 inches) or more in diameter.
T.1.7.2	Any wheel mounting system that uses a single retaining nut must incorporate a device to retain the nut and the wheel in the event that the nut loosens. A second nut (jam nut) does not meet this requirement
T.1.7.3	Teams using modified lug bolts or custom designs must provide proof that good engineering practices have been followed in their design.
T.1.7.4	If used, aluminum wheel nuts must be hard anodized and in pristine condition.

Table 1 above addresses SAE's wheel requirements for Formula racing cars. The most applicable standard is T.1.7.1 which specifies the wheel diameter. The other specifications, though important to wheel mounting, do not directly affect molding or wheel design.

All of these existing products will help to inform the team's wheel design decisions during the prototyping phase. Within wheel design, manufacturability also must be addressed. The team has discovered some technical literature and related patents to affirm manufacturing direction for the wheel.

2.2.2 Wheel Manufacturing

NASA is another major organization having joined the research with large scale automated stitching technology for advanced composites, published under US A90-33076 [8]. Their process attempts to tailor the composite part for improved damaged tolerance, using a similar reinforcement technique as Seriforge. Stitching of the plies would secure the shape of the preform and increase the interlaminar shear strength of the laminate. Formula racing wheels undergo high damage loading risk. The fact that NASA uses the same preform process validates its success and superiority over older methods of carbon fiber manufacturing to produce a higher quality part.

Investigations on Mechanics-Based Process Planning of Micro-End Milling in Machining Mold Cavities [9] describes the proper selection of axial depth of cut and feed per tooth for machining micro-mold cavities. The general process for micro-milling includes two steps: roughing and finishing. In roughing, the goal is to maximize material removal rate while avoiding tool damage. In finishing the goal is to obtain the desired surface finish. This information will be especially important in relation to achieving desired surface finish and sufficient material removal rate when designing the mold for the wheel.

Mechanical Behavior of Glass and Carbon Fiber Reinforced Composites at Varying Strain Rates and Temperatures [10] analyzes mechanical performance of carbon fiber and explores how these properties can be influenced by varying fabric architecture and structure. Mechanical testing was performed at different strain rates and temperatures, offering valuable insight applicable to loading experienced by a carbon fiber wheel. Also, the study explores strength and stiffness qualities that depend on fabric orientation and structure. This information will help optimize the wheel design.

Boeing has integrated carbon composite structures in its large 787 fuselage sections and is trying to speed up the production process [11]. A recent patent, US 20140141114 A1, the company details a method to reduce thickness gradients in molded parts caused by gravity-induced settling of the resin during curing. Their method layers carbon fiber around a rotating mold with a computer-controlled robot. Their rotational molding process may help with C6Wheels' attempt at molding a cylindrical piece and completely infusing all fabric with resin.

2.2.3 Wheel Loading

A car wheel (and its surrounding tire) is the contact point between a vehicle and the road. Any change in speed or direction of the vehicle results from various forces acting on the tire. Acceleration and braking act along the longitudinal axis of each wheel while turning forces act along the lateral axis of each wheel and normal forces along the vertical axis. These loads are assumed to act at the contact patch of the tire and transmitted directly to the wheel. See figure 5.

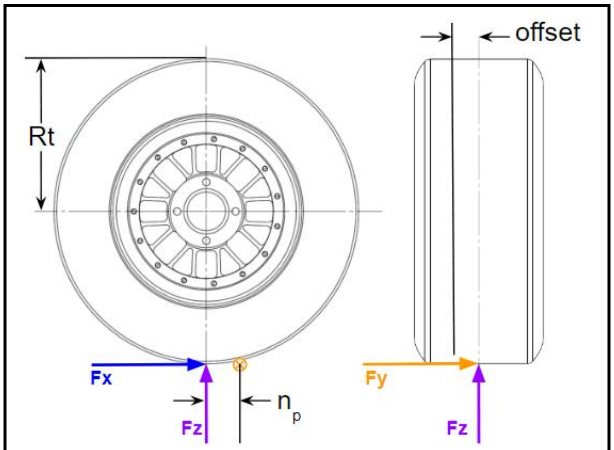


Figure 5 – Wheel loading diagram.

Load cases were developed based on tire data and car parameters provided by Formula SAE. Table 2 displays the loading cases for the Cal Poly Formula 2018-19 combustion track car. For analysis, the maximum loading case is being considered.

Table 2 – Wheel design loads.

Operating Case	Contact Patch Load (lb)		
	Fx	Fy	Fz
2.3 g Braking	-523	0	257
1.83 g Acceleration	155	0	54
2 g lat Cornering	0	465	257
1.23 g lat, -1.4 long Combined	-520	511	289

The loads at the tire contact patch are resolved as pressure distributions governed by the following equations:

$$Pw = Pw0 * cos((\pi/2) * (\theta w/\theta 0))$$

where Pwo is the maximum pressure of the tire, which is found using the equation:

$$Pw0 = (w * \pi)/(tb * rb * 4\theta 0)$$

where w is the normal load on the tire, tb is bead width, and rb is bead radius. The application of these pressure distribution to the wheel are illustrated in figure 6 below. For a typical automotive tire, θ ranges from -40 to 40 degrees. The resulting pressure distribution profiles for normal, longitudinal, and lateral loads are shown. The longitudinal and normal loads are applied symmetric about the wheel center plane to the inner and outer bead seats. The lateral load is applied only to the inner rim bead seat [1].

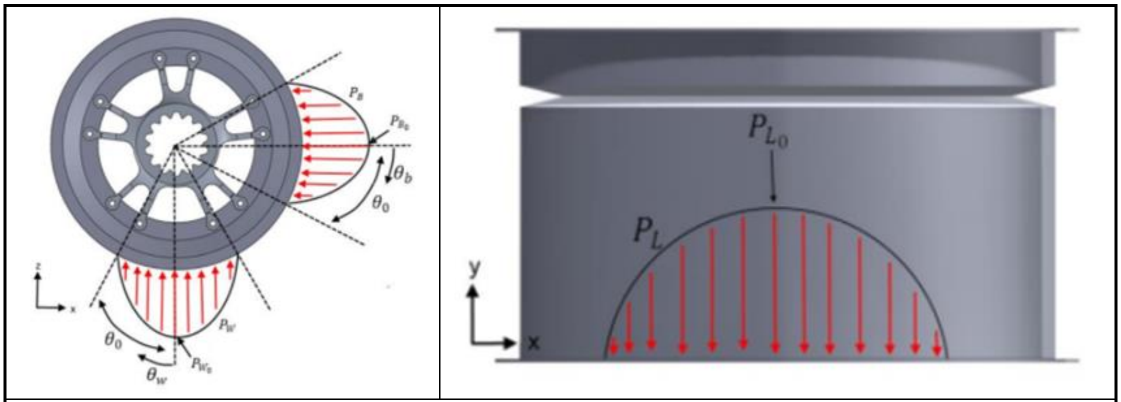


Figure 6 – Load distribution viewed from curb side (left) and from below (right).

2.2.4 Wheel stiffness

In addition to withstanding the forces on the wheel imparted by the tire, the wheels must be sufficiently stiff to keep the tire within a predicted camber position to prevent (too much) loss of grip. [1] Camber is the angle between the tilted plane of a wheel and the wheel's vertical plane.

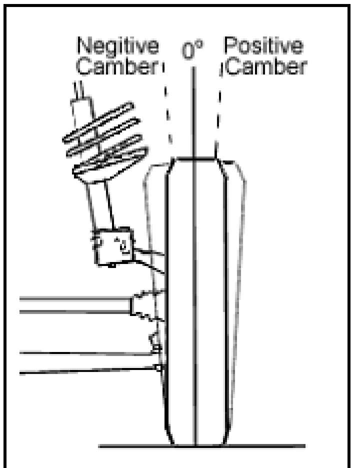


Figure 7 – Wheel camber diagram.

Positive camber is defined as an outward tilt of the wheel, so the top of the wheel extends farther from the vehicle than the bottom of the wheel. See figure 7 above. Negative camber is defined as the opposite; the bottom of the wheel extends farther outward than the top. During cornering at high speeds, the rim bends and the camber changes.

A stiff wheel allows for more responsive steering and quick changes of direction. The high specific stiffness of carbon fiber is suited to meet camber requirements during cornering and to achieve camber compliance. As the tire loads are transmitted through the bead and reacted at the center due to the hub bolted connection, the load distribution will depend on the stiffness of each member.

2.3 Mold Considerations

Perhaps the most challenging aspect of the design project is the creation of a mold that can successfully produce the composite wheel shells to the desired specifications. Three of the major considerations to be explored within this design challenge are the mold geometry, mold material, and resin delivery method. Some relevant technical literature and existing products have given insight into these parameters that will be useful during the design process.

2.3.1 Mold Geometry

It is important to assess the benefits and drawbacks of both male and female molds while considering mold geometry. C6 Wheels has chosen to consider a female mold. This type of mold creates sharp corners and highly detailed outer surfaces of a product. They are used when outer dimensions are important like with the outer surface of a wheel.

Draft angle is another important consideration in mold geometry design, as it has a great effect on release from the mold. It is vital to the success of the mold to create positive draft angles for each point of contact between the mold and part. If negative draft angles are present anywhere on the mold compared to its release direction, the part will not be releasable. For these reasons it is important to pay careful attention to draft angle during mold design.

2.3.2 Mold Material

Choosing a proper mold material for the manufacturing process will have major implications both in cost and design. The major materials in consideration are metals, graphite, foams, and composites. Each material has its advantages and drawbacks, which are outlined in the technical paper *Moldmaking for Composite Materials* [12]. Cost, coefficient of thermal expansion (CTE), surface finish, life cycle, and manufacturability must be considered for each material.

There are multiple metals to be considered in mold creation. The most common metals used are tool steel and aluminum. These are extensively used for mold and have predictable behaviors. Both metals would be purchased as solid billet and, for a large mold, the cost of this billet would be very expensive. Both steel and aluminum have CTE's that do not match with carbon fiber composites, which could pose design challenges. With proper machining, metal molds can achieve extremely fine surface finish, and they can be further polished. Metal molds can be run through thousands of autoclave cycles. Computer numerical controlled (CNC) machining is required to create a metal mold, and due to the density of the material, manufacturing of a metal mold is more time intensive.

Graphite has different advantages and disadvantages for mold design. Graphite is generally less expensive than an equivalent volume for aluminum and has a much lower CTE than both aluminum and steel. Graphite would also be easier to machine than an equivalent metal mold due to its lower density. However, since graphite is lighter and softer, it is much easier to damage than steel or aluminum and would not be able to handle as many cycles.

Various density foams are also a viable option for tooling material, the benefits of which are ease of machining and dimensional stability. Standard Renshape Foam is incredibly easy to machine and cost-effective but also has a relatively high CTE compared to other mold materials. The issue with foam is the need to seal the surface after machining and sand the sealed surface to achieve a smooth enough surface for release. This process can degrade the dimensional accuracy.

Using composite material to create a mold for a composite part has several advantages to be considered. The biggest reason that a carbon fiber composite tool is desirable for this application is that it can match the CTE for the molded part. Having a matching CTE makes the mold design much easier to create and is helpful in achieving tighter tolerance in the molded part as well as releaseability from the mold. Using traditional composite methods, a master mold would need to be created out of some other material, making this method costly and time consuming. However, the company Hexcel has created a composite material called HexTool that seems to eliminate these drawbacks. HexTool is a specially developed composite material that is machinable and can reach surface finish and tolerance requirements comparable to metals [13]. Thus, creating a mold out of HexTool would be much closer to a net shape process, with a general mold shape created in the layup process and specific geometric features added in post machining. This would eliminate large amounts of material waste that would be encountered machining a large mold from a metal billet, potentially reducing the relative cost of the mold material. Additionally, the nature of HexTool also allows for corrections and additions to an existing mold, so in the case that the first iteration of the carbon fiber wheel shell fails, instead of having to create an entirely new mold, the existing mold can be modified to a new geometry, greatly reducing both cost and manufacturing time [13]. For these reasons, HexTool was a viable option and was considered during the design process.

2.3.3 Resin Delivery Method

Epoxy thermosetting resins are a preferred choice for the matrix material in high performance composites applications for their contributions in compressive strength, adhesive properties, and durability. This material consists of a polymer chain which becomes permanently cured into a crosslinked network when mixed with a catalyst and heated [14]. Once cured, a unified rigid composite is formed where adhesion between the resin and the carbon fibers allows for load transfer and prevents debonding and cracking.

Curing of the resin occurs under elevated temperature and/or pressure in an oven, or vacuum bag, or both. It is crucial to ensure that a selected resin transfer system is compatible with the manufacturing process of the composite.

A variety of infusion techniques exist in order to follow the geometry of the part. A wet layup is a traditional method where resin is impregnated into fibers by hand, typically using a brush and rollers. Then the laminate is left to cure. The quality of a part made by this process is variable and depends on the skill of the applier. This process requires a low viscosity resin able to be worked by hand. Once layup is done, the laminate can be sealed in an air tight container using a vacuum bag. Air is evacuated from the bag and atmospheric pressure compresses the laminate, squeezing excess resin from within the laminate and compacting plies together.

The most common method of resin infusion is an infusion process using vacuum pressure to drive resin into the laminate. It consists of laying the plies over a rigid mold to the desired orientation and thickness and then covering with a release film, breather fabric and the vacuum bag. Use of a low viscosity thermosetting resin can be helpful for flowability. The function of the vacuum is to remove any excess air between layers and it requires leak tight seals.

An important feature to consider for the mold design is the exact path the resin will take to be delivered to the part and where to locate the input/output ports. Figure 8 below displays a resin delivery schematic.

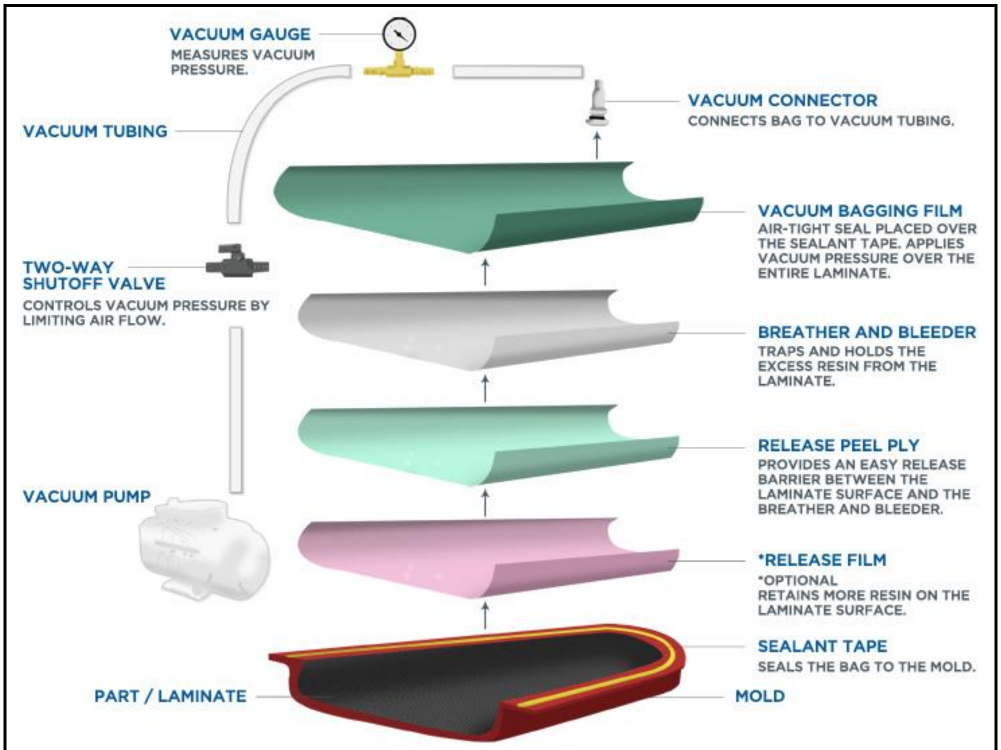


Figure 8 – Typical vacuum bag lay-up procedure. Not pictured is the vacuum line to resin trap [15].

Pre-impregnating fibers with resin prior to lay-up over a mold has become the modern choice of material as it reduces manufacturing steps but was not being considered in this project due to its incompatibility with the stitching method being employed. Due to the updated project scope, prepreg has become an available option for material. The advanced cutting and stitching machines of our sponsor were made for dry fabric. Without access to these machines, the carbon fiber will need to be hand cut and hand laid onto the mold. Prepreg allows us to avoid the complex step of infusing the dry fiber with resin but increases the challenge of precisely and uniformly following the shape of the mold without the help of our previous sponsor's precise carbon fiber manufacturing method. It also leads to better conformity and quality and a cleaner process. Better control of laminate thickness, ease of use

Additionally, curing times and temperatures can be adjusted to match available equipment requirements and chosen resin system.

2.3.4 Trapped Rubber Molding

The trapped rubber molding process is being pursued for its potential to produce high quality parts through the generation of large compaction pressures. It is well established in industry but is more frequently used for prepreg parts than for wet layups or infused parts. However, this process does lend itself to the resin transfer method (RTM). Rubber assisted resin transfer molding (RARTM) has been used by NASA in the creation of composite parts and the specific advantages are well suited to the creation of a carbon fiber wheel where the main goal is to reduce weight while maintaining strength and stiffness. The trapped rubber process, and specifically RARTM in this case, can achieve very high fiber volume fractions, far exceeding those achievable during more traditional RTM processes.

Typically, RTM is used with either a two-piece hard mold (male and female) or with a single piece hard mold and a vacuum bag. The two-piece approach yields better surface control and surface finish but is generally unable to compact the wetted composite layup before cure. The vacuum bagging method can compact the composite part at the cost of surface finish on the bagged side of the part. Additionally, the compaction pressure is limited to 1 atmosphere unless an autoclave is involved. Trapped rubber molding, conversely, can achieve compaction pressures upwards of 40 atmospheres without the use of an autoclave and produces much better surface finish than a vacuum bagged part.

Trapped rubber molding takes advantage of the disparity of the coefficient of thermal expansion (CTE) between aluminum (or steel) and silicone. Silicone has a linear CTE roughly 37x that of aluminum, so as the mold is heated, silicone trapped within will expand much more rapidly and exert pressure on whatever surfaces it contacts [16].

3. Objectives

FSAE wants to reduce the weight of their competition vehicle by implementing carbon fiber reinforced polymer wheels. In order to do this, they need a viable manufacturing method. The part must meet FSAE's specifications to be used in competition.

The nature of the relationship between FSAE and C6 Wheels mandates careful consideration of customer needs and wants. See Appendix A for a visual explanation of the inter-project relationships. Formula is primarily concerned with the structural soundness of the wheels and the development of a robust manufacturing process. Table 3 below summarizes the needs and wants FSAE. These needs and wants were directly drawn from the discussions that the team had with FSAE. The relative weight of each need and want is addressed in the House of Quality.

Table 3 – Customers' needs/wants

Formula SAE Needs/Wants
Need- Wheel must meet required geometry
Need- Satisfy loading requirements
Need- Handle subjected temperatures
Want- Number of wheels (4 for car 1 for destructive testing)
Want- Repeatable Manufacturing process
Want- Lighter than current wheels

After spending time interviewing, as well as receiving several engineering specifications for the project, the team constructed a House of Quality for the development of Quality Function

Deployment (QFD). Based on the scope of the project, two separate Houses of Quality were developed: Wheel Design and Manufacturing Process. The Wheel Design QFD focused on customer needs/wants relating to wheel function. The Manufacturing Process QFD expanded on the needs/wants for mold design.

Developing this QFD required collecting data from the team's customers and determining if the team's wheel and tooling design met all engineering specifications laid out by FSAE. The House of Quality can be viewed in Appendix B.

The QFD shows correct geometric dimensioning is the most important need for both the mold and the wheel. This is heavily dependent on mold manufacturability. Next, tire and seat pressure were important requirements for the wheel. A viable sealing method as well as a highly controlled bead seat are vital to its design. Additionally, releaseability of the wheel shell from the mold was weighted heavily, showing the importance of an easily released wheel. This specification will inform mold design decisions of geometry and material selection.

Within the design, C6 Wheels has developed engineering specifications to meet with the composite wheel. These design parameters are listed in Table 4.

Table 4 – Engineering specifications for wheel design

Spec. #	Parameter Description	Requirement / Target	Tolerance	Risk	Compliance
1	Wheel Mold Cost	\$2500 (Total)	Max	M	I
2	Camber Compliance	0.2°/g	Max	H	A, T
3	Weight	5 pounds per wheel	Max	H	I
4	Strength	Sustains loading*	Min	H	A, T
5	Tire Pressure	12 PSI	Min	H	A, T
6	Seating Pressure	35 PSI	Min	H	A, T
7	Manufacturability**	Pass/Fail	N/A	H	A, T
8	Manufacture Time	28 Hours per wheel	Max	L	A, I
9	Dimensional Accuracy	Meets drawing specs***	Min	H	A, S, T
10	Design Life	2 Seasons	Min	M	A, T

**See Appendix C for specific loading conditions*

***Wheel shells must be possible to preform using Seriforge's stitching robot (table dimensions: x = 600mm, y = 1000 mm; max stitching thickness: 1"), mold must be machinable on Haas VF2 using 3-axis machining (no 4th or 5th axis), and wheel shells must release from mold after resin cure*

****Drawing specs will include tolerances on critical surfaces and general tolerances for non-critical surfaces*

The four compliance methods assigned in the above table are: Analysis (A), Test (T), Similarity to Existing Designs (S), and Inspection (I). The High (H), Medium (M), and Low (L) risk assignments were given based on the relative importance of meeting the target or requirement. For instance, seating pressure is assigned a High (H) risk factor because previous carbon fiber wheels have failed during the bead seating process.

The only specification with an S compliance method is intended to be compared to the existing aluminum wheels that FSAE uses. The drawing specifications will be developed based on the dimensional accuracy of the aluminum wheels compared with their specified dimensions.

The high-risk specifications are largely interrelated. Dimensional accuracy plays a large part in the ability to hold pressure. Strength and stiffness are both functions of the geometry, as is the weight. The high-risk factor placed on weight comes from the stated reason for the project: to reduce the unsprung and rotational mass of FSAE's vehicles. Camber compliance, similarly, plays a direct role in the handling of the vehicle and the 0.2º/g target was given to the C6 Wheels team directly from FSAE.

The 28-hour manufacture time for a single wheel includes the preform stitching, resin infusion, molding, cure, and post machining. This target is based on Seriforge's estimate of approximately 1/2 day for preform stitching, resin cure times at approximately 8 hours, and setup and machining time. Reinventing the Wheel spent upwards of 80 hours in manufacture of a single wheel, much of that time in the layup. 28 hours for a target is reasonable based on current information and is a low risk specification because the manufacturing time has little effect on the overall success of the project.

The $2500 mold cost limit is currently based on the cost of a billet of aluminum large enough to machine the molds, with a margin for extra material. Aluminum is not necessarily the material of choice for the mold but is a decent starting place to estimate price. This number is subject to change based on the decisions made about mold materials.

C6 Wheel's risk mitigation strategies are as follows: FEA prior to molding to verify camber compliance, strength, and pressure resistance; analytical predictions of weight based on carbon fiber data and the resin system chosen for molding; sufficient foresight concerning manufacturability as well as a small-scale prototype; and full-scale molding and destructive testing. The last of these is expected to produce the most useful data to be used in a design iteration and second molding and production phase.

Overall, the objective for this project is to deploy functional carbon fiber wheels that meet these engineering specifications and deliver them to FSAE. To accomplish this, the team will create tooling and molds to accommodate the manufacturing of the wheels.

4. Design Concepts

The team first chose between a one-piece or a two-piece wheel shell, and following this decision, determined the mold architecture and materials. These design decisions were primarily informed by industry experts, the previous team, and technical research. These ideas were then vetted through a decision-making process involving Pugh matrices and technical discussion to drive our final design for both the wheel and mold.

4.1 Wheel Design

Deciding on a one-piece or two-piece wheel shell has major implications for the manufacturing of the project. The difference being that the two-piece design consists of an inner and outer shell bolted together at the inner flange where the shell connects to the spokes as shown in Figure 9 below.

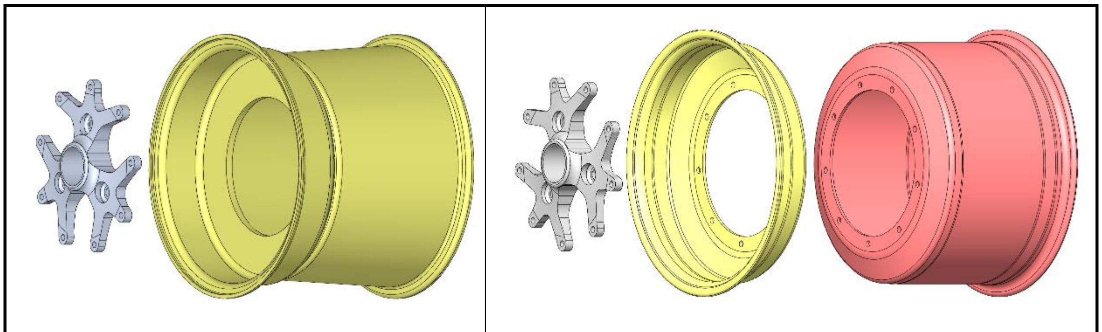


Figure 9 – One-piece wheel shell (left) and two-piece wheel shell (right). Note where the pieces would be joined together along the inner flange in a two-piece shell model.

The team met with Professor of Mechanical Engineering John Fabijanic (faculty advisor for FSAE), as well as KC Egger and members of the Reinventing the Wheel team to discuss the advantages and disadvantages of both designs in terms of weight, stiffness, manufacturability, and Reinventing the Wheel's experience and difficulties.

Using a one-piece wheel shell design eliminates strength, sealing, and tolerance issues present in a two-piece wheel shell design. For these reasons the one-piece wheel shell design should be chosen. However, producing a one-piece wheel shell has its own set of manufacturability issues. Table 5 below highlights the advantages and disadvantages of a one-piece wheel shell and a two-piece wheel shell.

Table 5 – Comparison of one- and two-piece wheel shells

One-Piece		**Two-Piece**	
Pros	Cons	Pros	Cons
Simple geometry	Manufacturability	Manufacturability	Sealing issues
Dimensional accuracy	Tire mounting	Tire mounting	Concentricity of two halves
Stiffness, strength maximized			Compliant connection between halves
No internal sealing issues			

A one-piece wheel shell eliminates a potential sealing problem at the inner flange. Normal two-piece aluminum wheel shells require sealant or calking to properly join this interface. A one-piece design also eliminates a potential for misalignment between shell pieces. Additionally, a one-piece maximizes stiffness and strength through the internal wheel flange. Figure 10 below shows a cutaway view of the one-piece shell with critical surfaces highlighted in red and yellow.

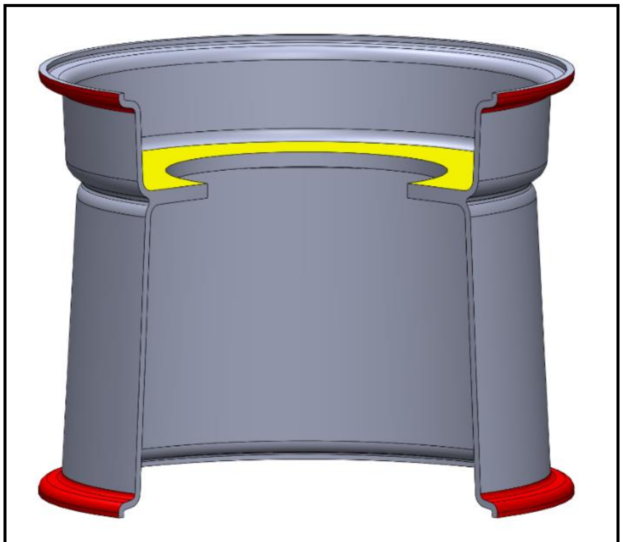
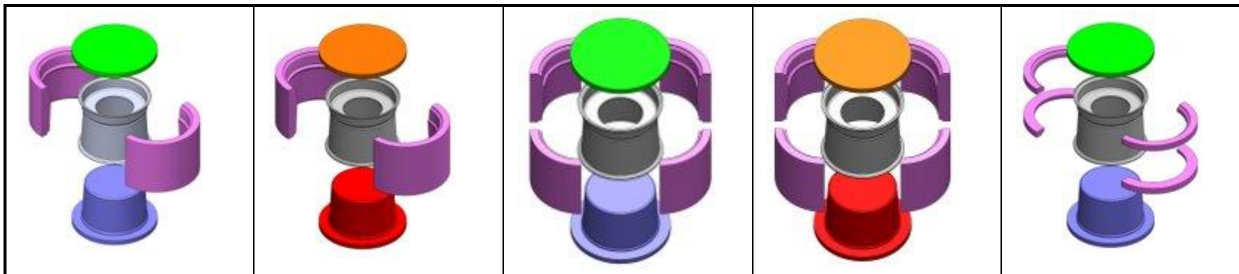


Figure 10 – One-piece wheel with cutaway. Critical surfaces are depicted in color. The bead seat surfaces are denoted in red and the inner flange in yellow. Note that the underside of the inner flange is also a critical surface.

4.2 Mold Design

With the wheel type decided, the team moved on to developing the mold design. The mold must control the geometry in three critical areas: the inner and outer bead seats, and the inner flange. The bead seats are geometry on the outside of the wheel shell and the inner flange is on the inside (see Figure 9 above). Reinventing the Wheel advised that the surface from a vacuum bag does not provide adequate dimensional accuracy. For this reason, the mold must incorporate both male and female elements. Male elements (also called male plug or male insert) being the pieces of the mold surrounded by carbon fiber, and female elements (also called female outer) being the pieces surrounding carbon fiber. Dry layers of carbon fiber will be stitched and placed into the mold and resin will be delivered. The C6 Wheels team brainstormed mold concepts for both one- and two-piece wheel shells but the concepts for two-piece were eliminated based on the decision to pursue a one-piece wheel shell. Based on the recommendation of Reinventing the Wheel all concepts without a female portion to the mold were also eliminated. The five best mold design ideas are shown in Figure 10 below. They are combinations of differing mold materials and female outer configurations.



1: Two-piece female, hard male inserts	2: Two-piece female, silicone plugs	3: Four-piece female, hard male inserts	4: Four-piece female, silicone plugs	5: Hard male with bead seat control rings

Figure 11 – Mold concepts for one-piece wheel design. These concepts are compared in a weighted decision matrix below.

The green and purple male inserts are machined from a hard material (i.e. aluminum) whereas the orange and red inserts are cast from a soft material (i.e. silicone). All the female pieces are represented in pink and are machined from a hard material.

Ease of release is a crucial factor, since that is where the previous team failed. Other aspects considered: surface control—meaning the control of the geometry at the critical surfaces of the wheel shell (the bead seat and the inner flange), manufacturability—specifically of the mold, resin infusion compatibility, minimizing flash (resin flowing out of the mold) at the mold seams, compaction achievable during the curing process, and cost of the mold. These factors were weighted and compared below in Table 6, and the team used the decision matrix to select an optimal design. Design 1 is used as a datum. The concepts in Table 6 correspond to the numbered concepts in Figure 11 above.

Table 6 – Weighted decision matrix comparing potential mold designs

Criteria \ Concept	Weight	1		2		3		4		5	
Surface control	5	0	0	0	0	0	0	0	0	-1	-5
Ease of release	4	0	0	1	4	1	4	2	8	1	4
Ease of manufacture	4	0	0	-1	-4	-1	-4	-1	-4	1	4
Resin infusion compatibility	3	0	0	2	6	0	0	2	6	1	3
Compaction	4	0	0	2	8	0	0	2	8	0	0
Minimize pinching	2	0	0	0	0	1	2	1	2	1	2
Minimize flashing	4	0	0	0	0	-1	-4	-1	-4	0	0
Cost	2	0	0	-1	-2	1	2	-1	-2	1	2
Sum of weighted scores		0		12		0		14		10	

Design 4, the four-piece female mold with silicone sleeved hard male inserts, shows the highest merit and as such will be the design moving forward. With a clamped outer female and male plugs, every surface of the wheel shell is controlled. Additionally, using silicone sleeves on the inside of the mold will yield greater compaction versus traditional vacuum bagging. All pieces should be manufacturable on campus using the Haas VF2 or Tool Room Mill in the Industrial and Manufacturing Engineering (IME) machine lab.

With a chosen mold geometry, the team had an informed discussion about choosing proper mold material. Silicone and graphite were ruled out as viable materials, leaving Aluminum, Tool Steel, Invar, Foam, and HexTool as viable mold materials. These were explored in a weighted decision matrix to inform material selection shown in Table 7 below.

Table 7 – Mold material weighted decision matrix

Criteria \ Concept	Weight	Aluminum		Tool steel		Invar		Foam		HexTool	
Matching CTE	5	0	0	0	0	1	5	-1	-5	2	10
Ease of fabrication	4	0	0	-1	-4	-2	-8	2	8	-2	-8
Cost	3	0	0	0	0	-2	-6	2	6	-1	-3
Controls tolerance	5	0	0	0	0	1	5	-2	-10	1	5
Surface finish	2	0	0	0	0	0	0	-2	-4	0	0
Long life	1	0	0	0	0	1	1	-2	-2	-1	-1
Low thermal mass	2	0	0	-1	-2	-2	-4	2	4	2	4
Sum of weighted scores		0		-6		-7		-3		7	

HexTool provides the most advantages, however, it is also an unknown material which adds additional complexity. Therefore, aluminum will be used as the material of choice for the mold.

4.3 Challenges, Unknowns, and Risks

There are risks associated with the chosen mold and shell designs; the mold risks, however, will be crucial to mitigate, as learned by Reinventing the Wheel’s mistakes. These risks include making sure the shell releases, controlling resin infusion, and minimizing resin flash. Table 8 below summarizes the risks and the mitigation strategies for each risk.

Table 8 – Wheel and mold risks and mitigation plans

Risks	Mitigations
One-piece shell eliminates potential easy tire seating process	-Ensure strength of bead seat, FEA.
One-piece shell increases complexity of ply schedule and stitching process	-Work closely with Seriforge, who has expertise in this area.
Reinventing the Wheel's shell did not release from the mold	-Use proper release agent. -Machine surfaces with high polish.
Even distribution of resin	-Informed, resin port locations -Resin channel locations -Number of channels -Design with CTEs in mind
Minimizing resin flash	-High quality surface finish on female connecting mold faces -Use proper sealing agent on female mold faces

A one-piece wheel shell eliminates the possibility of assembling the shell around the tire. The process of seating a tire on wheel shells is violent and has broken carbon fiber shells in the past notably those created by the 2009 Cal Poly Formula team. C6 Wheels must create a robust bead seat that will withstand the forces during tire seating. These loads will be analyzed through FEA.

Another risk associated with a one-piece shell is the increased complexity of a ply schedule and stitching process. A one-piece shell will necessitate a larger preform than a two-piece, possibly demanding more complicated stitching fixtures. C6 Wheels will need to develop a viable ply schedule and stitching strategy.

Ensuring the wheel will release from the mold is most important. C6 Wheels will make sure that mold-to-carbon surfaces are polished to a high surface finish. In addition, the selection of a proper release agent will be crucial. Reinventing the Wheel used an inadequate release agent which contributed to their wheel sticking to the mold.

Even resin distribution and resin flash are also important risk factors to consider. C6 Wheels wants to create a mold that will allow resin to travel to all necessary locations while also limiting the number and severity of flash sites. The team aims to pursue vacuum infusion with resin input ports along one rim of the wheel and vacuum ports along the other rim, however the resin infusion process depends on the mold geometry and is still under evaluation.

When addressing flash mitigation, C6 Wheels spoke with professor Trian Georgeou, a machining expert in the Industrial and Manufacturing Engineering Department at Cal Poly. Trian explained that with the proper surface finish, clamping force, and sealing mechanism, little to no flash should occur. These plans should mitigate potential risk associated with a one-piece wheel shell and the selected mold.

5. Final Design

The final design is a trapped rubber mold with a split four-piece female outer shell, silicone male plugs in contact with the carbon backed by aluminum male inner shells. See figure 11 below. Originally, resin would be delivered through the center of the upper aluminum male shell and exited through threaded 1/4 in. NPT barbed hose fittings located around the bead seat at both the top and bottom of the mold. This feature is no longer needed as prepreg will be the material of choice.

Table 9 – Resin Infusion vs Prepreg

Criteria \ Concept	Weight	Resin Infusion		Prepreg	
Ease of use	5	0	0	1	5
Complexity	5	-1	-5	0	0
Cost/Availability	5	-1	-5	0	0
Control of Fiber Volume Fraction	4	0	0	1	4
Conformity	4	0	0	1	4
Cleaner Process	3	0	0	1	3
Sum of weighted scores		-10		+16	

Locating pins will be press fit into the female outer shell pieces, one round and one diamond for each piece so as not to over-constrain the mold. The mating sleeves for the locating pins will also be press fit into the female outer shell pieces, two for each. The female pieces will be held together using 1/4-20 machine screws.

The octagonal shape on each of the male aluminum shells will mate with a matching feature formed by the four female pieces. The male shells will be fastened with 1/4-20 machine screws as well. See figure 12 below.

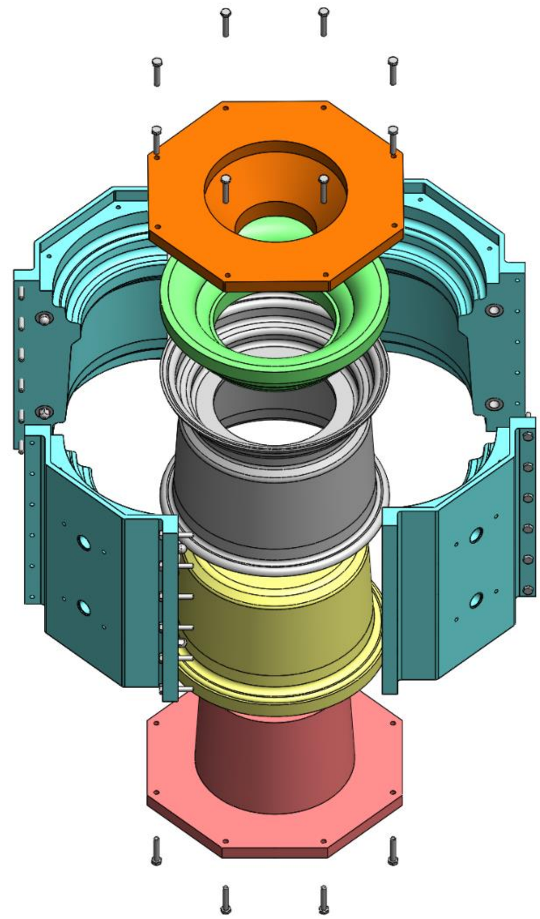


Figure 12 – Detailed, exploded view of trapped rubber mold.

5.1 Wheel Layup Design/Stitching Method

The laminate design was initially guided by manufacturability in accordance with Seriforge's stitching effort then adjusted for the use of prepreg. The chosen material for the wheel is a 2x2 TC275/HTS40 prepreg twill manufactured by Tencate and supplied by the formula team.

Drapability of the plies, the ability of the fabric to lay down smoothly, dominated the type of carbon fiber fabric to select. The malleability of the fabric is a combined effect from several factors such as stiffness, flexural rigidity, weight and thickness.[15] [16]. The stiffness of the fabric itself depends on its geometric arrangement. A 2x2 twill weave is recommended by the design engineers at Seriforge. It is formed from an over-over-under-under braided pattern, see Figure 13 below, and is considered for complex shapes because of its loose weave.

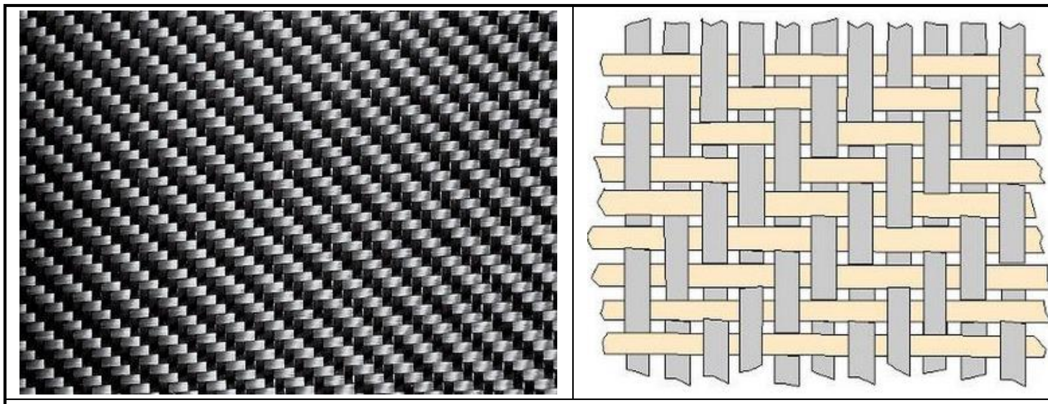


Figure 13 – 2 by 2 twill weave carbon fiber pattern drawing (left) and carbon (right)

A drape analysis in Laminate Tools, an industry software for evaluating drapability, was performed by Seriforge. It modelled the effect of draping of 12 plies of 200 gsm Carbon Fiber 2x2 twill. The analysis generated a single flat pattern, shown in Figure 14 below, with 4 darts (relief cuts) as the simplest way to manufacture this preform. A similar method would be employed for the long portion of the barrel. The center hole would need to be cut out to allow for the insertion of the wheel center.

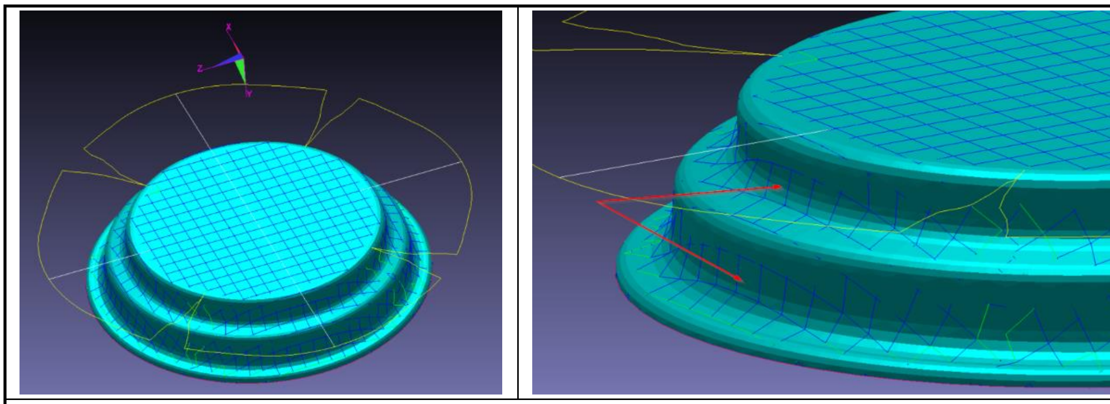


Figure 14 – Fabric draping for shallow portion of the wheel rim. Due to the way the fabric lays down, there is an approximate hoop at the flanges and vertical faces.

This pattern would be placed for 12 layers, ply by ply, rotated at increments of $[0/45/-45]_4$. See figure 19 below. The ply rotations will load the hoop strength continuously through the "pie" sections and rely on radial zero's for bead stiffness.

A detailed FEA with material properties of standard carbon fiber fabric similar to 2x2 twill and ran for a 1/8" thick layup (12 plies) will inform us if target allowables are met with this design.

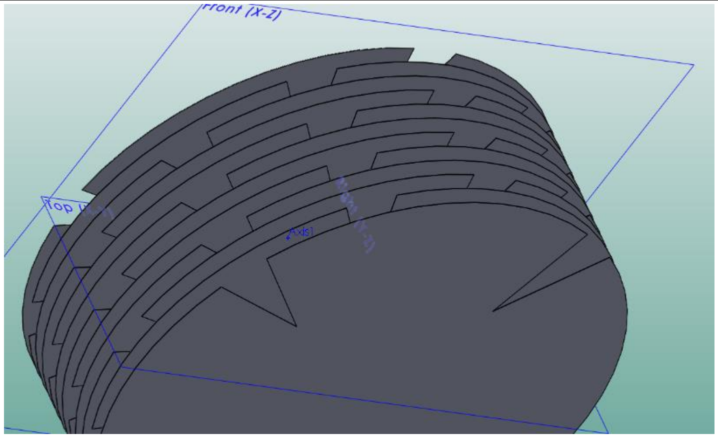


Figure 15 – Ply schedule with layers offset by 45°.

5.2 Wheel Analysis

For preliminary analysis, FEA was done on the wheel in Abaqus using Aluminum 6061 as the material, with a 1/8 in. thickness all around. The wheel center and rim were tie bounded at the joining holes along the flange to approximate the bolted connection.

High stress areas were concentrated around the bead seat as expected. Unlike isotropic material, the carbon fiber wheel will have directionally-dependent strength properties.

After developing the model using the simplified assumption of an isotropic material to verify that the loading and boundary conditions had been properly applied, (see figure 20 below), a preliminary carbon fiber layup was applied to the model. See figure 16 below.

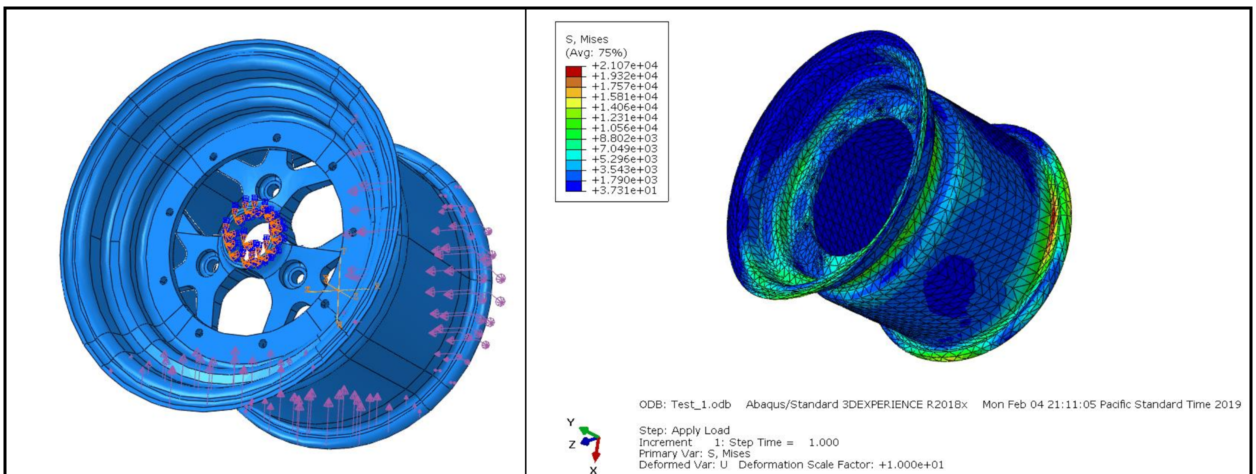


Figure 16 – Distributed wheel loads modelled in Abaqus (left) and preliminary stress results (right). Analysis is focused on the wheel rim, although the tire loads are transmitted through the bead, and reacted at the center due to the hub bolted connection

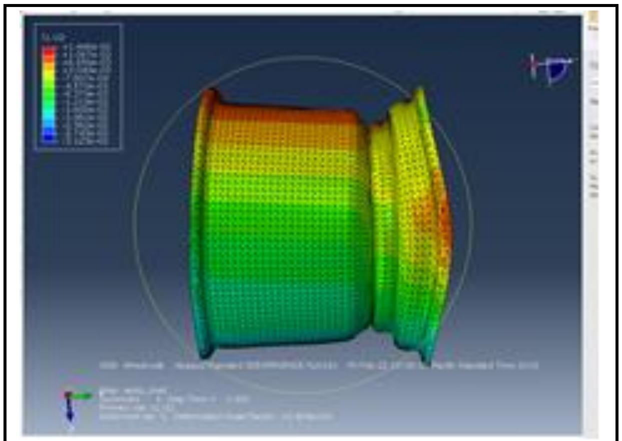


Figure 17 – Carbon fiber comprised of 10 layers each 0.012” thick applied to the Abaqus model.

The preliminary layup of $[0,45\text{-}45]_4$ was modified to $[0,45,-45,-45,45,0]_S$ where the subscript S denotes *symmetric*. A laminate is symmetric if the angles and thickness of the layers are the same above and below the midplane. A symmetric laminate is desired because the applied stresses result only in in-plane strains and shear but no coupled curvature is produced.

The layup used in the FEA model is 12 layers of 2x2 twill each 0.012” thick forming a quasi-isotropic material. The material properties were determined from the manufacturer’s data sheets. The rule of mixtures combining the properties of the fiber and the matrix in the equation $E_C = E_F V_F + E_M V_M$ was used to adjust the engineering constants to more closely approximate the expected final properties of the laminate.

The stiffness target of the wheel is 0.2°/g. Half of this allowance is allocated to the aluminum center, and half to the carbon shell. This means that the shell, under 1 g cornering should deflect 0.1° or less. To measure the angular deflection of the wheel shell, the point of highest deflection in the Y direction (as defined in the FEA model) is measured, as well as the point on the opposite rim of the wheel. The inverse tangent of the Y distance between these points divided by the diameter is the angular deflection. In other words:

$$\tan(0.1°) * 10 \geq 0.0175$$

where 10 in. is the diameter at the measurement point and 0.0175 in is the Y distance between the two measured points. Figure 19 below shows the max deflection at a value of 0.02 in. This is slightly higher than the allowable 0.0175 in, but this is based on the most conservative numbers for material properties from the carbon fiber manufacturers. When the model is run using even the midrange numbers, the camber compliance goal is met.

The FEA model displays the von Mises stresses – a direct measure of the distortion energy observed on the body by summing the stress from all load cases. Using material properties of the 2x2 twill being used in the test, the wheel does not fail under the applied loads.

Additionally, under this layup, the wheel shell weighed 2.7lbs, a 30% savings from the existing aluminum barrel.

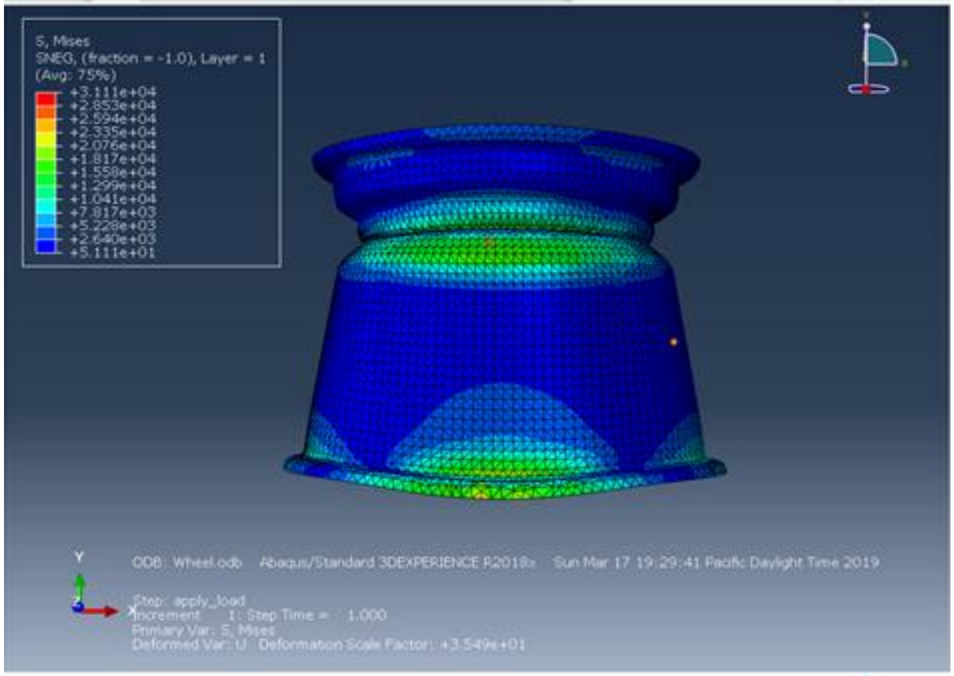


Figure 18 – Von mises stress results

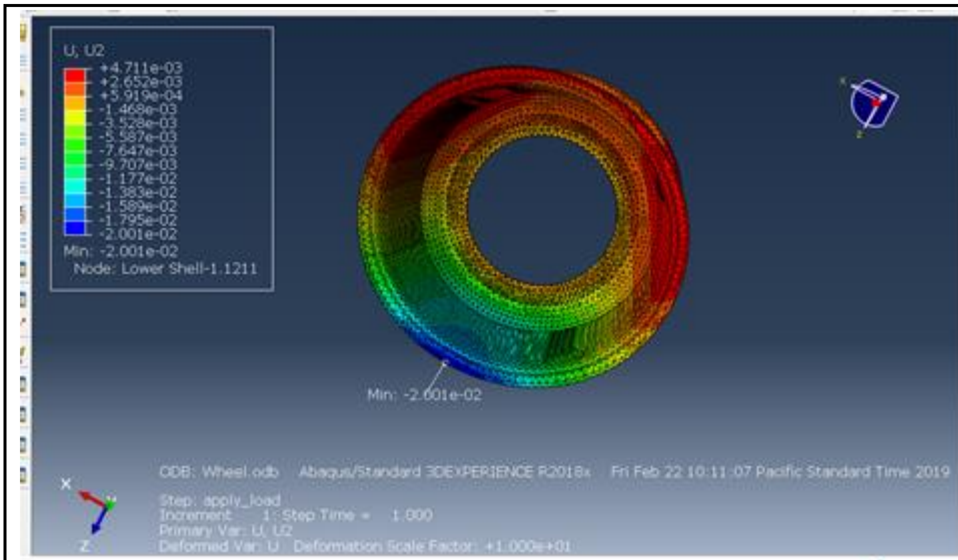


Figure 19 – Maximum deflection in the Y direction on the wheel rim from the Abaqus model.

Further analysis using this model will be made as the ply lay up changes to accommodate a hand laid prepreg layup. Physical testing of the wheels will ultimately be performed to validate the physical design requirements before being used in competition.

6. Manufacturing

The manufacturing portion of the design project includes the manufacture of the coupon test mold, female mold fixture base, and one component to the female mold. C6 Wheels utilized the HAAS Tool Room Mill for all CNC machining operations, located in Cal Poly Building 41. This section has been updated to reflect the actual manufacturing process that C6 Wheels followed to produce the coupon test mold, female wheel mold, and fixture block. It also includes manufacturing recommendations for the completion of the wheel mold.

Manufacturing of each component began with procurement of materials. Aluminum for the coupon test mold, female mold fixture base, and female mold were all purchased through Coast Aluminum using the Cal Poly IME department account. Silicone for the coupon test mold was purchased through BJB enterprises, and other hardware, acrylic, and tooling were purchased through McMaster-Carr. Note that a piece of aluminum stock was also purchased through McMaster-Carr due to a slight design change in the coupon test mold after the initial purchasing of coupon test mold stock from Coast Aluminum. All purchasing receipts are attached in Appendix L. Table 10 shows the final cost breakdown for the project.

Table 10 – Cost of assembly

Category	Cost
Female Wheel Molds and Fixture	$934.03
Coupon Test Mold	$355.89
Miscellaneous	$130.66
TOTAL	$1420.58

Since the mold and wheel manufacturing process involve machining, handling of heavy stock, mixing of chemicals, and usage of a heat source, C6 Wheels has performed a Risk Assessment to understand the inherent risks of the manufacturing process to those participating in it. This Risk Assessment, which offers mitigation for each of these risks, can be found in Appendix E.

6.1 Coupon Test Mold Manufacturing

The coupon test mold shown in section 6.2 was produced through multiple machining operations. There were four main components that were machined for the test mold: The mold top, the mold middle, the mold bottom, and the mold bosses (quantity of eight). Before machining, C6 wheels used BobCAM and HSMWorks to produce tool paths for each operation. An example of this is shown in Figure 20. Once each tool path was completed, a stock simulation was used to ensure there would be no machining issues during the job operation, and that the tool path would machine each component to the proper dimensions. Once this check had been done, the tool paths were converted to G-Code using a HAAS post-processor and uploaded to the Tool Room Mill (TRM) controller.

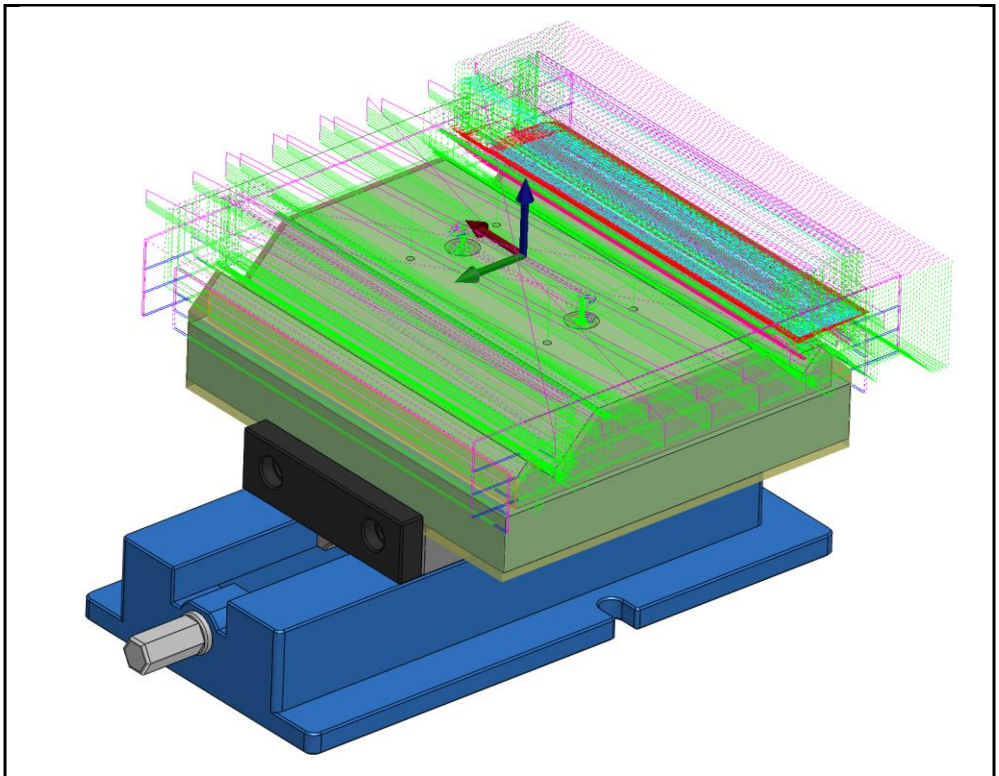


Figure 20 – Example of generated tool paths on female wheel mold using BobCAM

The mold middle was machined out of a 2.5”x6”x12” piece of aluminum 6061 T6 stock. The stock was fixtured in a traditional vice using hard jaws and a parallel set on the Tool Room Mill. A mallet was used to ensure proper seating on the parallels, and a chuck wrench was used to achieve proper clamping. After properly fixturing the stock, a locating edge finder was used to set the proper working coordinate system, and each individual tool was touched off of a 3-2-1 block to set proper tool heights for the operation. After this preparation, the first operation ran, facing the top of the part, clearing out stock in the pockets of the test mold as well as around the outside. A spot drill located where future holes would be drilled. Figure 21 shows the middle mold after the first operation.

Figure 21 – Coupon Test Mold middle after operation 1

The second operation utilized the same preparation steps as the first operation (fixturing, locating, and tool offsets) with the other side of the stock flipped on top. For this component, the same operation was performed since the component is symmetrical about the mid plane. After both CNC operations were completed, a drill press and size #7 drill bit were used to peck drill the holes that had been spot drilled during the CNC operations. After the holed had been drilled, they were tapped to ¼-20 size.

The bottom mold began machining once the middle mold had finished its CNC operations. The bottom mold was machined out of a .75"x6"x12" piece of aluminum 6061 T6 stock. The bottom mold was similarly fixtured and located using the same techniques and equipment as the middle mold. The first operation for the bottom mold contoured the outside edge of the stock, faced the top for proper flatness, added a chamfer for safe handling, and spot drill holes to guide future drilling operations. The second operation likewise flipped the component over the midplane. The second operation began with a face mill to ensure parallelism, continued with an outer contour to match the first operation, and used an end mill to machine pockets with ¼" depth to match the pockets machined on the middle mold. A chamfer was added to all sharp edges to ensure safe handling. Post-operation, through holes were peck drilled into the component using a size F drill bit to ensure a clearance fit for the bolts that fasten the mold pieces together.

The top mold began machining once the middle mold had finished its CNC operations. The top mold was machined out of a .75"x6"x12" piece of aluminum 6061 T6 stock. The top mold was similarly fixtured and located using the same techniques and equipment as the previous mold components. The top mold operations included face milling, outer edge contour, and spot drilling. Since the component is symmetrical about the midplane, the first and second operation were approximately the same, barring some material removal around the fixtured area of the component. Once CNC operations were completed for the top mold, through holes were peck drilled into the component using a size F drill bit to ensure a clearance fit for the bolts that fasten the mold pieces together.

Lastly, the bosses were machined. To begin, a piece of 2”x6”x12” was cut int 2”x6”x1.25” sections for each of the eight bosses. The mold bosses were similarly fixtured and located using the same techniques and equipment as the previous mold components. The first operation for each boss included a face, contour, and chamfer. Figure 22 shows the contour during the first operation on a boss. The second operation included an adaptive tool path to clear excess stock down to .010” above the desired final height, a finishing face mill pass, contour, chamfer, and spot drill. Two bosses each were machined to a separate height, for a total of four final heights. After CNC operations, each boss was peck drilled as a blind hole with a size #7 drill bit, and then tapped to ¼-20 size.

Figure 22 – Contour during the first operation on an aluminum boss.

After all aluminum machining had concluded, 3/16” acrylic pieces were laser cut to pocket size with an accompanying through hole to match the bosses. These pieces were inserted under the bosses in the assembled mold so that the silicone pucks could be poured to the precisely desired height, guaranteeing proper dimensions for both the puck and desired process gap.

To create the silicone pucks, the TC-5050 two-part silicone was mixed at a ratio of 10:1 for parts A and B, respectively. Since mixing allows for air bubbles to be trapped in the silicone mixture, the silicone was set in a vacuum chamber and de-gassed for five minutes before pouring to ensure no air would be trapped during silicone curing. Once de-gassing was finished, the silicone mixture was poured into each pocket of the coupon test mold all the way up to the top of the middle mold. The top mold was then bolted to the middle mold to create a closed cavity. The mold then sat overnight to allow the silicone to cure. This process was discussed more in depth in the test plan section since future engineering students may want to create varying sized silicone pucks for testing purposes.

Once the silicone had successfully cured, the mold was disassembled, the acrylic spacers under the bosses were removed, and the mold was then reassembled. At this point the coupon test mold was ready to be used to produce carbon fiber coupons for compaction and strength testing. Figure 23 shows the completed coupon mold.

Figure 23 – Completed Coupon Test Mold with Silicone pucks cast inside.

6.2 Wheel Mold Manufacturing

Due to the project rescope, the manufacturing of the wheel mold became more focused on proofing out the manufacturing process of the female mold. Manufacture of the female mold began with the machining of the female mold fixture block. This block was necessary in order to machine the geometry of the female mold. Figure 24 shows the stock that was used for both the fixture block as well as female mold. Note that while C6Wheels only produced one female mold piece, the team procured material so that future students can machine the remaining three.

Figure 24 – Stock for fixture block and female mold.

The fixture block was machined on the Tool Room Mill in two operations: The bottom and the top. The stock was fixtured in the vice the same way that previous components were for the coupon test mold, and then located similarly using an edge finder. The first operation included a face mill to qualify the bottom face, a contour to qualify the sides, a bore cycle to create the pockets for the diamond and round locating pins, and then a spot and peck drill operation to create through holes using a size F drill bit. After this, the piece was un-fixtured, flipped, and re-fixtured and located. The second operation consisted of a face mill to qualify the top surface, an adaptive clear with a face and end mill to hog out material on the angled faces of the fixture block, a bore cycle to create space for the socket head shoulder screws that are used to attach the fixture block to the female mold, and then a finishing pass with a 45° end mill to create a datum surface on each angled face of the fixture block.

Once the fixture block was completed, machining for the female mold began. The first operation for the female mold began by fixturing and locating using the same methods discussed for previous components. Figure 25 Shows the initial set up with the job stock.

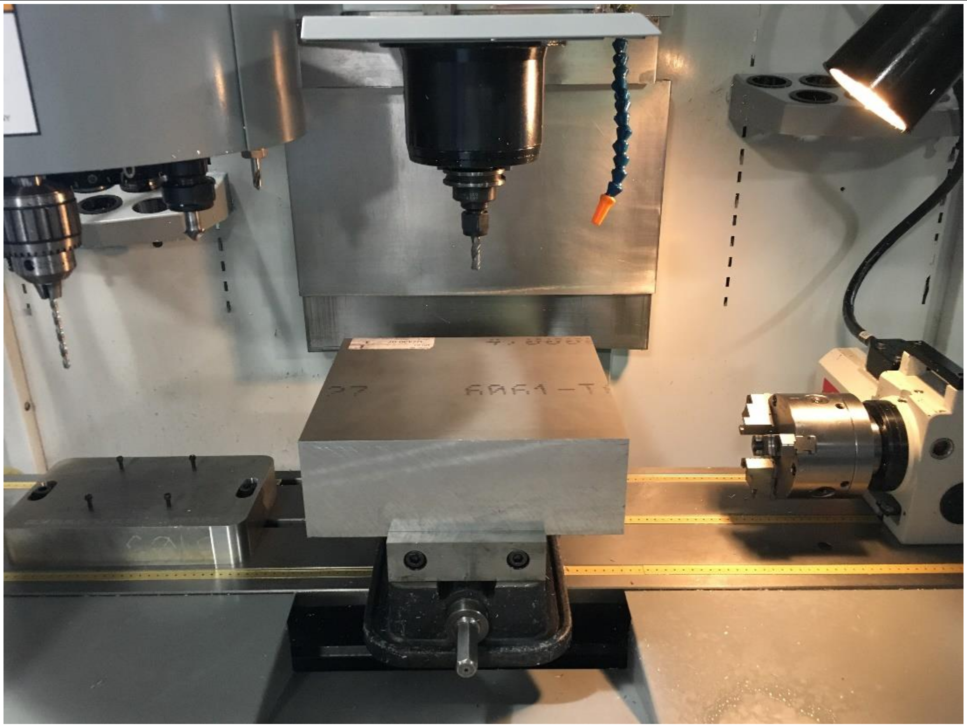


Figure 25 – Female mold stock setup for Op 1 on Haas Tool Room Mill.

Note that, due to the size of the job stock, the vice needed to be modified to have its clamping jaws on the outside as opposed to the inside. Since the size of the workpiece was so large, a rubber mallet was used in conjunction with a chuck wrench to guarantee the highest clamping force possible. The first operation included a face mill to qualify the top surface, a contour around the outer surface, an adaptive clear using the face mill and a flat end mill to hog out material near the angled faces, an adaptive ball end mill tool path to achieve the curved surfaces on the outside, a bore cycle to clear pockets for the sleeves that mate with the locating features on the fixture block, a spot and peck drill cycle using a size #7 drill bit (to be tapped later) so that the fixture block and handles can both be properly attached to the female mold, and finally a finishing pass with the 45° end mill to finish the angled surfaces of the mold. Figure 26 shows the workpiece after completion of the first operation.

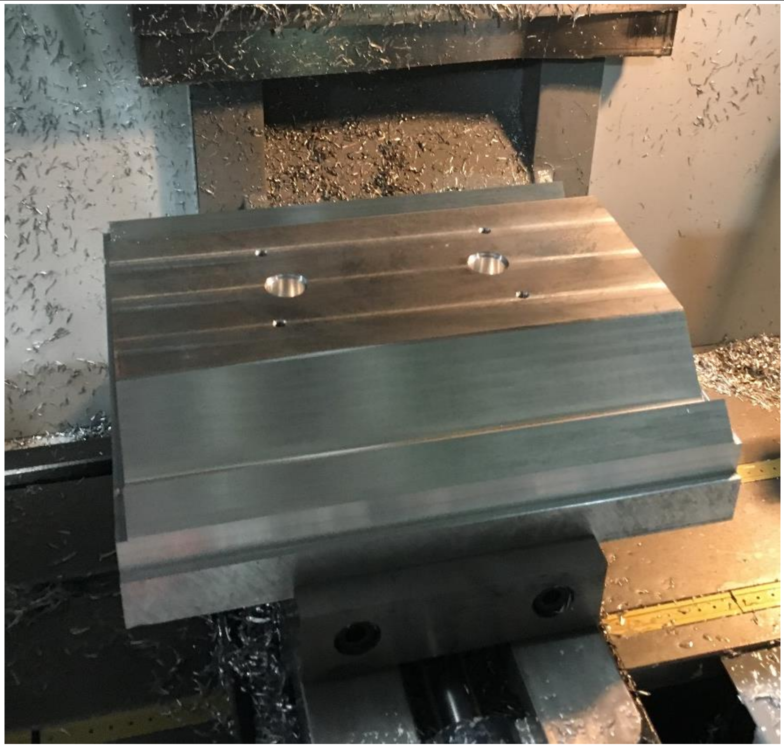


Figure 26 – Female mold workpiece in vice on second machining operation

After the first operation, the stock was rotated and stood up on end for the next operation. The second operation included the same fixturing and locating process as all previous operations. The vice jaws were moved back to the inside of the vice since the clamping surfaces are closer together for these operations. The second operation began with a face mill to hog out most of the material, an end mill to finish the internal wall that will mate with the male plug, a spot and peck drill with a size #7 drill to be tapped later, and a chamfer on the wall surfaces. The third operation was the same as the second operation on the other side of the workpiece. Figure 27 shows the set up for these operations.

Figure 27 – Female mold setup for job operations two and three.

6.3 Manufacturing Challenges

During the manufacturing process of both the coupon test mold and female wheel mold, many challenges presented themselves that were unforeseen. While some challenges were constrained to each mold, one challenge that presented itself was the schedule of the machine shop. Due to both IME 335 and IME 450 being taught in the spring quarter, access to the VF2 was impossible for these operations. This led to all outside project work being directed to the Tool Room Mill. Since many students needed to machine components for personal or academic projects, there were several days that the team expected to machine but were not able to. Additionally, several new CNC machines were added to the shop mid-quarter. Because of this, the shop was closed for several days to set up the new machines and modify the space. This occurred during a time that was essential for the manufacturing schedule of the project, so these occurrences caused unrecoverable setbacks that led to the hardware of the project being unfinished by the time of Senior Project Expo.

6.3.1 Coupon Test Mold Challenges

The first challenge faced during the coupon test mold manufacturing was due to a design modification done after ordering the stock material for the mold that split the coupon test mold bottom and bosses into their own components. This challenge was resolved by taking one of the original pieces of stock and ban sawing it into multiple pieces to be repurposed as bosses, and then ordering an extra piece of stock from McMaster-Carr for the new mold bottom.

The second challenge faced during the machining of the coupon test mold related to the schedule of the machine. Another student needed to produce a part on the Tool Room Mill using soft jaws. In order to do the machining operations that day, a separate pair of vice jaws was instituted on the outside of the vice and the coupon mold was clamped long-ways. Unfortunately, this fix caused a lot of chatter in the face milling operation, so the finish on that component was low quality compared to the other operations; however, this did not affect the functionality of the part.

The third challenge faced was the slip fit of the bosses within the coupon mold. One of the main functions of the bosses was to determine the height of the silicone pucks and act as a bottom during the silicone pouring and curing process. When the first boss was first machined, the boss did not fit properly in the coupon mold. To accommodate the bosses, they were redesigned and machined to a slightly smaller width and length, and a slightly larger corner radius. The dimensional modification was done in small increments until the boss eventually fit properly in each pocket of the coupon mold. This was determined during the machining of the first boss so that the remaining seven bosses did not need to go through this process again. The CAD and tool paths were modified for each subsequent boss so that they were machined to final dimensions on the first run.

6.3.2 Wheel Mold Challenges

Machining a work piece the size of the female wheel mold is a challenge in itself, but there were multiple specific challenges that arose throughout the process. The first challenge during the machining was to proof out the usefulness of the 45° end mill. Programming for the end mill was difficult since BobCAM did not recognize the specific tool. The first pass of the tool cut showed a very important fact: the end mill must start from the top of an angled surface and march downward. The first iteration of toolpaths that were generated for the wheel mold fixture block began the tool path near the bottom of the angled face. This caused there to be an overhang of material over the cutter, and the cutter ultimately pulled itself out of its collet during the cut, causing a large gash on the part. Luckily, this gash did not interfere with the functionality of the fixture block, so the part was not scrapped. After this gaff, the team programmed a new tool path that marched down in the Z-direction and proved that the 45° end mill was sufficient to produce a quality 45° face. This significantly reduced machining time, since without it a scalloping tool path would need to be used to achieve the same geometry. Generating such a tool path would be of little use, due to the next challenge.

The second challenge during machining of the wheel mold was running into the memory limit for the machine. Since the Tool Room Mill runs off a floppy disk, the maximum file size for a G-Code program to run is about 1.3 MB. Using adaptive tool paths and having a work piece as large as it was, exceeding this file size was incredibly easy. Unfortunately, this caused a significant increase in shop time, since otherwise quality tool paths needed to be parsed into multiple operations to achieve a file size of less than 1.3 MB. Due to this limiting factor, the final operation for the female wheel mold could not be completed until finals week. The finishing pass is a complex scalloping tool path that cannot be parsed and is necessarily larger than 1.3 MB, therefore, machining for this operation could not be done until a VF2 was available for it.

It is easy during the machining of such large and complex components to make mistakes on the mill. In the case of the female wheel mold, two mistakes were made that caused gashes in the part. The first was a failure to properly set the retract height above the part for a milling operation. The cutter plunged straight into the work piece and sheared clean off, leaving a gash on the outer surface of the female wheel mold. The second mistake was a blunder with the handle jog on the machine. A mistake like that is easy to make after a long week of machining and is a reminder to maintain caution and meticulousness throughout the entire process. These gashes did not occur on critical surfaces, and therefore are not critical to fix. However, they can be fixed by filling in by TIG welding and then re-machining the local area.

Lastly, achieving a slight interference fit for the locating pins and sleeves was a challenge. The first boring operation on the fixture block created 3-thousandths undersized bores, so the bore diameter was slightly adjusted, and the bore cycle rerun. After the second bore cycle, the bore was slightly oversized. Due to the angled face geometry of the fixture block, the work piece was flipped over and the original bore cycle was run to create new bores. This time, instead of modifying the toolpaths, a spring pass was performed (running the same toolpath again without changing it). This procedure produced the results desired within about a thousandth of an inch. Due to the slight interference fit, the locating pins and sleeves were placed in the freezer to cause shrinkage, and then they were pressed in to the fixture block and female wheel mold.

7.4 Future Mold Manufacturing Recommendations

Due to the project rescope, much of the manufacturing originally planned for C6 Wheels was unable to be completed. However, the machining has given insight that will be beneficial for future students working to complete the wheel mold. The female mold piece was produced to prove out the machining process for the remaining three female mold pieces, and to create a fixture making it feasible to machine the pieces on any equipped mill using just a vice fixture. Specific instructions for machining these components is attached in Appendix M as a machining manual. Use the manual as reference for how to fixture the job stock to successfully machine the female mold components, and to guide the generation of the specific tool paths that will be used in these future job operations.

It is recommended to use a VF2 or an equivalently powerful CNC Mill for all machining. While the Tool Room Mill was sufficient for multiple operations, the problems that come with it make machining much more difficult. Namely: The spindle is much less powerful, the table has a smaller range of travel, the tool carriage can get in the way during operations two and three, the open nature of the TRM allows for excessive chip throwing and coolant loss to the surrounding area which necessitates much longer clean up times, the use of an edge finder to locate a work piece is inherently less accurate than using the probe on the VF2, and the small file size increases the complexity and number of tool paths needed for the same job. For these reasons it is heavily advised to perform all machining operations on the VF2 when available.

Professor Trian Gorgeou is a great resource for all machine related inquiries. In the case of a less experienced student generating tool paths to cut mold components, it is recommended to check all operations with Trian and discuss any areas of confusion. Additionally, it is highly recommended as a Cal Poly student to take IME 335, 336, and 450 if possible, prior to or concurrently to machining for this project if the student does not have much machining experience.

The final design of the aluminum male plugs will be influenced and determined by how the future team decides to machine the parts as well as the results of the silicone compaction tests. It is recommended for the future team to run their own compaction tests using the coupon test mold to test the cure cycle before trying to cure a wheel shell. Further coupon tests could also proof out different ply schedules, and the coupon test mold is designed so that any variation of bosses can be created to vary the test. This requires pouring of silicone.

To create the silicone plugs, a mold must be created to pour silicone into to achieve the proper shape. It is recommended to use the aluminum male plugs as one half of this mold, and to 3D print the female portion of the mold. Another option is to 3D print the exact shape of the wheel then place it in the final mold assembly, with the aluminum female outer and male plugs and to pour the silicone in the designed gap that the sleeve would fill. Consider the tolerance of 3D printers as well as the cost of material and consider how to locate the two molds to each other to assure proper tolerances and cylindricity of the silicone plugs. This will help to ensure even compaction during the wheel shell cure. It is important to degas the silicone after it is mixed so that voids do not exist in the final cured silicone piece. Since both silicone plugs require a large amount of silicone, check that the mixing container can hold enough silicone mixture and that it can fit in the available degassing chamber.

General recommendations for this project's continuation are discussed in section 8 and 9.

7. Design Verification

High pressure is key to packing a mold with high fiber content. High fiber content is the driving factor for strength and stiffness, two crucial qualities for a racing wheel subjected to extreme loads. Engineers from the School of Materials Science and Engineering of Beihang University in Beijing China, summarize the justification for trapped rubber molding:

"It is of great difficulty to provide appropriate compaction pressure to composite parts with a three-dimensional complex structure such as tubes, inserts, ribs, etc. Thus, voids, delaminations and fiber bridging, which significantly reduce the mechanical properties of composites, are often observed in these structures. As to overcome these problems, thermal expansion molding method was introduced to apply uniform compaction pressure over a complex surface" [17].

Figure 12 below illustrates the effects of various compaction pressures on a laminate tested by this same university. With too much pressure applied to the laminate, there is possibility for resin overbleed. With too little pressure, poor consolidation of layers and voids could exist. An optimal compaction pressure exists for the specific thickness of the laminate.

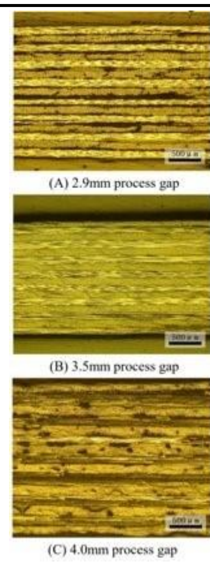
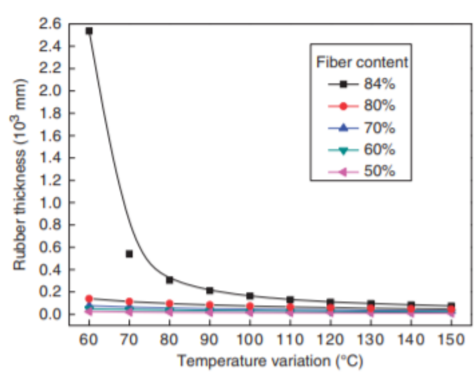


Figure 28 – Micrographs from a paper published by Beihang University Engineers [17].

Figure 12. Micrographs of Carbon Coupon cross section from a trapped rubber test

In order to create a part with high fiber content, the ratio of fiber to resin must be high. This is called a fiber volume fraction (FVF), or the ratio of the volume of a carbon fiber part without resin to the volume of the part post resin infusion and cure. It is generally accepted that the higher the FVF the stronger the part. A FVF of 70% has been chosen as a goal based on research from Tianjin Polytechnic University that concluded FVF's of up to 84% were achievable with trapped rubber expansion [18]. See figure 29 and table 11 below for a summary of their findings.



Fiber content (%)	84	80	70	60	50
Silicone rubber thickness (mm)	74.5	46	28	19	9.4

Figure 29 – Temperature variation and silicone thickness effect on fiber content graph from a paper published by Tianjin Polytechnic University [18].

Table 11 - Fiber content and associated silicone thicknesses [18].

Fiber content (%)	84	80	70	60	50
Silicone rubber thickness (mm)	74.5	46	28	19	9.4

One alternative to a trapped rubber molding process is vacuum bagged infusion and compaction, however this process is not suitable for creating a high-quality wheel. With a vacuum bag, a theoretical max pressure of 1 atmosphere or 0.1 MPa can exist to compact the plies. Trapped rubber molding can exceed 16 MPa based on research from Tianjin Polytechnic University [18].

Trapped rubber molding also creates better surface control than vacuum bagging and can act as protective backing to prevent warpage of the laminate. In the vacuum bag process, wrinkling often occurs which is difficult to mitigate with tight, complex geometry like the wheel bead seat. The Reinventing the Wheel team specifically warned against using a vacuum bag against any control surface as the surface created would not be suitable to seal a tire against. A trapped rubber process achieves a higher quality part and is better suited for a complex wheel shape.

7.1 Design Plan and Details

A test was developed to verify the expansion rate of silicone in order to validate the trapped rubber mold design. It will demonstrate the compaction due to thermal expansion of silicone during cure.

As shown below in figure 30 the molding plan for testing variable silicone thicknesses includes a three-piece aluminum mold. Four thicknesses of silicone will be tested: .75in, 1.0in, 1.25in, and 1.5in. The base has different height reliefs that allow the silicone coupons to sit level when assembled. It is very important for all carbon coupons to start at the same height to achieve valuable test results. The center portion has 1 x 5 inch slots which hold the reliefs from the base, silicone and carbon coupons, and joins the three mold pieces together. The mold is tightened with ¼-20 machined screws and once cured, the results will validate the thickness of silicone required to achieve proper compaction.

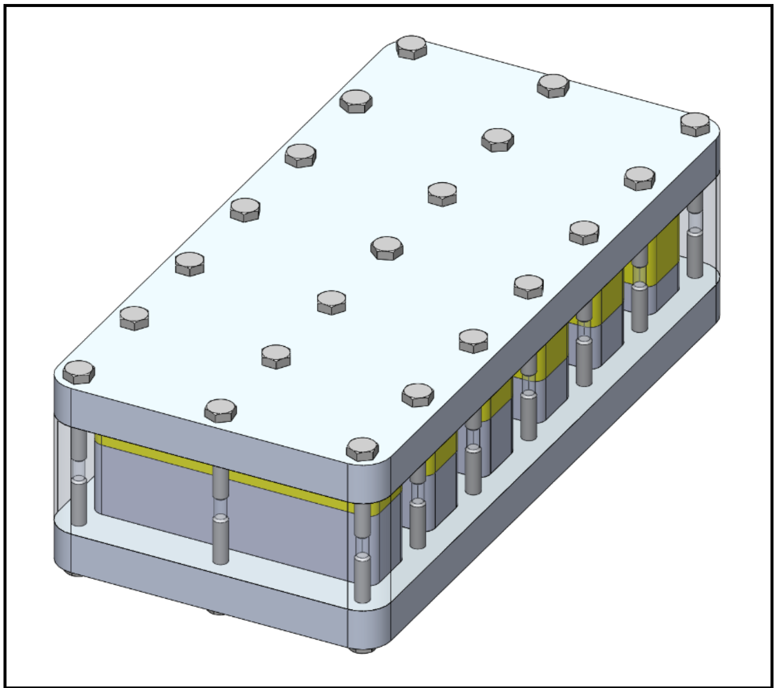


Figure 30 – Isometric of the silicone coupon test mold.

Multiple trials of the tests were performed to incorporate a process gap between the coupons and the lid of the mold. The first trial of the test included this thin gap because it was being considered in the final mold design for ease of assembly of the carbon fiber into the mold as well as in anticipation of resin bleed. The gap was created by casting the silicone sleeves with a 1/16 in. shim in place in the base of the mold but then removing the shim when inserting the carbon coupons and pushing the silicone down to the base. These shims were laser cut out of acrylic to fit into the slots.

Figure 31 – Plastic shims used to define the process gap.

The second trial removed the process gap by placement of the 1/16 in. shims in the base of the mold during cure. The third trial tested the effect of pre-compacting the coupons with the insertion of larger shims.

BJB enterprises, a casting and mold making company, has helped to specify material selection for the trapped rubber. From their advice, a platinum cure silicone was selected for the testing, specifically the TC 5050- A/B 50 Shore A. This is a two-part silicone selected for its ability to withstand high temperature and for its CTE being the largest of the products BJB distributes. They have run their own thermal expansions tests to which we can compare our results. Material properties for the silicone can be found on its data sheet in the appendix of the test plan shown in Appendix H.

The silicone A + B components are mixed together and can be poured into a mold while still in a liquid state. TC 5050 is a room temperature cure silicone with a 30-minute work time and a 24-hour demold time. The coefficient of thermal expansion (CTE) determined by BJB for the TC 5050 is 16.5 x 10-5 in/in/°F. Note that this is the linear CTE; the volumetric CTE is three times the linear CTE.

The test uses pre-preg carbon HTS40 3k 2x2 Twill supplied by the Cal Poly FSAE club team with a post cure optimal fiber content around 65%. This is the value for which the test will aim to verify a silicone thickness. Changing the carbon to pre-preg simplifies the mold: it no longer has resin input or output ports, it no longer needs resin flow channels, and it no longer needs a degassing chamber and resin pumps. See figures 15 and 16 below. The detailed test plan can be found in Appendix H.

7.3 Procedure for Conducting Silicone Coupon Test

A test was conducted with the intent of determining an optimal thickness of Silicone rubber to supply compaction pressure to Carbon Fiber plies. A mold was CNC machined, silicone pucks of different thicknesses were casted, and Carbon Fiber coupons of identical layups and thicknesses were cut, cured, and tested.

7.3.1 Casting Silicone

Casting of the TC5050 Silicone should be done carefully to minimize spilling. First, it is important to have to right equipment and materials to successfully cast. A list of necessary items are:

- Rubber latex gloves
- Stirring sticks
- Scale
- At least two containers
- Degassing Chamber
- Coupon mold – 3 pieces (bottom, center, lid)
    - Spacers
    - Height bosses
    - ¼-20 screws (at least 12)

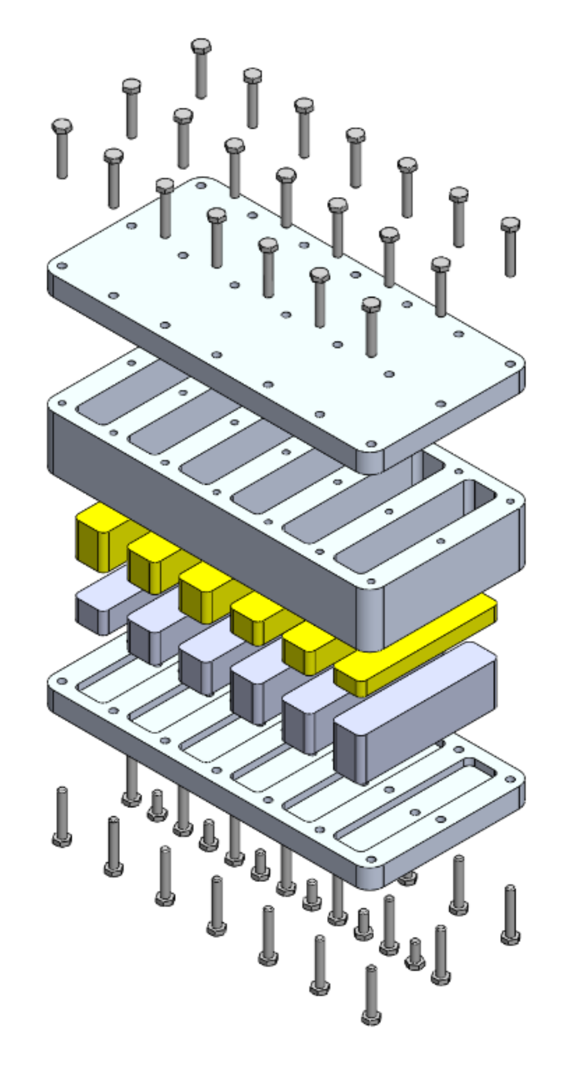


Figure 32 – Exploded view of coupon test mold components.

The first step is to prep the mold to be ready for casting. This means the bottom section of the mold should be fastened to the center portion using the ¼-20 screws. We recommend equally spacing six screws on bottom and top. Then spacers should be inserted at the bottom before the different height bosses are placed in the slots. The purpose of the spacers is to account for the thickness of the carbon fiber coupons that will be placed in the mold and cured later. We found best compaction results with no process gap, meaning that the coupons sit perfectly flush with the top of the center portion of mold.

Figure 33 – Mixing silicone by weight for the test coupon mold.

Mixing the silicone is next; this process is extremely messy and must be done quickly and thoroughly. Make sure to pour more silicone than needed because it is very viscous and sticks to all surfaces. We used a 10:1 by weight silicone to hardener ratio as recommended by the supplier. The silicone will begin to set 30 minutes after adding the blue hardener to the base silicone, so it is crucial to work quickly. The hardener must be thoroughly mixed with the base to ensure uniform pieces after casting with no cavities. Once the mixture has been fully mixed, it must be put in a degassing chamber to remove any air bubbles formed during the mixing process. These air bubbles can cause voids in the finished piece and alter the volumetric expansion as well as cause asymmetric compaction of the lamina. To degas, simply put the container in the chamber, seal the lid, and fasten a vacuum pump to the chamber inlet; the vacuum must read 29-30 inches of Mercury We found that 5 – 7 minutes in the degassing chamber was enough to remove significant air bubbles.

Figure 34 – Mixed silicone in the degassing chamber (left) and with the chamber being depressurized (right).

Figure 35 – The degassing chamber at full vacuum.

After degassing, the silicone is ready to be poured. Before pouring, cover the extra, unused threaded holes in the center portion of the mold with painters tape to prevent silicone from leaking into them. The mixture is extremely viscous and difficult to pour cleanly, so it helps to use a container with a sharp corner to aid in the precision of the pour. Make sure to pour completely to the top and even a little over the surface so that when the lid is fastened on during cure, some silicone squeezes out the sides. This ensures all the pucks have a flat even top. It is important that the top surface is flat and even because it will dictate the uniformity of the carbon compaction. Return to the mold in 24 hours once the Silicone has fully cured.

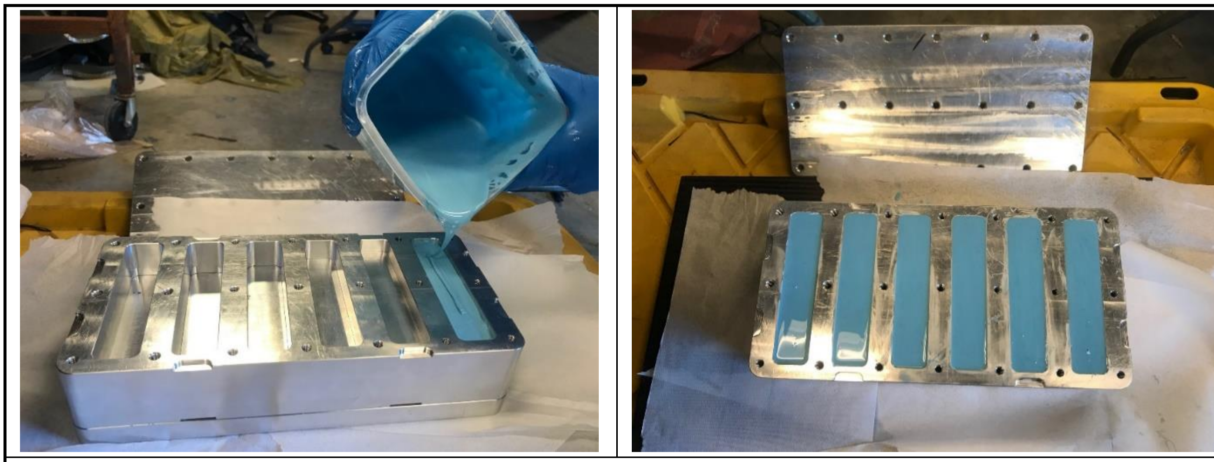


Figure 36 – Pouring the silicone blocks into the coupon mold (left) and all silicone blocks poured (right).

7.3.2 Cutting and Laying-up Carbon Fiber

Laying up the coupons requires simply peeling off the adhesive layer from each strip and bonding it to the next. It must be done with precision so that all coupons are consistent and results from comparisons are meaningful. The chosen lay-up is $[0\ 45\ \text{-}45\ 0\ 45\ \text{-}45]_S$ which is balanced and symmetric. See section 5.1 to see more details on lay-up validation. To cut the carbon we recommend using an exacto-knife however a sharp box cutter will also work. Cutting the 0 degree samples is straightforward, however the 45 and -45 samples should be done very carefully. It is important to measure the angle precisely and make sure that all samples are consistent. Changing the orientation by only a few degrees can change the mechanical behavior of the coupon. The most efficient way to cut the layers is to cut long 1" strips and then from the strip cut 5" pieces. The coupons can be laid-up as 1"x5" rectangles and later trimmed and adjusted with scissors and or a razor blade to fit snugly into the mold slots.

7.3.3 Assembling Mold and Prepping for Cure

Mold assembly must be done carefully and methodically due to the close fit of all the pieces. Proper assembly and sufficient mold release are integral for a successful coupon cure. It is crucial that the pucks sit flush on top of the height bosses and the bosses sit flat at the bottom of the reliefs on the base. Unevenness in either of these will result in uneven compaction of the coupons and will compromise validity of any data gathered using those coupons. One way to accomplish even assembly is to stack the Silicone on the bosses and insert them into the slot of the center mold piece as one unit, this will ensure no gaps between them. The Silicone pucks stick to the inner slot surfaces due to friction, so it helps to pre-freeze the pucks to shrink them and allow for ease of assembly. Leave the bosses sticking out the bottom of the mold slightly more than the depth of the release they will be sitting in on the mold base. Use the base of the mold to push the bosses and silicone pucks slightly further up the slots, this will ensure the bosses sit perfectly flat in the reliefs on the base. Then, fasten the base onto the mold center with ¼-20 screws.

Squeezing in the silicone required a bit of working because they are sized to fit exactly into the slots. Once the silicone is in, mold release needs to be applied to the surfaces on the middle portion and top portion of the lid which will be in contact and along the edges of the slots. An effective application of mold release was found to be 2 layers of Meguiar's M8 Maximum Mold Release Wax, followed by a layer of pva film 10, and finally two more layers of the mold release wax. Wax must also be applied along the threaded holes to restrict any resin flash from entering.

The remaining parts to assemble after this are the carbon coupons and the mold lid. The coupons should be placed on top of the silicone pucks as shown in figure 37 and the assembly tightened together as shown in figure 38.

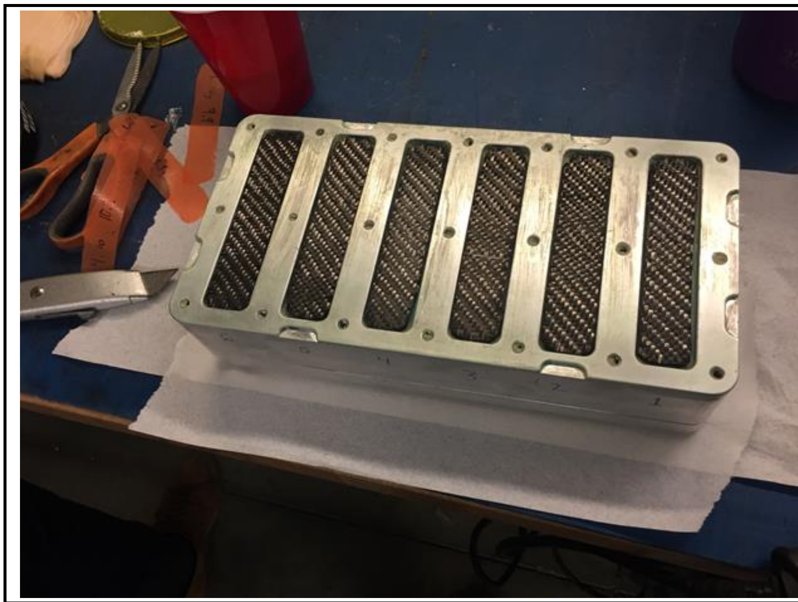


Figure 37 – Prepreg carbon fiber in the test coupon mold.

After tightening the bolts, the secured assembly is ready to be cured. The curing of the test mold was done in the composites lab in room 135 building 192. The cure cycle was followed from the manufacturer Tencate's recommendation to ensure complete crosslinking of the polymers in the thermosetting epoxy resin matrix.

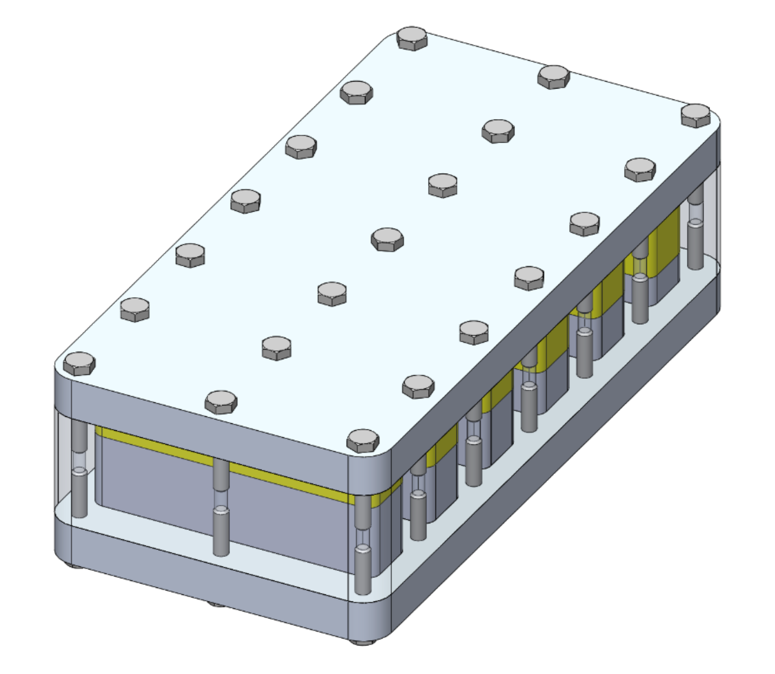


Figure 38 – Assembled Silicone coupon test mold rendering

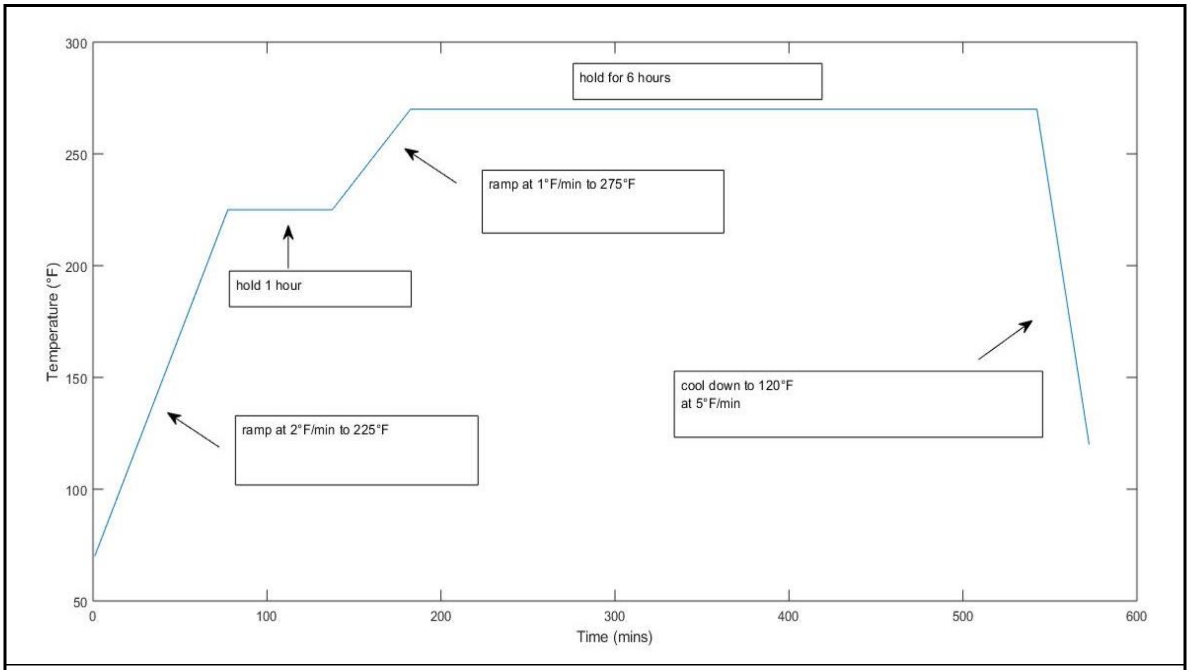


Figure 39 – Recommended cure cycle for TC275/HTS40 Prepreg Carbon Fiber.

After completion of the cycle, the mold is removed from the oven using insulating gloves and the coupons are removed and inspected immediately.

7.4 Results

The first test upon removal of the coupons from the test mold was a visual inspection of the cross section of each coupon to identify the quality of compaction.

Trial 1

For the first trial, a process gap of 1/16 in. existed between the top of the coupons and the lid of the mold. By inspection of the coupon, it can be immediately noted that voids exist. This meant that compaction pressure did not get applied to the coupons and trapped air was not sufficiently removed. For all silicone thicknesses, the silicone did not expand enough to push the prepreg coupons up against the lid of the mold.

Figure 40 – Coupon Cross section: 1/16 in. process gap, insufficient compaction, formation of voids

Next, the thickness of the coupons were measured with a caliper to see how much they varied from the desired thickness of 1/8 in. Due to the lack of compaction pressure from the silicone, the thicknesses did not vary significantly from precure to postcure as shown in table 12.

Table 12 – Before and After Cure Coupon Thicknesses

Trial 1		
Silicone Thickness	Precure Coupon Thickness	Post cure Coupon Thickness
.5"	0.12	0.117
.5"	0.12	0.115
.75"	0.12	0.113
1.0"	0.12	0.115
1.25"	0.12	0.112
1.25”	0.12	0.114

Since the final cured thickness of each coupon was less than the desired 1/8 in. it was decided to add 2 more layers to the ply layup during the next trial.

Trial 2

The test was repeated but with a few adjustments in attempt to get better results from the samples. Since trial 1 resulted in an insufficient amount of coupon compaction due to the 1/16” gap, shims were added to the bottom of the mold underneath the height bosses to account for this preexisting gap. The resulting process gap was effectively zero which caused the coupons to sit flush at the top of the slots.

The minimized process gap resulted in better compaction as can be seen in the image below. There are few void defects and the layers in the laminate are uniformly aligned.

Figure 41 – Coupon cross section: No process gap, proper consolidation, no overbleed

As expected, the reduced gap allowed for more expansion of the silicone to transmit directly to the coupons. A bit of resin was squeezed out of the laminate resulting in reduced post cure thicknesses. The resulting coupon thicknesses were recorded and tabulated in table 13.

Table 13 – Before and After Cure Coupon Thicknesses Trial 2

Trial 2		
Silicone Thickness	Precure Coupon Thickness	Post cure Coupon Thickness
0.5	0.144	0.115
0.5	0.144	0.117
0.75	0.144	0.111
1	0.144	0.1
1.25	0.144	0.101
1.25	0.144	0.101

Trial 3

The final trial was conducted using pre-compaction in combination with thermal expansion pressure. The purpose of this trial was to achieve a significantly greater compacted coupon and to test its mechanical properties in bending to compare with coupons of less compaction. The results would then verify the optimal amount of compaction that would display the highest strength.

When the lid of the mold was removed for this trial, there were pools of resin which had formed on the surface. This indicates that high pressures were achieved. An inspection of the coupons showed that too much pressure was applied because resin had over-bled from the prepreg stack. This is undesirable because it can lead to delamination as the layers are starved of resin and poorly bonded.

Figure 42 – Coupon Cross section: 1/16 in. pre-compaction, Resin over-bleed and poor bonding

Due to the large pressures, the cured coupons were much thinner than their precure thicknesses and well below the desired thickness of 0.125 in.

Table 14 – Before and After Cure Coupon Thicknesses Trial 2

Trial 3		
Silicone Thickness	Precure Coupon Thickness	Post cure Coupon Thickness
0.5625	0.144	0.084
0.8125	0.144	0.108
0.8125	0.144	0.079
1.0625	0.144	0.08
1.0625	0.144	0.078
1.3125	0.144	0.078

The coupons with the best compaction upon inspection were selected for mechanical tests. These were the coupons compacted by the .75 in. and 1 in. silicone with no process gap. To compare the quality of compaction to mechanical properties, the corresponding coupons compacted with the same thickness of silicone were also tested.

Flexure tests are popular tests for quality control and will allow us to easily compare the mechanical properties of the coupons of varying compaction quality. An initial bend test was chosen to reflect bending as the dominating load type the wheel will experience. A simple tensile could have been chosen to identify the compaction effect on failure mode.

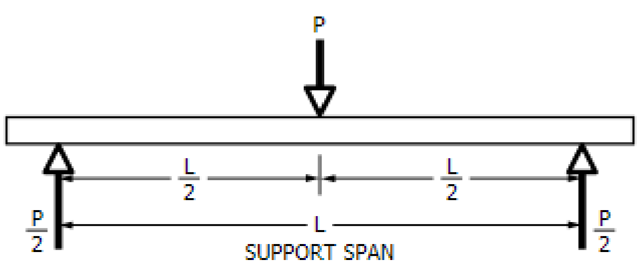


Figure 43 – – Flexural loading diagram for 3-point bend test

The test coupons were cut to satisfy the ASTM standard for bend test specimen sizing. A standard support span-to-thickness ratio (length to thickness) of 16:1 for each coupon was chosen to ensure consistency when comparing different thickness beams, as geometry is the major factor when considering moments of inertia. This forces failure to occur at the outer surface of the specimens due to the bending moment. A span to width ratio of 4:1 was also maintained.

An Ametek LD50 Dual Column 50kN Testing Machine with a three-point bend test fixture was used for loading application.

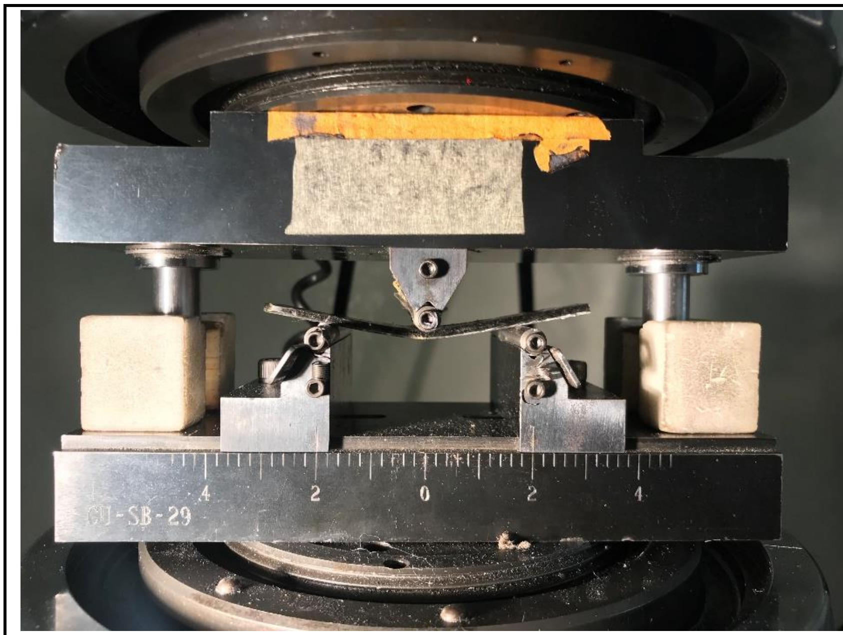


Figure 44 – An Ametek LD50 Dual Column 50kN Testing Machine with a three point bend test fixture used for loading application.

Prior to testing and upon inspection of the specimens, the apparatus had to be properly calibrated. Then the specimens were inserted into the test fixture so they were centered within the fixture. Specimens were loaded in three-point bending. Each coupon/specimen was held in the fixture by 2 roller supports and subjected to a concentrated load at its center, as described in figures 43 and 44. Each specimen was subjected to ramped load, with the loading nose set to a speed of .05in/min until failure was reached.

Bend test results from coupons molded from 0.75 in. and 1.0 in. silicone are compared in figure 45. These two thicknesses were selected based on our results from trial two where we found coupon thickness closest to our target and optimal compaction qualities.

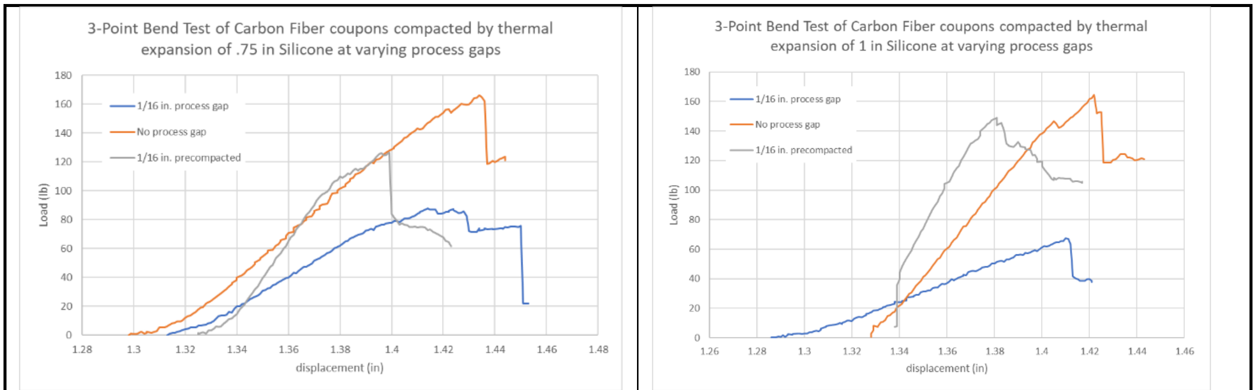


Figure 45 – Graph of the carbon fiber coupon loading in the tensile tester from trial 2, compacted by 0.75" Silicone samle (right) and 1" Silicone samle (left)

Failure loads were recorded and are displayed in table 15 and table 16. Fiber volume fractions were calculated using the pre and post cure weights and the densities of the matrix and fiber reinforcement.

Table 15 – Properties of coupons compacted by expansion of 0.75 inch silicone

	Fiber Volume Fraction	Load at Failure (lbf)
Process gap	58%	87.0
No process gap	65%	166.0
Precompacted	76%	126.6

Table 16 – Properties of coupons compacted by expansion of 1.0 inch silicone

	Fiber Volume Fraction	Load at Failure (lbf)
Process gap	58%	67.3
No process gap	67%	164.0
Precompacted	78%	148.8

For both silicone thicknesses, the coupon failure load was minimal when there was a process gap. This is shown in the tables as failure at 87 lbf and 67.3 lbf, for the 0.75 in and 1.0 in silicone respectively. These coupons contained many visible voids which negatively affected the mechanical properties of the composite. Conversely, the coupons compacted with no process gap exhibited the greatest bending strength of 166 lbf and 164 lbf for the 0.75 in. and 1.0 in. silicone. This is supported by these coupons displaying the best compaction qualities as well.

This test suggests that a silicone thickness of 0.75in or 1 in. should be used for the silicone sleeve. It also demonstarates that variation of the process gap affects the magnitude of the expansion pressure. Additionally, more layers need to be added to the initial layup in order to obtain a final thickness of 1/8 in. More tuning with the silicone thickness and the number of layers in the prepreg could be done if desired.

7.5 Uncertainty and Future Considerations

The challenge with inclusion of the process gap was that the exact expansion of the silicone was not directly measured. It was predicted using the coefficient of thermal expansion but there was no test measure or use of strain gauges to confirm the amount. Similarly, the exact pressures generated by thermal expansion of the silicone were also not directly measured with this test procedure. A direct measurement rather than using the results of compaction to identify the maximum pressure would be necessary to validate the robustness of this design. A possible method to measure this pressure could involve placing a pressure transducer on the surfaces being displaced by the expansion of a silicone coupon between them.

Another challenge was maintaining consistency of carbon coupons because the dimensions were small and cut by hand, yet important for comparing test results. Usually at least five specimens per test condition should be tested for valid results, but we were able to use fewer specimens since this was a designed experiment.

One major molding consideration is resin bleed. An optimal amount of compaction will squeeze out resin from the pre-preg plies, and resin in certain undesired areas could cause the mold to stick. This resin should have somewhere to travel to prevent the mold from gluing shut. It is recommended to machine reservoirs to which excess resin may flow. Another option would be to cut slits in the silicone and place cotton or some absorbent material to suck up excess resin.

Overall using the coupon compaction quality as well as the bend tests were good metrics to confirm the capability of the silicone to provide pressure. This indicates that the mold could be used for fabrication of the wheel.

8. Project Management

The completion of C6 Wheels' senior project sought to follow this workflow: Scoping of the project, research and ideation, preliminary design review, analysis and design validation, critical design review, procurement of materials, manufacturing, and design verification. Due to C6 Wheels losing its sponsor after critical design review, the project needed to be rescoped, the design needed to change to reflect the loss of the sponsor's manufacturing method, and a new budget needed to be constructed to reflect the money that could be secured from other sources. MESFAC approved the project for up to $1000, and the rainy-day fund for senior project was $500, so the total budget came to $1500.

C6 Wheels excelled at accomplishing manufacturing and testing related tasks once the material had been procured. However, a few issues, including unforeseen circumstances surrounding shop availability and the loss of the project sponsor, caused most of the later stages of the project to be postponed. If the project were to be restarted, there are a few changes that would have made the deliverables for the project more feasible to achieve. The first change would be to have a more reasonable scope of work off at the onset of the project. The complexity of designing and manufacturing a successful carbon fiber wheel mold is a reasonable deliverable for a full-time student project. Starting the year with a scope that included the mold, five complete wheel shells, a stitching fixture, and a post-machining fixture was significantly over-reaching. The second change would be to move forward with a design direction sooner. While ideation and design validation are important, C6 Wheel's correspondence with the project sponsor caused the initial design stage to repeat itself and waste time that could have been effectively used for manufacturing and testing. It is important to recognize that while ideation, analysis, and theory are important in proofing out a design, testing and on-the-ground engineering hold much more weight in industry and to the success of the project. The third big change that would have aided the success of the project would be to implement more team work meetings. Scheduling specific times to work on the project throughout the week would have been extremely helpful in keeping the team on track and in better communication. Appendix F shows the final Gannt Chart that reflects the completion of the project.

9. Conclusion

The original goal of this project was to develop the molds and create a carbon fiber wheel shell to pair with an aluminum center. This was a feasible task until the loss of our sponsor, Seriforge. From that setback, the team was able to recover through MESFAC (*Mechanical Engineering Student Fee Allocation Committee*) funding, but crucial time and momentum were lost. The scope of the project was changed to delivering a feasible manufacturing process for a carbon fiber wheel mold, and provide data on the effectiveness of trapped rubber molding for compaction in carbon fiber.

Given the nine month timespan to come up with a design, build it, and test it, it is clear looking back that too much time was spent choosing between paths to take for the mold design. This was partly due to concern from our sponsor in the ability to complete the complex, trapped rubber mold in time. But it was also due to the sequence of lengthy discussions we had with our sponsor in which we hypothesized the trouble of each mold design. These were important discussions but given the time constraint, the likelihood of successfully producing an actual wheel would have increased if the team had chosen a design earlier and rolled with it by dealing with potential problems when they arose rather than letting hypothetical issues stall progress. This was a learning experience that showed how important it is to move forward to see the validity of a design instead of trying to flush out every option hypothetically.

The scope changes also required a radical shift in research and development. A significant amount of time was spent designing for the resin infusion capable version of the mold. An issue encountered which was circumvented by the switch to prepreg was the trouble of finding a suitable high temperature resin system. Just prior to the news about our sponsor's acquisition, the team found many of the possible resin systems unable to be purchased in the smaller quantity we needed as compared to large aerospace orders, on top of month-long lead times when testing needed to be done as soon as possible.

9.1 Next Steps

C6 Wheels has proved out trapped rubber molding as a feasible method to achieve optimal compaction during the wheel molding process. The team has also proved out the machining method for the female mold components and created a fixture block to allow for repeatability of the machining steps. It is recommended that another senior project team in the near future continues this project where C6 Wheels has left off. This means that the future team would need to utilize the machining methods created by C6 Wheels to complete the remaining female wheel molds, create a specific ply schedule for the carbon fiber wheel, create and machine the silicone and aluminum plugs based on data from C6 Wheels coupon tests (or data from repeats of the test), and layup and cure the carbon fiber wheels. A stretch goal would be to also create a post-machining fixture for the wheels as well. C6 Wheels is leaving aluminum stock in the Formula shed to be used for the remaining female molds. Material for the male plugs and silicone sleeves will need to be purchased by the future team. C6 Wheels is confident that the process and data procured during this senior project will help lead the way to Cal Poly FSAE's first successful carbon fiber wheels.

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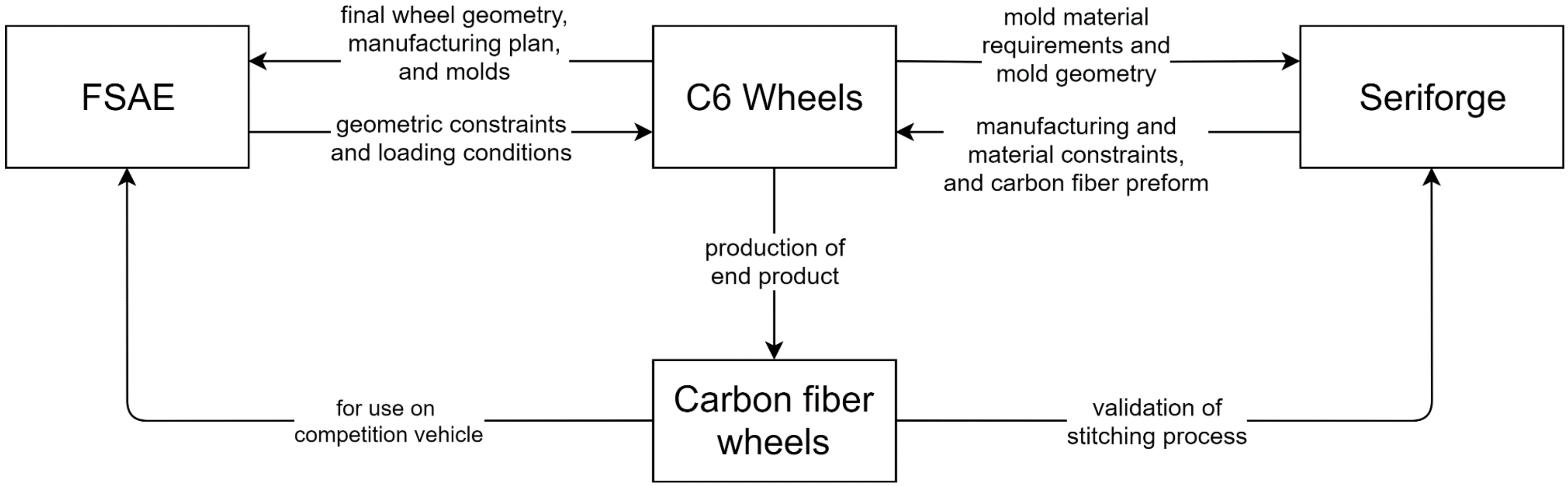
Appendix A: Project relationships (Initially)



Appendix B: QFD House of Quality

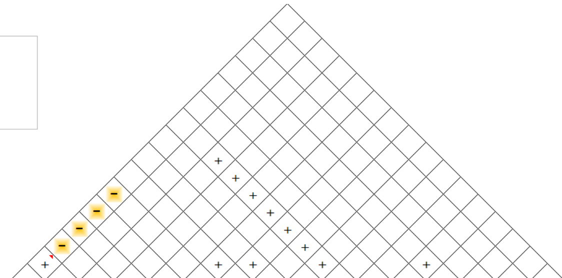
Correlations	
Positive	+
Negative	–
No Correlation	

Relationships	
Strong	●
Moderate	○
Weak	▽

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼

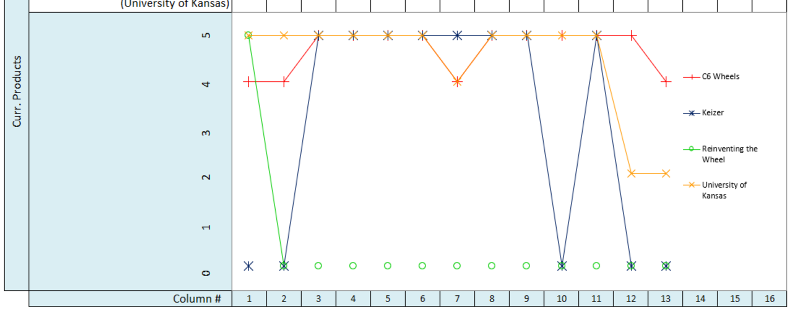
QFD House of Quality

Project: C6 Wheels- Wheel Design
Revision Date: 11/4/18



Row #	Weight Chart	Relative Weight	FSAE	Seriforge	Maximum Relationship	WHAT: Customer Requirements (Needs/Wants) / HOW: Engineering Specifications (Tests)	Weight	Rotational Intertia	Longitudinal Max Load	Lateral Max Load	Combined Max Load	Overall Stiffness	Bead Stiffness	Seat Pressure	Tire Pressure	Meets Geometric Dimensions	Assembleable	Wheel Manufacture Time	Fits within Stitch Table				Composite 3-Piece Wheel w/ Al. Hub (C6 Wheels)	Aluminum Wheel (Keizer)	Composite 1-Piece Wheel (Reinventing the Wheel)	Composite 1-Piece Wheel (University of Kansas)	Row #
						Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16					
						Direction of Improvement	▼	▼	▲	▲	▲	◇	◇	◇	◇	◇	◇	▼	▼				NOW: Curr. Products				
1		9%	10	1	9	Inertial Improvement	●	●															4	0	5	5	1
2		15%	10	5	9	Seals		○				○	○	●	●								5	5	0	5	2
3		12%	5	5	9	Ease of Assembly										●	●						5	5	0	3	3
4		7%	8	1	9	Strength	○		●	●	●												4	3	0	5	4
5		5%	4	1	3	Long Life			○	○	○												3	5	0	3	5
6		5%	5	1	3	Ease of Tire Mounting							○			○	○						5	5	0	2	6
7		15%	10	5	9	Fits on Car										●							5	5	5	5	7
8		7%	8	1	9	Stiffness						●	▽										5	5	5	5	8
9		24%	10	10	9	Manufacturable										●		○	○				4	5	0	2	9

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
HOW MUCH: Target Values	3.5 Pounds	TBD	2.48 G	2.7 G	1.4 Gx, 1.5 Gy	<.2 Deg/G Camber at Max Cornering	TBD	35 lb/in^2	12 lb/in^2	Per Drawing	Pass/Fail	28 Hours	Pass/Fail			
Max Relationship	9	9	9	9	9	9	3	9	9	9	9	3	3			
Technical Importance Rating	101.43	125.71	80	80	80	112.86	69.524	139.29	139.29	476.43	122.86	71.429	71.429	0	0	0
Relative Weight	6%	8%	5%	5%	5%	7%	4%	8%	8%	29%	7%	4%	4%	0%	0%	0%
3-Piece Wheel w/ Al. Hub (C6 Wheels)	4	4	5	5	5	5	4	5	5	5	5	5	4			
Aluminum Wheel (Keizer)	0	0	5	5	5	5	5	5	5	0	5	0	0			
Composite 1-Piece Wheel (Reinventing the Wheel)	5	0	0	0	0	0	0	0	0	0	0	0	0			
Composite 1-Piece Wheel (University of Kansas)	5	5	5	5	5	5	4	5	5	5	5	2	2			



Templ

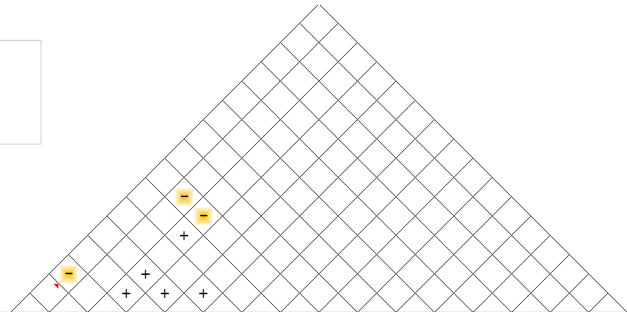
Correlations	
Positive	+
Negative	–
No Correlation	

Relationships	
Strong	●
Moderate	○
Weak	▽

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼

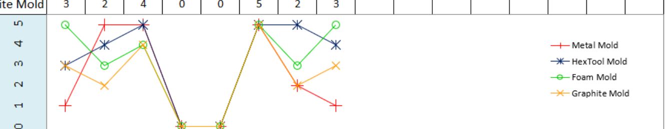
QFD House of Quality

Project: C6 Wheels- Manufacturing Process
Revision Date: 11/4/18



						Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16					
	WHO: Customers					Direction of Improvement	▼	▲	◇	◇	◇	◇	◇	▼									NOW: Curr. Products				
Row #	Weight Chart	Relative Weight	FSAE	Seriforge	Maximum Relationship	HOW: Engineering Specifications (Tests) / WHAT: Customer Requirements (Needs/Wants)	Cost	Mold Life Cycle	Meets Geometric Dimensions	Fits within Stitching Table	Successfully Stitches PreForms	Visual Inspection	Releases Part	Total Manufacture Timespan									Metal Mold	HexTool Mold	Foam Mold	Graphite Mold	Row #
1		12%	8	8	3	Affordable	○																1	3	5	3	1
2		16%	10	10	9	Repeatable Process		○			●		●										5	4	3	2	2
3		16%	10	10	9	Viable Mold	▽		●				●										5	5	5	4	3
4		8%	1	10	9	Cylindrical Stitching Tool				●	●												0	0	0	0	4
5		8%	1	10	9	Showcases Z-Axis Stitching					●	○											0	0	0	0	5
6		16%	10	10	9	Succeed in Creating Wheel			●				●										5	5	5	5	6
7		10%	7	5	9	Produces Quality Surface Finish						●											4	5	4	4	7
8		16%	10	10	9	Manufacturable	▽							●									2	4	5	3	8

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
HOW MUCH: Target Values	$2500 Total	100 Cycles	Per Drawing	Pass/Fail	Pass/Fail	Pass/Fail	Pass/Fail	2 Weeks								
Max Relationship	3	3	9	9	9	9	9	9								
Technical Importance Rating	68.73	46.86	281.2	69.54	279.7	109.3	421.8	140.6	0	0	0	0	0	0	0	0
Relative Weight	5%	3%	20%	5%	20%	8%	30%	10%	0%	0%	0%	0%	0%	0%	0%	0%
Curr. Products: Metal Mold	1	5	5	0	0	5	2	1								
HexTool Mold	3	4	5	0	0	5	5	4								
Foam Mold	5	3	4	0	0	5	3	5								
Graphite Mold	3	2	4	0	0	5	2	3								



Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16

Templ

Appendix C: Preliminary analyses or benchmark test results

Table 12 – Approximate loading on tire

Operating Case	Acceleration	Contact Patch Load (lb)					
		Front			Rear		
		Fx	Fy	Fz	Fx	Fy	Fz
Braking	-2.2 long	-527	0	283	-152	0	52
Acceleration	1.7 long	194	0	75	529	0	260
Cornering	2.17 lat	0	544	273	0	645	336
Combined	1. 4 lat, 1.3 long	372	354	169	484	654	343
Average	1.0 lat, .5 long	436	392	189	529	540	272

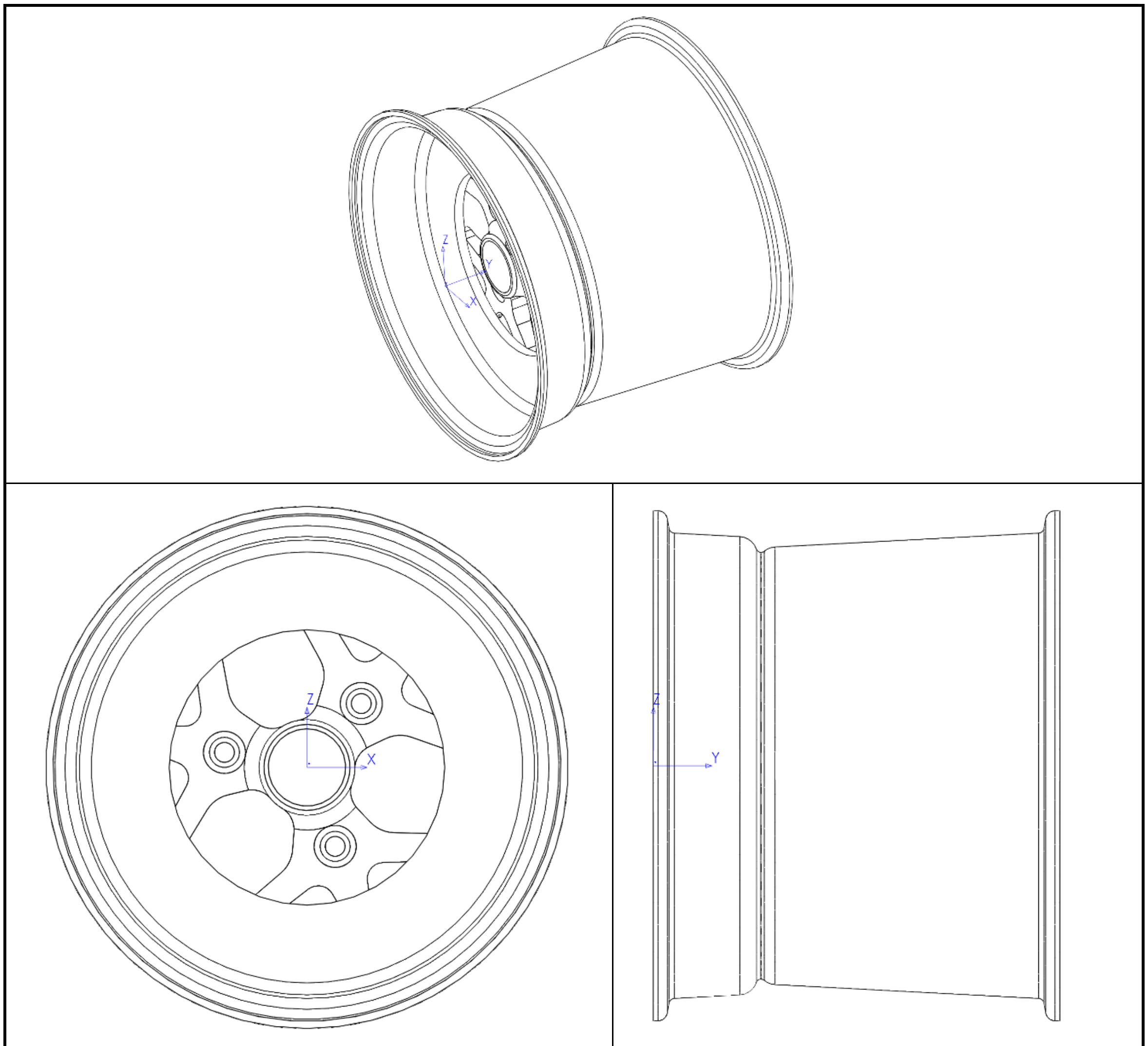
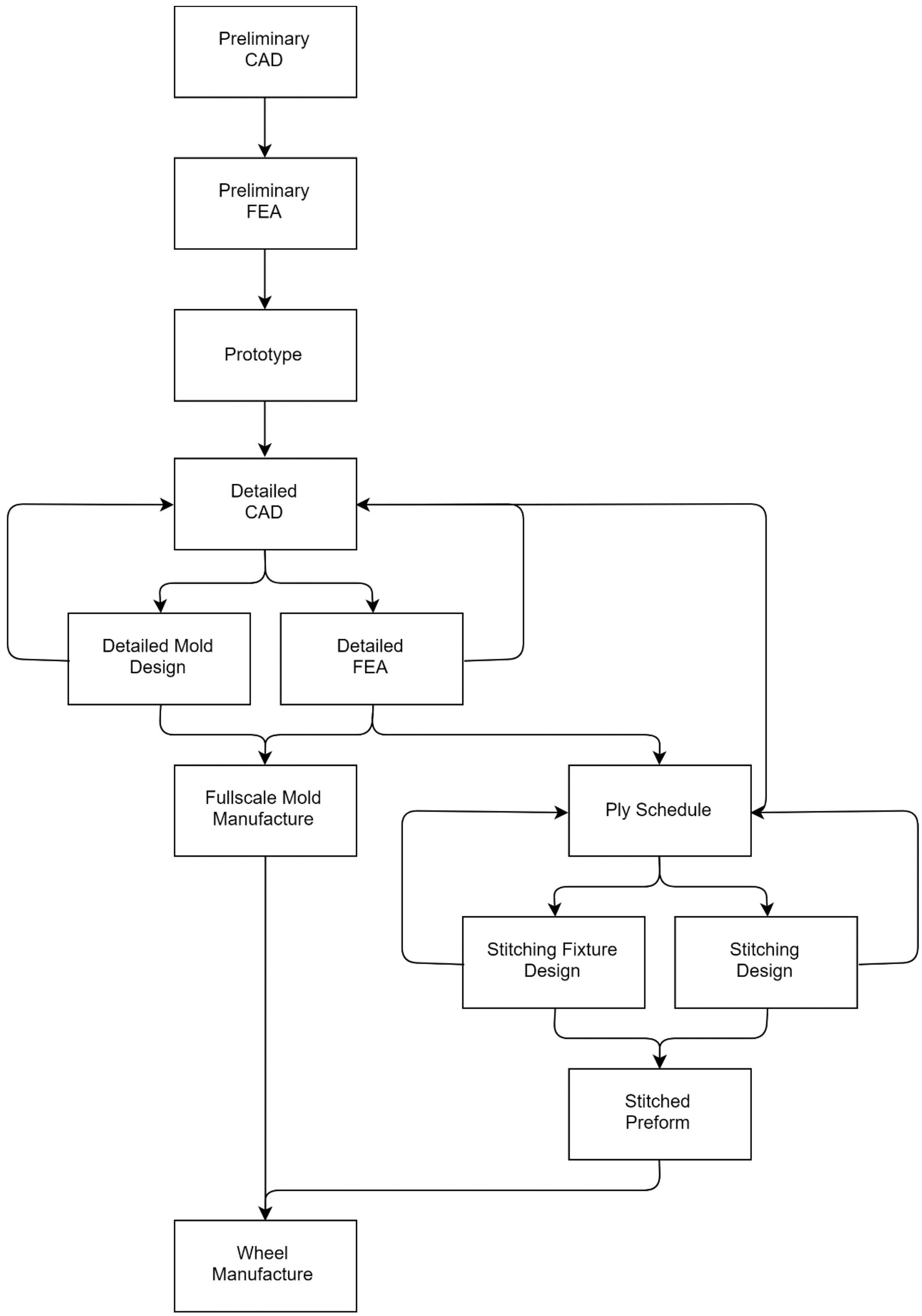


Figure 46 – Coordinate system for forces in Table 12.

Appendix D: Preliminary Process Flowchart



Appendix E: Risk Assessment

designsafe Report

Application:	Wheel Mold	Analyst Name(s):	Luke Martin
Description:	Assessment of C6Wheels Manufacturing	Company:	C6Wheels
Product Identifier:	Wheel Mold	Facility Location:	Cal Poly
Assessment Type:	Detailed		
Limits:			
Sources:			
Risk Scoring System:	ANSI B11.0 (TR3) Two Factor		

Guide sentence: When doing [task], the [user] could be injured by the [hazard] due to the [failure mode].

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
1-1-1	Mold Manufacturer Handle Stock	slips / trips / falls : falling material / object Dropping Stock	Moderate Unlikely	Low	Handle with more than one person, use dolly or pallet for long transport, standard procedures	Moderate Remote	Negligible	
1-1-2	Mold Manufacturer Handle Stock	ergonomics / human factors : lifting / bending / twisting Carrying Heavy Stock	Minor Likely	Low	Assure proper posture while handling, standard procedures,	Minor Remote	Negligible	
1-1-3	Mold Manufacturer Handle Stock	material handling : excessive weight Stock >50lbs	Minor Likely	Low	Assure proper grip while handling, standard procedures,	Minor Remote	Negligible	
1-2-1	Mold Manufacturer Place Stock in Vice	mechanical : pinch point Finger pinching when set down	Serious Unlikely	Medium	Lean stock to one side, have one person release hands first, then the second person, standard procedures	Serious Remote	Low	
1-2-2	Mold Manufacturer Place Stock in Vice	ergonomics / human factors : lifting / bending / twisting Extending to place stock in vice	Minor Unlikely	Negligible	Handle jog the vice to be as close to the CNC door as possible before placing stock in vice, special procedures	Minor Remote	Negligible	

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
1-3-1	Mold Manufacturer Handle Tooling	mechanical : cutting / severing Cutting hands while handling end mills for the CNC	Serious Unlikely	Medium	Hold cutters from base and not from cutters, standard procedures,	Serious Remote	Low	
1-3-2	Mold Manufacturer Handle Tooling	slips / trips / falls : trip Tripping while holding a sharp tool	Moderate Remote	Negligible	Focus solely on tool transport while handling cutters, standard procedures,	Moderate Remote	Negligible	
1-4-1	Mold Manufacturer CNC Components	electrical / electronic : unexpected start up / motion CNC starting while someone is loading or adjusting components	Catastrophic Unlikely	Medium	Only one person may touch the CNC at one time. Communicate with team members on who is currently operating the system, two hand controls, E-stop control, adjustable enclosures / barriers	Catastrophic Remote	Low	
1-4-2	Mold Manufacturer CNC Components	electrical / electronic : power supply interruption Power Outage	Moderate Remote	Negligible	N/A	Moderate Remote	Negligible	
1-4-3	Mold Manufacturer CNC Components	ergonomics / human factors : duration Large amount of standing time during CNC ops	Minor Likely	Low	Rotate members that are monitering CNC progress, job rotation,	Minor Remote	Negligible	
1-5	Mold Manufacturer Perform Measurements	<None>						
1-6-1	Mold Manufacturer Mix Silicone	fire and explosions : improperly mixed chemicals Bad silicone mix ratio due to negligence	Moderate Remote	Negligible	Have two team members check part measurements before silicone mixing, supervision,	Moderate Remote	Negligible	

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
1-7-1	Mold Manufacturer Pour Silicone	ergonomics / human factors : posture Poor set up of silicone mixing arrangement	Moderate Unlikely	Low	Assure silicone mixing station is on an ergonomically leveled surface	Moderate Remote	Negligible	
1-8-1	Mold Manufacturer Cut Gaskets	mechanical : cutting / severing Cutting hands while cutting gasket	Serious Unlikely	Medium	Secure gasket to surface and cut away from body and fingers, special procedures,	Serious Remote	Low	
1-9-1	Mold Manufacturer Assemble Mold	mechanical : pinch point Pinching fingers while tightening mold screws or assembling components	Serious Unlikely	Medium	Do not place fingers between pinching components while any tightening is taking place, standard procedures	Serious Remote	Low	
2-1-1	Wheel Manufacturer Lay Up Preform	mechanical : pinch point Pinching while laying preform around mold	Moderate Unlikely	Low	Pay careful attention while piecing together the mold during the lay up process, standard procedures	Moderate Remote	Negligible	
2-1-2	Wheel Manufacturer Lay Up Preform	ergonomics / human factors : repetition Mistakes due to long lay up effort	Minor Unlikely	Negligible	Have work reviewed by teammates, supervision,	Minor Remote	Negligible	
2-1-3	Wheel Manufacturer Lay Up Preform	ergonomics / human factors : duration Potentially lengthy lay up effort	Minor Unlikely	Negligible	Rotate team mate actively laying up part depending on duration, job rotation,	Minor Remote	Negligible	
2-2-1	Wheel Manufacturer Assemble Mold	mechanical : pinch point Pinching fingers while tightening mold screws or assembling components	Serious Unlikely	Medium	Do not place fingers between pinching components while any tightening is taking place, standard procedures	Serious Remote	Low	

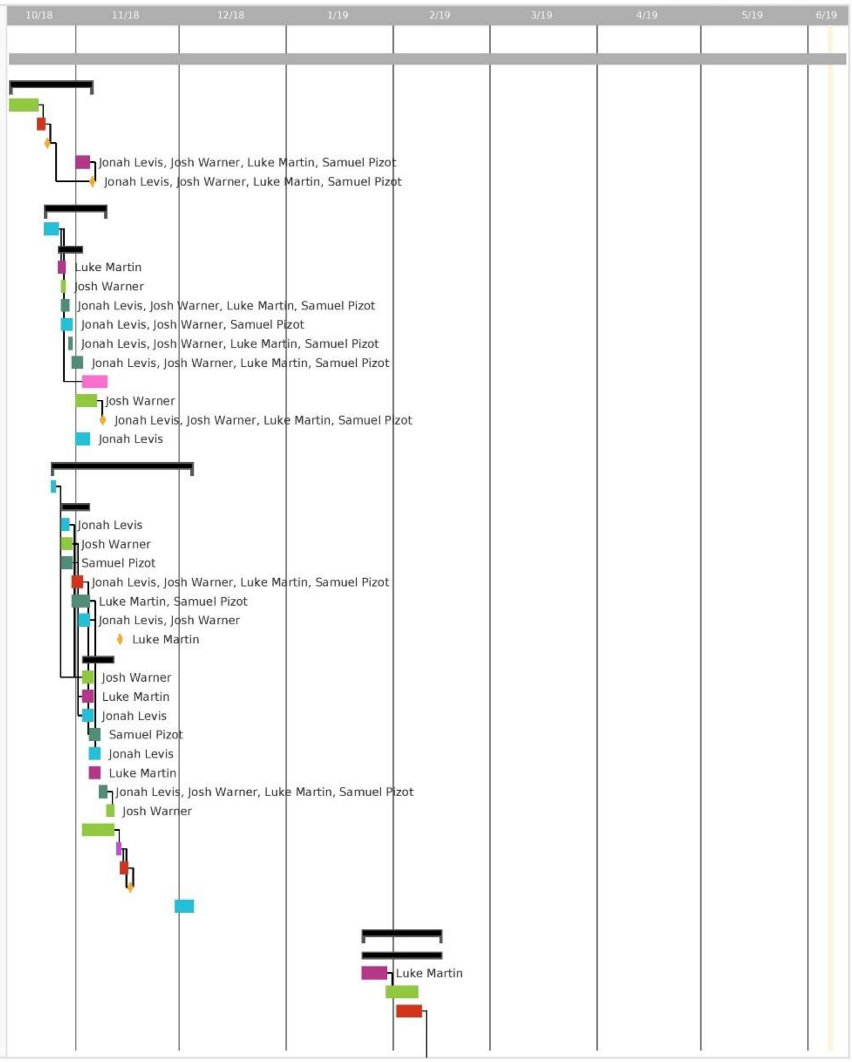
Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
2-3-1	Wheel Manufacturer Mix Resin	chemical : reaction to / with irritant chemicals Rash caused by contact with resin	Moderate Likely	Medium	Wear Gloves & Long Sleeves,	Moderate Remote	Negligible	
2-3-2	Wheel Manufacturer Mix Resin	chemical : skin exposed to toxic chemical Abrasion caused by resin skin contact	Serious Likely	High	Wear Gloves & Long Sleeves	Serious Remote	Low	
2-4-1	Wheel Manufacturer Perform Resin Infusion	fire and explosions : improperly mixed chemicals Infusion failure due to improper resin ratio	Serious Unlikely	Medium	Have two members check component measurements before mixing, supervision,	Serious Remote	Low	
2-4-2	Wheel Manufacturer Perform Resin Infusion	fluid / pressure : high pressure Mold rupture due to high pressure	Serious Unlikely	Medium	Proper fastener calculations and tightening	Serious Remote	Low	
2-4-3	Wheel Manufacturer Perform Resin Infusion	fluid / pressure : vacuum Complications from vacuum release	Moderate Likely	Medium	Unfasten the mold slowly	Moderate Remote	Negligible	
2-4-4	Wheel Manufacturer Perform Resin Infusion	fluid / pressure : fluid leakage / ejection Excess resin squeeze out	Minor Unlikely	Negligible	Clean out excess resin from mold	Minor Remote	Negligible	
2-5-1	Wheel Manufacturer Place Mold in Oven	mechanical : crushing Fingers crushed when placing mold in oven	Moderate Unlikely	Low	Use handles to handle mold	Moderate Remote	Negligible	
2-5-2	Wheel Manufacturer Place Mold in Oven	ergonomics / human factors : lifting / bending / twisting Strain from placing heavy mold in oven	Moderate Likely	Medium	Have two team members place mold in oven	Moderate Unlikely	Low	
2-5-3	Wheel Manufacturer Place Mold in Oven	heat / temperature : inadequate heating / cooling Wheel failure from lack of compaction	Moderate Likely	Medium	Use thermometers inserted in mold to measure heating	Moderate Unlikely	Low	

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
2-6-1	Wheel Manufacturer Remove Mold From Oven	ergonomics / human factors : lifting / bending / twisting Strain from removing heavy mold	Moderate Likely	Medium	Have two team members retrieve the mold	Moderate Unlikely	Low	
2-6-2	Wheel Manufacturer Remove Mold From Oven	heat / temperature : radiant heat Burn from oven heat	Moderate Unlikely	Low	Wear protective gear while handling hot components	Moderate Remote	Negligible	
2-7-1	Wheel Manufacturer Release Mold & Remove Wheel	mechanical : pinch point Pinching while undoing the mold	Moderate Unlikely	Low	Unfasten one component at a time	Moderate Remote	Negligible	
2-8	Wheel Manufacturer Store Wheel	<None>						

Appendix F: Gantt Chart

Printed: 06/07/2019

42 - c6wheels	start	end	0h	99%
Scope of Work	**10/13/18**	**11/05/18**	**0h**	**100%**
Write Scope of Work	10/13	10/20	0	100%
Edit and Format SOW	10/21	10/22	0	100%
Scope of Work Complete	10/23	10/23	0	100%
Migrate information from Reinventing...	11/01	11/04	0	100%
Scope of Work Rewrite	11/05	11/05	0	100%
Creating Design Direction	**10/23/18**	**11/09/18**	**0h**	**100%**
Ideation	10/23	10/26	0	100%
Create Initial Tooling CAD Models	**10/27/18**	**11/02/18**	**0h**	**100%**
Create Initial Tooling CAD File Locat...	10/27	10/28	0	100%
Send current wheel to 3D printer	10/28	10/28	0	100%
Ideation expansion	10/28	10/29	0	100%
Create Initial tooling CAD	10/28	10/30	0	100%
Tooling CAD expansion during class	10/30	10/30	0	100%
Focus on Resin Delivery	10/31	11/02	0	100%
3D Print Prototype Concept	11/03	11/09	0	100%
Meet with Prof. Fab about 2v3 piece	11/01	11/06	0	100%
Decide 2 or 3 piece wheel	11/08	11/08	0	100%
Determine fixed dimensions on whee...	11/01	11/04	0	100%
Preliminary Design Review	**10/25/18**	**12/04/18**	**0h**	**100%**
Create PDR Document	10/25	10/25	0	100%
Draft PDR	**10/28/18**	**11/04/18**	**0h**	**100%**
Modify Introduction for PDR	10/28	10/29	0	100%
Modify Background for PDR	10/28	10/30	0	100%
Modify Objectives for PDR	10/28	10/30	0	100%
Write Concept Design Section	10/31	11/02	0	100%
Add to Project Management	10/31	11/04	0	100%
Add to Conclusions	11/02	11/04	0	100%
Send Pre PDR to seriforge	11/13	11/13	0	100%
Edit and Format PDR	**11/03/18**	**11/11/18**	**0h**	**100%**
Edit Introduction	11/03	11/05	0	100%
Edit Background	11/03	11/05	0	100%
Edit Objectives	11/03	11/05	0	100%
Edit Concept Design	11/05	11/07	0	100%
Edit Project Management	11/05	11/07	0	100%
Edit Conclusion	11/05	11/07	0	100%
Full Readthrough Edit	11/08	11/09	0	100%
Final Edit	11/10	11/11	0	100%
Make a PDR Powerpoint	11/03	11/11	0	100%
PDR Presentation	11/13	11/13	0	100%
Peer Review PDR and Re-Edit	11/14	11/15	0	100%
PDR Complete	11/16	11/16	0	100%
PDR Presentation to Sponsor	11/30	12/04	0	100%
Critical Design Review	**01/23/19**	**02/14/19**	**0h**	**100%**
CDR Documentation	**01/23/19**	**02/14/19**	**0h**	**100%**
Modify PDR into CDR Draft	01/23	01/29	0	100%
Add Data and Design Validation	01/30	02/07	0	100%
Edit and Format CDR	02/02	02/08	0	100%



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Create Tooling Drawing Package	02/08	02/14	0	100%
CDR Complete	02/12	02/12	0	100%
Design Analysis and Validation	**01/14/19**	**02/10/19**	**0h**	**100%**
Finalize Design of Wheel	01/14	01/27	0	100%
FEA on Wheel Shell Design	01/21	02/03	0	100%
FEA Approval	02/04	02/10	0	100%
Coupon Creation and Test	**01/28/19**	**05/17/19**	**0h**	**100%**
Determine test variables	01/28	02/03	0	100%
Update Test Plan	04/07	04/09	0	100%
Develop coupon lay up procedure	01/28	02/03	0	100%
CAD Coupon Mold	01/28	02/08	0	100%
CAM Coupon Mold	04/01	04/03	0	100%
Order Coupon Mold Material	02/15	02/17	0	100%
Machine Coupon Mold	**04/08/19**	**04/19/19**	**0h**	**100%**
Machine Middle Mold	04/08	04/09	0	100%
Machine Top Mold	04/15	04/16	0	100%
Machine Bottom Mold	04/15	04/16	0	100%
Machine Aluminum Bosses	04/18	04/19	0	100%
Pour Silicone Pucks	04/20	04/21	0	100%
Formula Acquisition of Carbon Fiber	04/08	04/08	0	100%
Cut Coupons Coupons	04/22	04/26	0	100%
Cure Coupons	04/27	05/03	0	100%
Compaction and Bending Tests	05/04	05/17	0	100%
Tooling Manufacture	**01/25/19**	**06/11/19**	**0h**	**93%**
confirm flange location (w/ FSAE)	01/25	01/31	0	100%
Wheel Mold Creation	**04/22/19**	**06/11/19**	**0h**	**91%**
Order Mold Material	04/22	04/26	0	100%
Finalize Mold CAD	04/26	04/28	0	100%
Develop Mold CAM	04/29	05/01	0	100%
Machine Female Molds	**05/24/19**	**06/11/19**	**0h**	**82%**
Female Mold Op 1	05/28	05/29	0	100%
Female Mold Op 2	05/30	05/30	0	100%
Female Mold Op 3	05/31	05/31	0	100%
Female Mold Op 4	06/07	06/07	0	100%
Female Mold Op 5	06/07	06/07	0	100%
Female Mold Op 6	06/07	06/07	0	100%
Fixture Block Op 1	05/24	05/24	0	100%
Fixture Block Op 2	05/27	05/27	0	100%
Finishing Op	06/10	06/11	0	0%
Class Assignments	**04/05/19**	**06/07/19**	**0h**	**97%**
Operator's Manual Draft	04/05	04/09	0	100%
Expo Needs Survey	04/20	04/25	0	100%
Confirmation Prototype Sign Off	04/20	04/30	0	100%
Update Manufacturing Plan	04/20	04/30	0	100%
Test Results Sign-Off	05/11	05/16	0	100%
Update Design Verification (Testing ...	05/16	05/21	0	100%
Expo Poster	05/18	05/23	0	100%
Final Ops Manual	05/18	05/30	0	100%
Final Expo Poster	05/18	05/30	0	100%

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					10/18	11/18	12/18	1/19	2/19	3/19	4/19	5/19	6/19
Final CAD Files	06/01	06/07	0	100%	Jonah Levis, Josh Warner, Luke Martin, Samuel Pizot								
Submit FDR	06/05	06/07	0	0%	Jonah Levis, Josh Warner, Luke Martin, Samuel Pizot								

Appendix G: Bill of Materials

Wheel Mold

Part #	Part Name	Description	Qty	Units	Supplier	Unit Cost	Cost
4PL61	Female Mold	4x11x48 in. Aluminum 6061 Plate	1	ft.	Coast Aluminum	$ 682.20	$ 682.20
1218R61	Male Mold	12.125 in. Aluminum 6061 Round Stock	1	ft.	Coast Aluminum	$ 452.85	$ 452.85
31335A34	Diamond Locating Pin	0.5 in. Diamond Head Locating Pin	4		McMaster Carr	$ 13.15	$ 52.60
31335A54	Hole Liner	0.5 in. Hole Liner	8		McMaster Carr	$ 7.79	$ 62.32
31335A14	Round Locating Pin	0.5 in. Round Head Locating Pin	4		McMaster Carr	$ 7.81	$ 31.24
TC-5050	Silicone Plug Material	TC-5050 A/B 50 Shore A Room Temp. Curing Silicone	2	Gallon	BJB	$ 120.30	$ 240.60
92196A542	Socket Head Screws	1/4-20 Stainless Steel 18-8 Socket Head Cap Screw	1	Pack of 50	McMaster Carr	$ 14.93	$ 14.93
9452K376	O-Ring	Oil Resistant O-Ring ID 11.484" OD 11.762"	2		McMaster Carr	$ 11.05	$ 22.10
9407K12	O-Ring Chord	Oil Resistant O-Ring Chord 1/8 in.	10	ft.	McMaster Carr	$ 0.40	$ 4.00
	Total		**33**				**$ 1,562.84**

Coupon Mold

Part #	Part Name	Description	Qty	Units	Supplier	Unit Cost	Cost
2126B61	Test Bottom Mold	2.5x6 in. Aluminum 6061 Rectangular Bar Stock	2	ft.	Coast Aluminum	$ 71.70	$ 143.40
126B61	Test Top Mold	0.5x6 in. Aluminum 6061 Rectangular Bar Stock	1	ft.	Coast Aluminum	$ 27.00	$ 27.00
	Total		**3**				**$ 170.40**

Appendix H: Test Plan

EXPANSION OF SILICONE COUPON TEST

Presented by: C6 Wheels

Purpose: Investigate validity of silicone rubber expansion under heat to provide laminate compaction. Various thicknesses of silicone rubber will be tested to compact carbon fiber epoxy coupons and the resulting fiber volume fractions will be recorded.

This test will inform the final design of the trapped rubber mold as well as provide the team with experience in small scale machining of molds, and the composites manufacturing process.

Background/Intro:

Trapped rubber molding – use of elastic tooling to provide a method of increasing fiber volume, resulting in a higher-quality laminate. Rubber-assisted resin transfer molding (RARTM) relies on placing a rubber insert into the tool that expands a predetermined amount during cure, providing pressure to compact the fiber reinforcement.

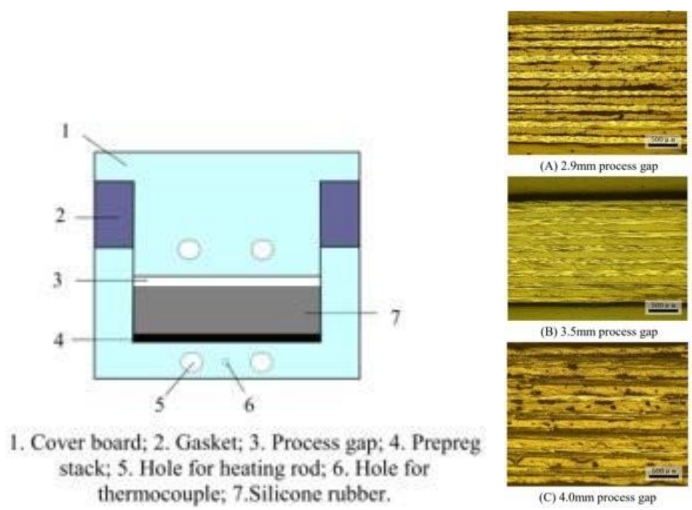


Figure 1. Example trapped rubber test fixture (left) and corresponding laminate compaction results from various expansion pressures (right)

Test Material: Silicone

BJB enterprises, a casting and mold making company, has helped to specify material selection for the trapped rubber. From their advice, a platinum cure silicone will be selected for the testing, specifically the TC 5050- A/B 50 Shore A. This is a two part silicone selected for its ability to withstand high temperature and for its CTE being the largest of the products BJB distributes. They have run their own thermal expansions tests to which we can compare our results.

The silicone A + B components are mixed together and can be poured into a mold while still in a liquid state. The curing will occur once the allotted time specified by the manufacturer has passed and the final coupon shapes will be formed. (work time)

Detailed product sheet is attached in the appendix A.

Calculating Expansion of Silicone:

Exposing the silicone to elevated temperature will increase the energy into the material causing atoms to vibrate and stretching of the chemical bonds thus producing an expansion. The coefficient of thermal expansion (CTE) determined by BJB for the TC 5050 is 16.5 x 10-5 in/in/°F (from Product Sheet).

To predict the total expansion, the following equation can be used:

EXPANSION THICKNESS [IN] = CTE/3 [1/F] X TEMP RANGE [F] X COUPON THICKNESS [IN]

Density, Weight and Volume Fractions:

The density of the composite is easily calculated by adding up the mass of each component, i.e. the mass of the fibers, M_f, and the mass of matrix, M_m

$$M = M_f + M_m$$
$$M = \rho \cdot V$$
$$\rho \cdot V = \rho_f \cdot V_f + \rho_m \cdot V_m$$
$$\rho \cdot V = \rho_f \cdot f \cdot V + \rho_m \cdot (1-f) \cdot V$$
$$\rho = f \cdot \rho_f + (1-f) \cdot \rho_m$$

To convert from volume fraction of fibers, f, to weight fraction of fibers, f_w, we just need to establish the ratio of the mass of the fibers to the total mass, this is simply

$$f_w = \frac{M_f}{M_f + M_m}$$
$$f_w = \frac{\rho_f \cdot fV}{\rho_f \cdot fV + \rho_m \cdot (1-f)V}$$
$$f_w = \frac{f\rho_f}{f\rho_f + (1-f)\rho_m}$$

To convert from weight fraction, f_w, to volume fraction, f, we need to establish the ratio of the volume of reinforcement to the total volume of the composite. Again, this is simply

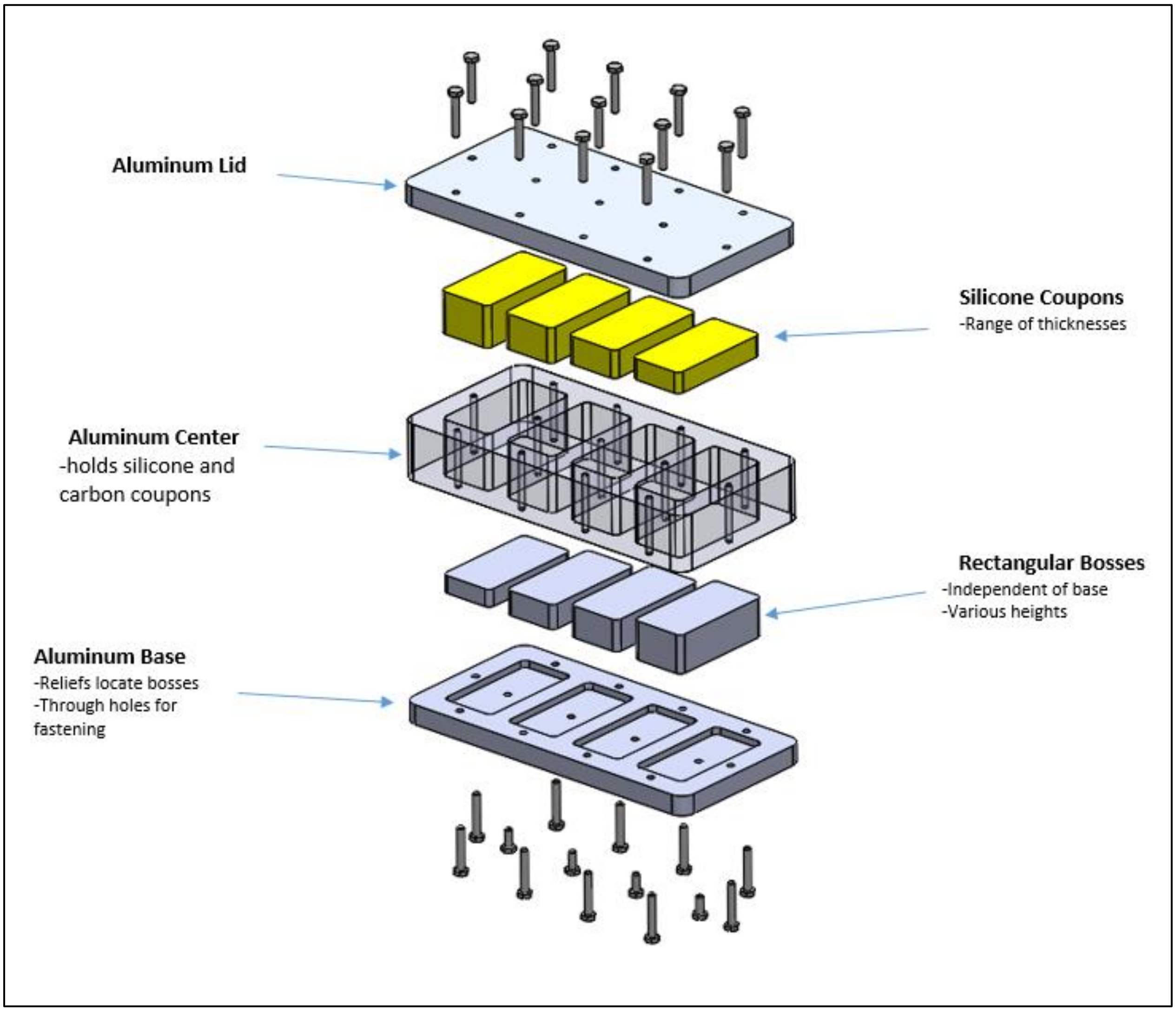
$$f = \frac{V_f}{V_f + V_m}$$

$$f = \frac{\frac{M_f}{\rho_f}}{\frac{M_f}{\rho_f} + \frac{M_m}{\rho_m}}$$

$$f = \frac{\frac{f_w M}{\rho_f}}{\frac{f_w M}{\rho_f} + \frac{(1-f_w)M}{\rho_m}}$$

$$f = \frac{f_w}{f_w + (1-f_w)\frac{\rho_f}{\rho_m}}$$

Schematic:



Test Component Details:

- Mold bottom plate will have bosses at different heights to allow all silicone coupon top surfaces to be level.
- Mold center will have four through hole pockets and a groove machined as shown below for O-ring stock.
- Mold lid will sit flush on top of center portion and will be fastened together with all 3 mold components.
- All Carbon coupons will be identical in ply schedule. They will sit in between the silicone coupons and the lid for resin infusion with a process gap between the top of the carbon coupon and the lid.
- The mold will be baked at 350F for 2 hours.
- Each carbon sample will be compressed against the lid by the silicone expanding underneath it.
- Aiming at 1/8in final thickness for carbon.
- Resin ports will be located on the top of the coupons, one in the middle of each channel connecting two coupons, this will ensure equal resin flow through all 4 coupons.
- Bolt holes will be machined all throughout the perimeter of the plate, and one hole in between each coupon.
- The middle plate will have through holes and a groove machined for an O-ring.
- The mold lid will be a flat aluminum plate, resin ports and fasteners will interface here.
- Location: **Cal Poly Mech. Eng. Composites Lab room 135 – building 192**

Data Prep and Collection

Laminate Test coupon: in-plane dimensions of __ in × __ in w/ a nominal thickness of ___

Table 1.

Specimen	Silicon coupon thickness	Post-cure Silicone thickness	Predicted Expansion	Actual Expansion	% difference
1					
2					
3					
4					

Table 2.

Specimen	Carbon Fiber Coupon Precure Weight	Post cure weight	Fiber volume fraction	Compaction or Resin Infusion Quality
1				
2				
3				
4				

Features to be tested

- Pre-infusion carbon coupon weight
- Post infusion Carbon coupon weight
- Thicknesses of Silicone and their resulting volume fraction
- Expansion pressures of different silicone thicknesses based on resultant volume fraction
- Optimal process gap

Materials:

- Resin: TenCate RS 50 (data sheet in appendix A)
- Carbon: 4, 2 x 3in 12ply, coupons $[0/30/-30]_4$ layup.
- Aluminum: rectangular stock
- O-Rings: Mold and barbed fittings
- Fasteners: X 26
- Ports: X 4
  - Hoses: X 4 sections
- Silicone: 1 quart, 2 part mixture

Bill of Materials:

Part #	Part Name	Description	Qty	Units	Supplier	Unit Cost	Cost
2126B61	Test Bottom Mold	2.5x6 in. Aluminum 6061 Rectangular Bar Stock	2	ft.	Coast Aluminum	$71.70	$143.40
126B61	Test Top Mold	0.5x6 in. Aluminum 6061 Rectangular Bar Stock	1	ft.	Coast Aluminum	$27.00	$27.00
TC-5050-AB	Silicone	2 part mixture	1	Quart	BJB Enterprises	$70.00	$70.00
Epoxy resin	Tencate RS 50	6-8 week delivery			Tencate		
92240A546	Machine screws	18-8 Stainless Steel Hex Head Screw	50		McMaster Carr	$0.16	$7.91
1283N108	Mold O-ring	1/8” width x 3 1/8” ID silicone o-ring	5		McMaster Carr	$1.75	$8.71
5346K730	Brass Barbed Hose Fitting	Barbed hose fitting for 3/16” ID hose	5		McMaster Carr	$1.88	$9.38
1283N424	Barbed Fitting O-ring	1/16” width x 3/16” ID silicone o-ring	25		McMaster Carr	$0.17	$4.20
-	Carbon Fiber	2 x 2 twill 200gsm. 2 x 3 in coupon	4	in	Seriforge	-	-
	Total		**3**				**$270.60**

*Epoxy resin selected may need to be replaced w/ Seriforge provided due to lead time

Machinery

- Autoclave: supplied on campus
- Vacuum pump: supplied on campus
- Degassing chamber: supplied on campus

Carbon Fiber Coupon Creation

Location: Composites Shed at Aero Hangar

Material: HTS40/TC275 3k 2x2 Twill

Step 1 Pull prepreg from freezer.

Step 2 Let the roll defrost/debulk for an hour before placing it on fabric roll holder.

Step 3 Roll out a flat piece/sheet.

Step 4 Place backing material on table under rolled out piece/sheet.

Step 5 Pull the sheet taught and cut off a large (4' by 2') ply. Cut across by hand using boxcutter/razor.

Step 6 Determine local coordinate axes/reference on sheet .

Step 7 Using aluminum boss from mold as a trace, cut 1" by 5" at 0° ply orientation (x 40)

Step 8 Using the established reference frame, cut 1" by 5" coupons at 45°. Use a protractor and ruler for proper alignment. Cut out 40 strips.

Step 9 Using the established reference frame, cut 1" by 5" coupons at -45°. Use a protractor and ruler for proper alignment. Cut out 40 strips.

Step 10 Assemble all 12 coupons with the proper ply schedule of [0,45, 0, -45, 0]s.

Step a. Take first layer

Step b. Use heat gun to prepare the next layer to adhere to preceding layer

Step 11. Place assembled coupon into tupper ware and into freezer until ready to test.

Silicone Plug Procedure

Step 1: Load 3/16" shims into mold bottom piece.

Step 2: Load the proper height bosses on top of the shims into the bottom piece.

Step 3: Screw the height bosses into place finger tight.

Step 4: Place middle mold piece over height bosses onto bottom mold piece.

Step 5: Tighten height boss screws fully.

Step 6: Screw the bottom piece into the middle piece to full tightness.

Step 7: Mix silicone and de-gas.(10 to 1 by weight)

To remove trapped air in the silicone which form during mixing of the two parts of the system together

Helps with surface finish, as well want to ensure the properties of the silicone are as close to the manufacturer claims

Mix the high visvous part A with 1/10 of its weight part B catalyst in a container and mix with wood mixer. *insert photo

When the color of the mixture is uniform, it is ready to be degassed. Place the container in the chamber and seal the lid by tighteing the clamps along along the rim.

Connect hose from pump to valve on degassing chamber and leave the other valve closed *insert photo

Turn on the pump Degas for 5 minutes. Then turn the pump off, depressurize the chamber by opening the air relief valve. The silicone is properly degassed if airbubbles are gone..

Remembering to account for the degassing time to calculate the remaining pot life to pour into the slots on the test fixture.

Allowed to cure at room temp overnight. *insert photo of completed pucks

Step 8: Pour silicone into the mold cavities to the top. Pop any bubbles.

Step 9: Put the mold top piece on and secure with screws tightened fully.

Step 10: Allow to cure overnight per BJB recommendation.

Step 11: Remove the screws connecting the mold top piece to the middle piece and the screws connecting the mold bottom piece and middle piece.

Step 12: Remove the mold top piece using the pry slots if necessary. Repeat for the mold bottom piece.

Step 13: Remove the silicone from the mold and trim flash.

Test Plan Procedure

Prep: Apply mold release generously to inner surfaces of the slots and to bottom surface of aluminum lid.

Step 1: Assemble aluminum center over bottom plate and place silicone coupons in appropriate slots so all coupons sit level.

Step 2: Insert one carbon coupon in each slot and place lid on top of middle section.

Precure steps:

Apply 2 layers of mold release wax

Apply pva film 10 using paint brush

Apply 2 more layers of wax

*also put wax along threaded holes

Step 3: Fasten all three mold components together.

Step 4: Place mold in oven and cure at *275F for 6 hours*.

Step 5: Remove lid and coupons.

Step 6: Place appropriate label on each coupon with tape and pen to designate varying thickness

Step 7: Sand down one side of coupon for observations.

Step 8: Inspect and record compaction observations.

Step 9: Rank each coupon as over-compact, under-compact, or properly compact.

Bend Test Procedure

Prep: Cut coupons in half to form .5 x 5 inch coupons.

Step 1: Place the coupon on the two supporting pins of the test fixture.

Step 2: Position the loading pin in the middle of the test specimen.

Step 3: Use a low approach speed to engage the loading pin into the specimen.

Step 4: Apply load until delamination occurs and visual deformation is apparent.

Step 5: Remove specimen and analyze data.

References:

1. Doane, William and Hall, Ronald. DEVELOPMENT OF A LOW-COST, MODIFIED RESIN TRANSFER MOLDING PROCECESS USING ELASTOMERIC TOOLING AND AUTOMATED PREFORM FABRICATION . General DYnamci s COnvair Division. https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19950021847.pdf

Attachments

BJB ENTERPRISES

An ISO-9001 Certified company

SILICONE CASTING RUBBERS

"Dedicated to QUALITY, SERVICE, SAFETY, and INNOVATION"

TC-5050 A/B

50 SHORE A

ROOM TEMPERATURE CURING SILICONE

TC-5050 A/B is a room temperature, addition/platinum curing silicone rubber designed for mold making, encapsulation applications, pressure pads, gaskets, and various types of parts. It is also used to make molds for casting low melting metals into. With the use of talc powder as an interface the TC-5050 A/B has been used in production with cast metal temperatures running 650°F (344°C) and has been subject to temperatures up to 850°F (454°C) for making a limited number of casts. With the ability to withstand high temperatures the TC-5050 A/B works very well as a mask for metal spraying and welding operations.

PHYSICAL PROPERTIES	TEST METHOD	RESULTS
Hardness, Shore A	ASTM D2240	50 ± 5
Cubic Inches per Pound	N/A	22.2
Color/Appearance	Visual	Blue
Tensile Strength (psi)	ASTM D412	620
Elongation (%)	ASTM D412	325
Tear Strength (pli)	ASTM D624 Die B	87
Coefficient of Thermal Expansion, (in/in/°F)	ASTM E831	16.5×10^{-5}
Shrinkage (in/in) linear	ASTM D2566 @ 1" depth	Nil

HANDLING PROPERTIES	Part A	Part B
Mix Ratio by weight	100	10
Mix Ratio by volume	100	12
Specific Gravity @ 77°F (25°C)	1.23	0.99
Color	Off White	Blue
Viscosity (cps) @ 77°F (25°C) Brookfield	121,400	490
Mixed Viscosity (cps) @ 77°F (25°C) Brookfield	90,000	
Work Time, 100g mass @ 77°F (25°C)	30 minutes	
Gel Time	60 minutes	
Demold Time @ 77°F (25°C)	24 hours	
Heat Cure @ 150°F (66°C)	2 – 4 hours	

INHIBITION:

Certain materials will cause inhibition or neutralization of the curing agent. These materials are sulphur and organometallic salt containing compounds such as organic rubbers and many condensation cured RTV silicone rubbers. Inhibition may easily be determined by brushing a small quantity of TC-5050 over a localized area of the surface to be reproduced. If the TC-5050 is gummy or uncured after the curing time, then you know the mold surface is acting as an inhibitor. Molds made from wood, plaster, metal or plastic should not cause inhibition if they are clean. To insure against possible problems, it is advisable to seal the surface with RF-5215 or other appropriate sealer. Contact BJB's Tech Sales for additional information.

STORAGE:

Store ambient temperatures, 65-80°F (18-27°C). Unopened containers will have a shelf life of 12 months from date of shipment when properly stored at recommended temperatures. Purge opened containers with dry nitrogen before re-sealing.

PACKAGING	Part A	Part B	Cubic Inches per Kit
Quart Kits	2 lbs.	3.2 oz.	49
Gallon Kits	8 lbs.	13 oz.	196
5-Gallon Kits	40 lbs.	4 lbs.	977
55-Gallon Drum Kits	450 lbs.	45 lbs.	10,989

SAFETY PRECAUTIONS:

Use in a well-ventilated area. Avoid contact with skin using protective gloves and protective clothing. Repeated or prolonged contact on the skin may cause an allergic reaction. Eye protection is extremely important. Always use approved safety glasses or goggles when handling this product.

IF CONTACT OCCURS:

Skin: Immediately wash with soap and water. Remove contaminated clothing and launder before reuse. It is *not* recommended to remove resin from skin with solvents. Solvents only increase contact and dry skin. Seek qualified medical attention if allergic reactions occur.

Eyes: Immediately flush with water for at least 15 minutes. Call a physician.

Ingestion: If swallowed, call a physician immediately. Remove stomach contents by gastric suction or induce vomiting only as directed by medical personnel. Never give anything by mouth to an unconscious person.

Refer to the Material Safety Data Sheet before using this product.

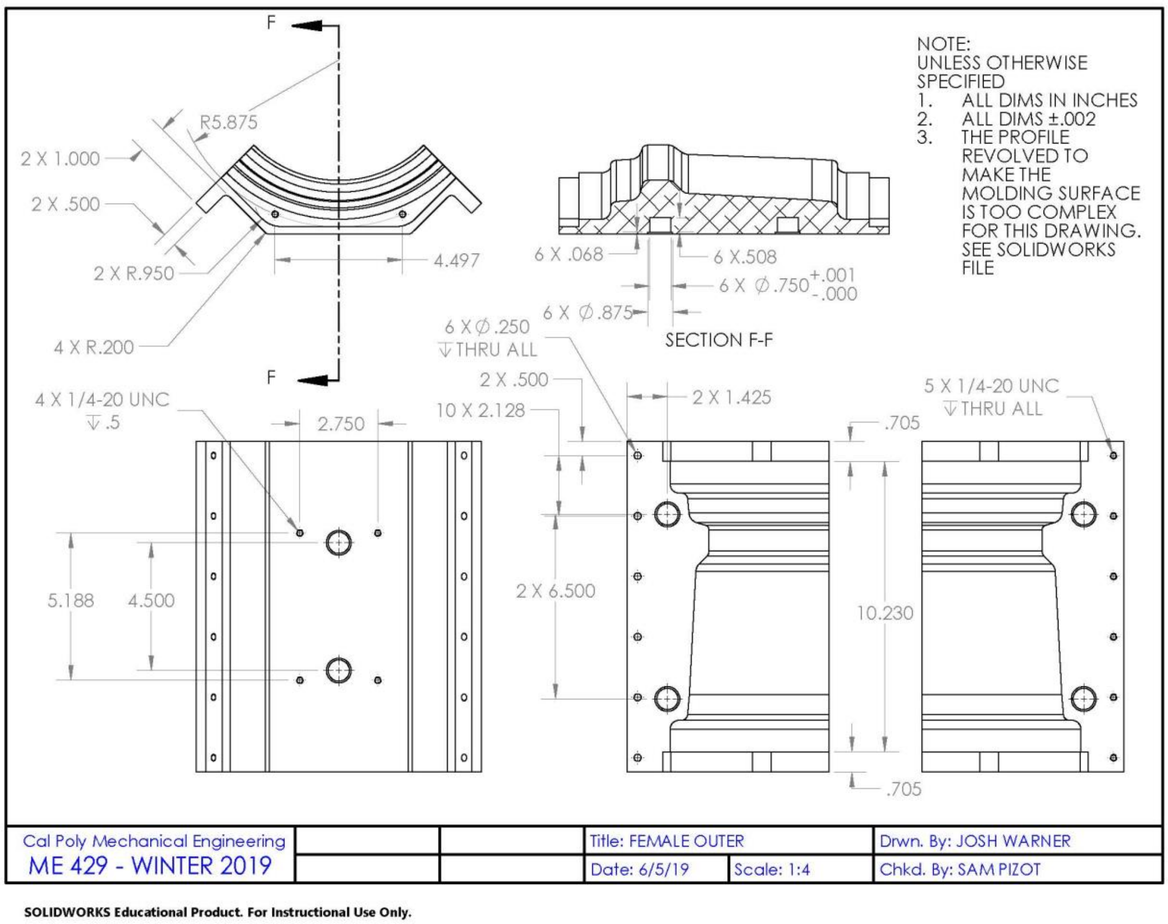
Silicone Handling Guide

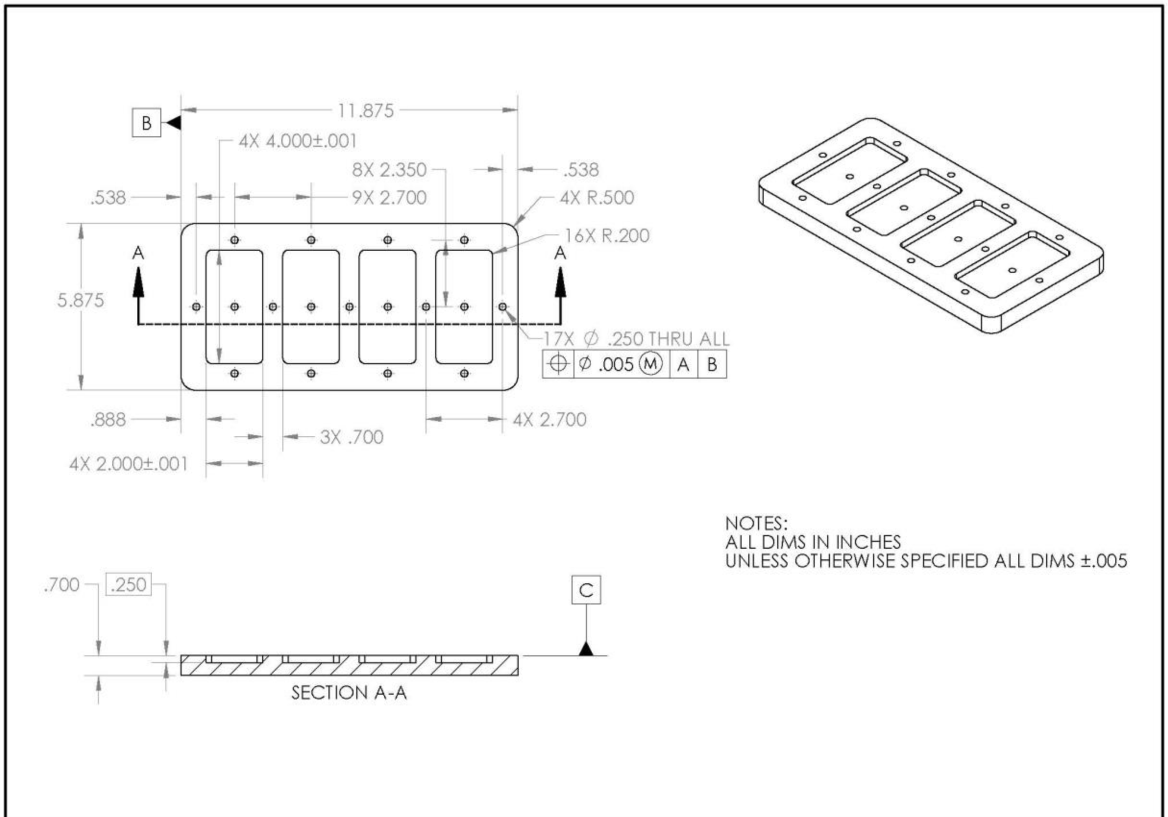
TC-5050 Part A SDS

TC-5050 Part B SDS

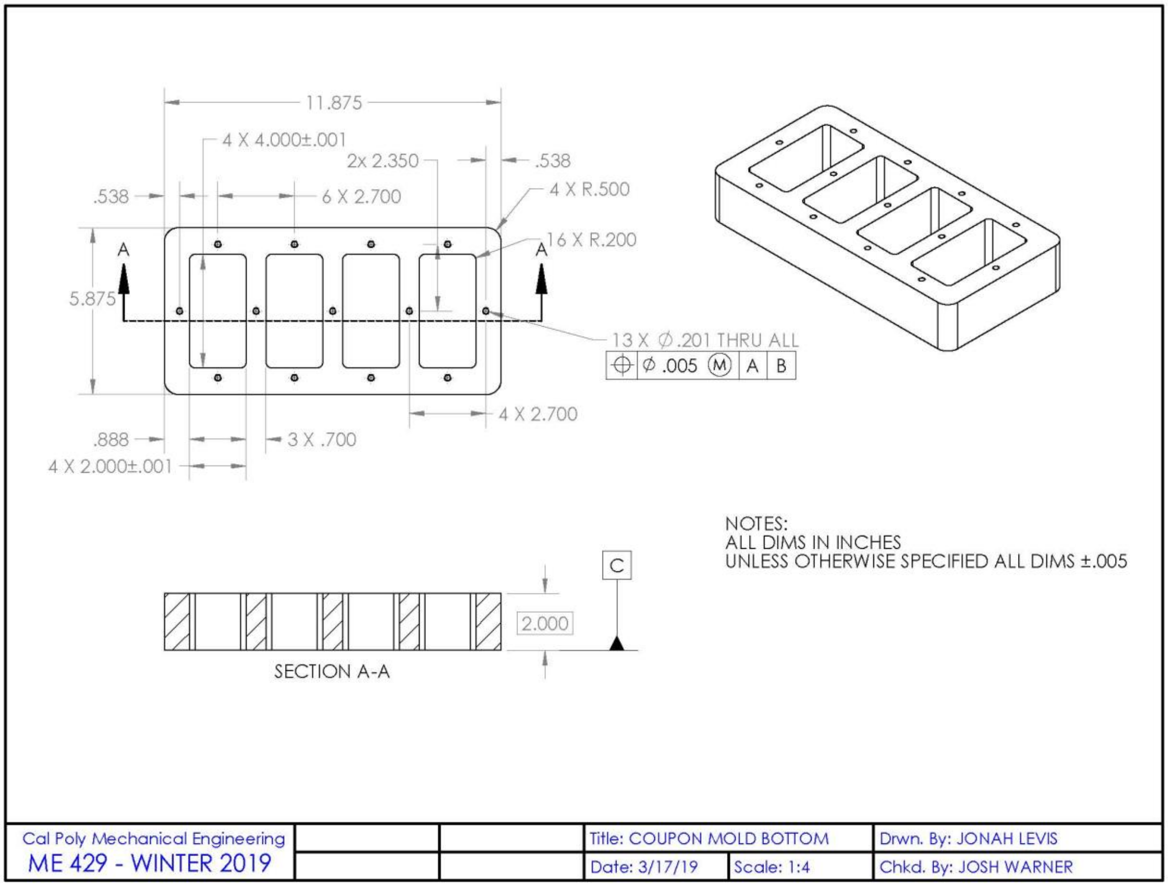
For more information call BJB Enterprises, Inc. (714) 734-8450 Fax (714) 734-8929

Appendix I: Drawings





Cal Poly Mechanical Engineering			Title: COUPON MOLD BOTTOM	Drwn. By: JONAH LEVIS
ME 429 - WINTER 2019			Date: 3/17/19 | Scale: 1:4	Chkd. By: JOSH WARNER


11.875
4 X 4.000±.001
2x 2.350
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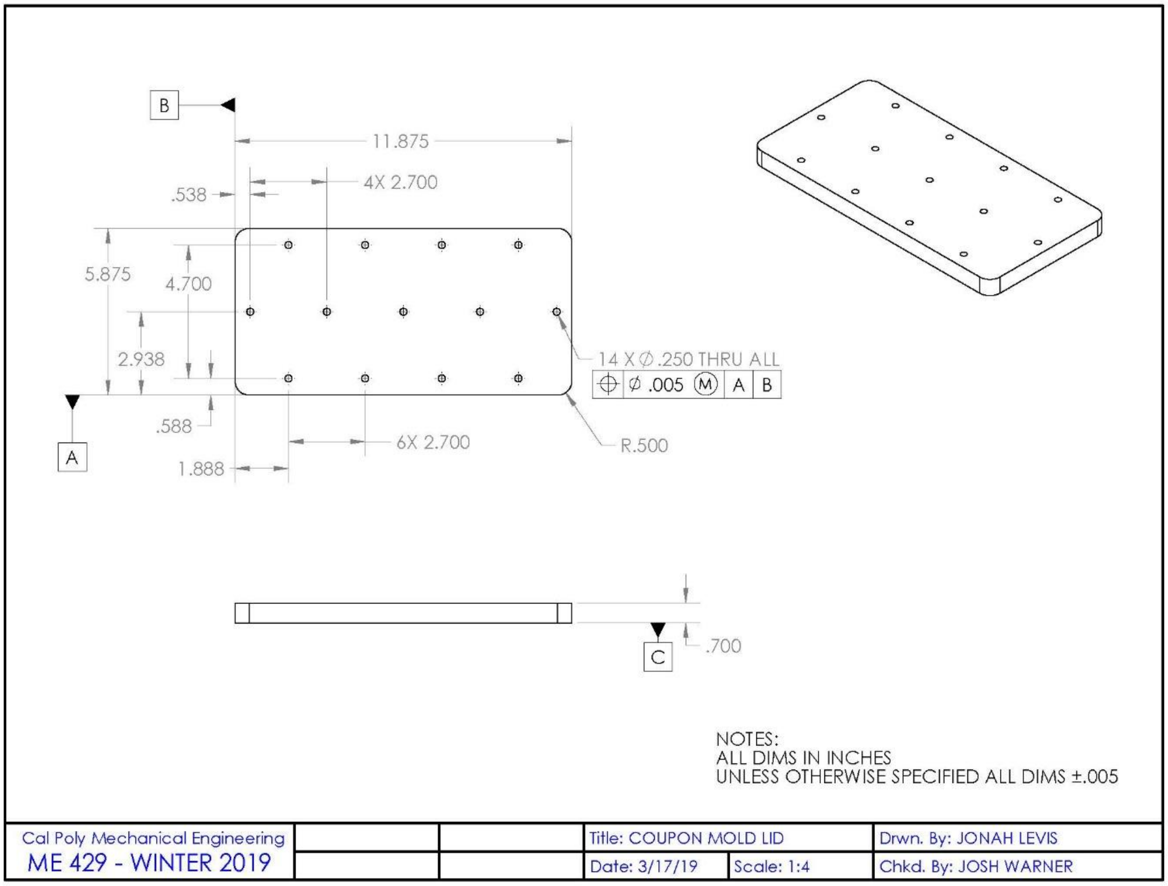
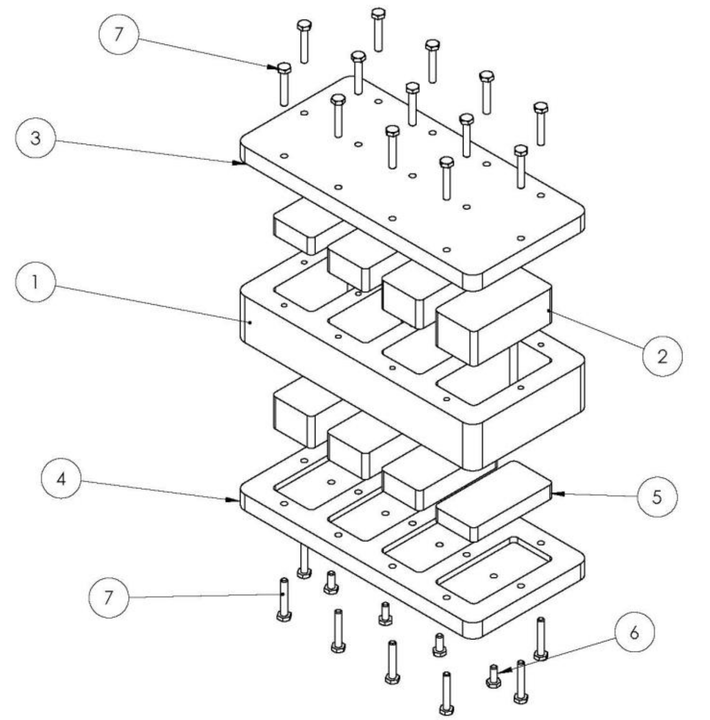
.538
6 X 2.700
4 X R.500
16 X R.200
A
A
5.875
13 X ∅.201 THRU ALL
⌖ ∅ .005 Ⓜ A B
4 X 2.700
.888
3 X .700
4 X 2.000±.001
NOTES:
ALL DIMS IN INCHES
UNLESS OTHERWISE SPECIFIED ALL DIMS ±.005
C
2.000
SECTION A-A
Cal Poly Mechanical Engineering
ME 429 - WINTER 2019
Title: COUPON MOLD BOTTOM
Drwn. By: JONAH LEVIS
Date: 3/17/19
Scale: 1:4
Chkd. By: JOSH WARNER



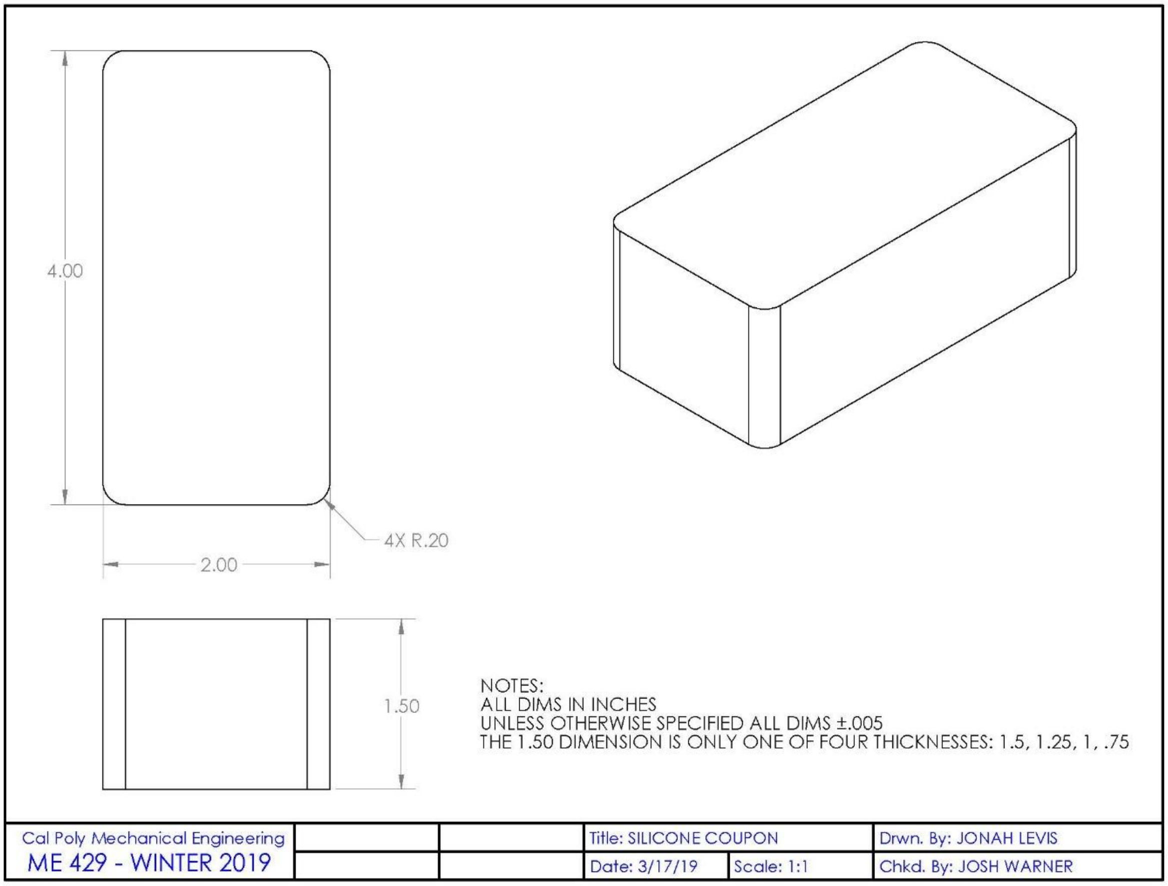
SOLIDWORKS Educational Product. For Instructional Use Only.

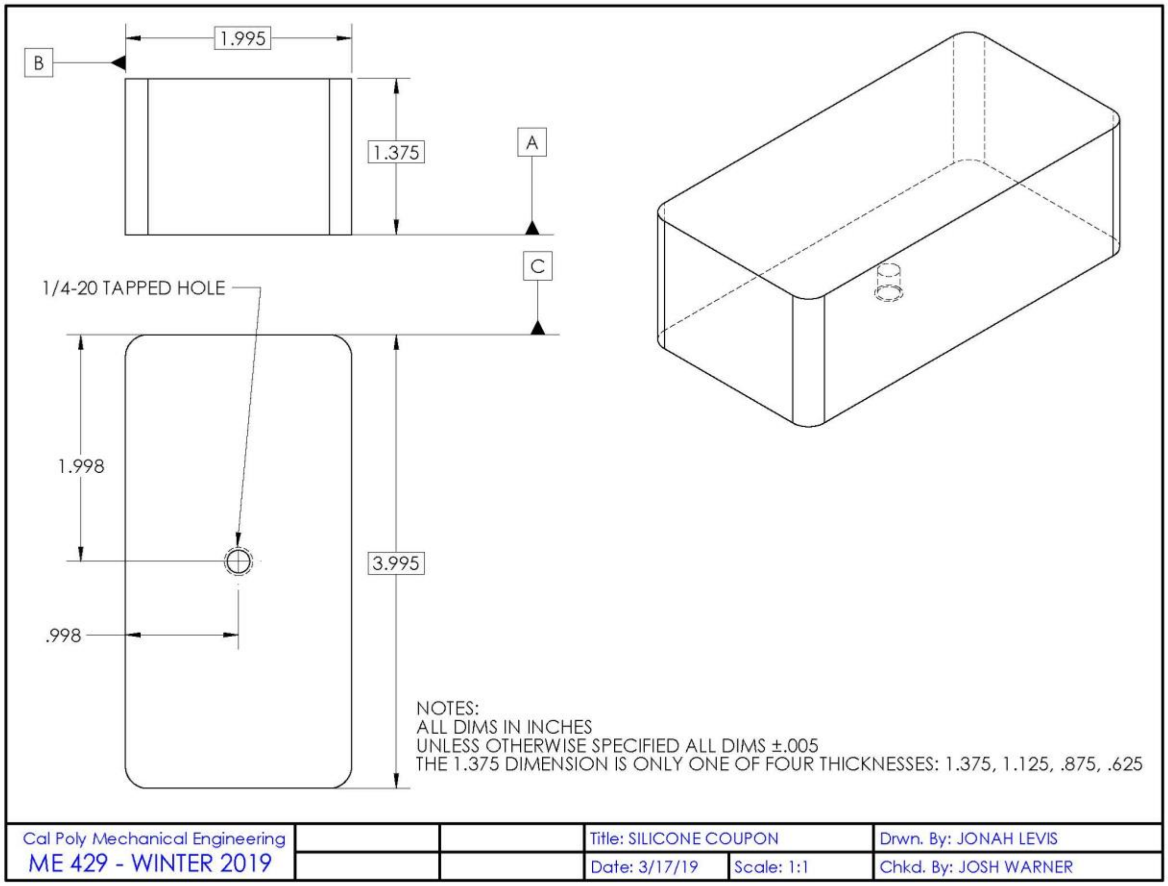


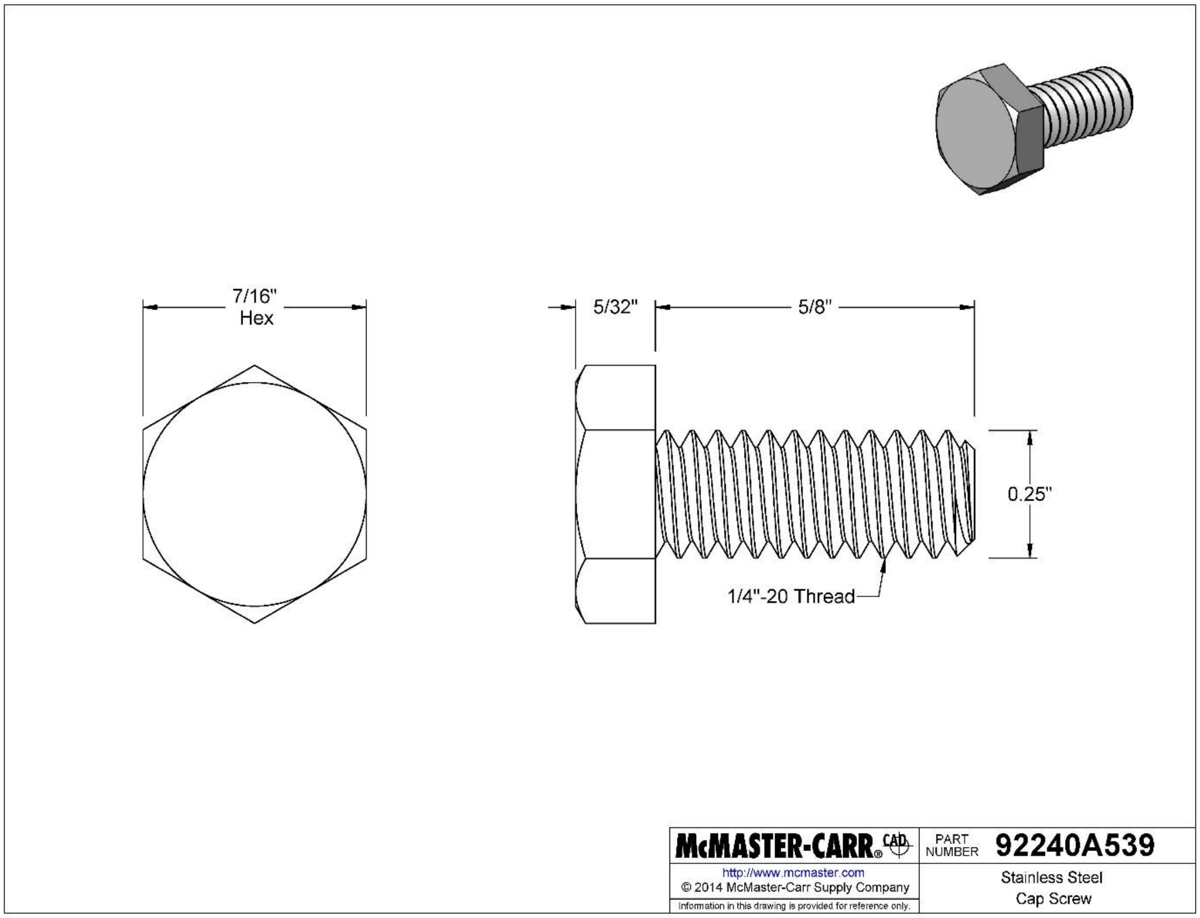
ITEM NO.	PART NUMBER	QTY.
1	Coupon Mold Middle	1
2	Silicone Coupon	4
3	Coupon Mold Lid	1
4	Coupon Mold Bottom	1
5	Height Boss	4
6	92240A539	4
7	92240A546	23

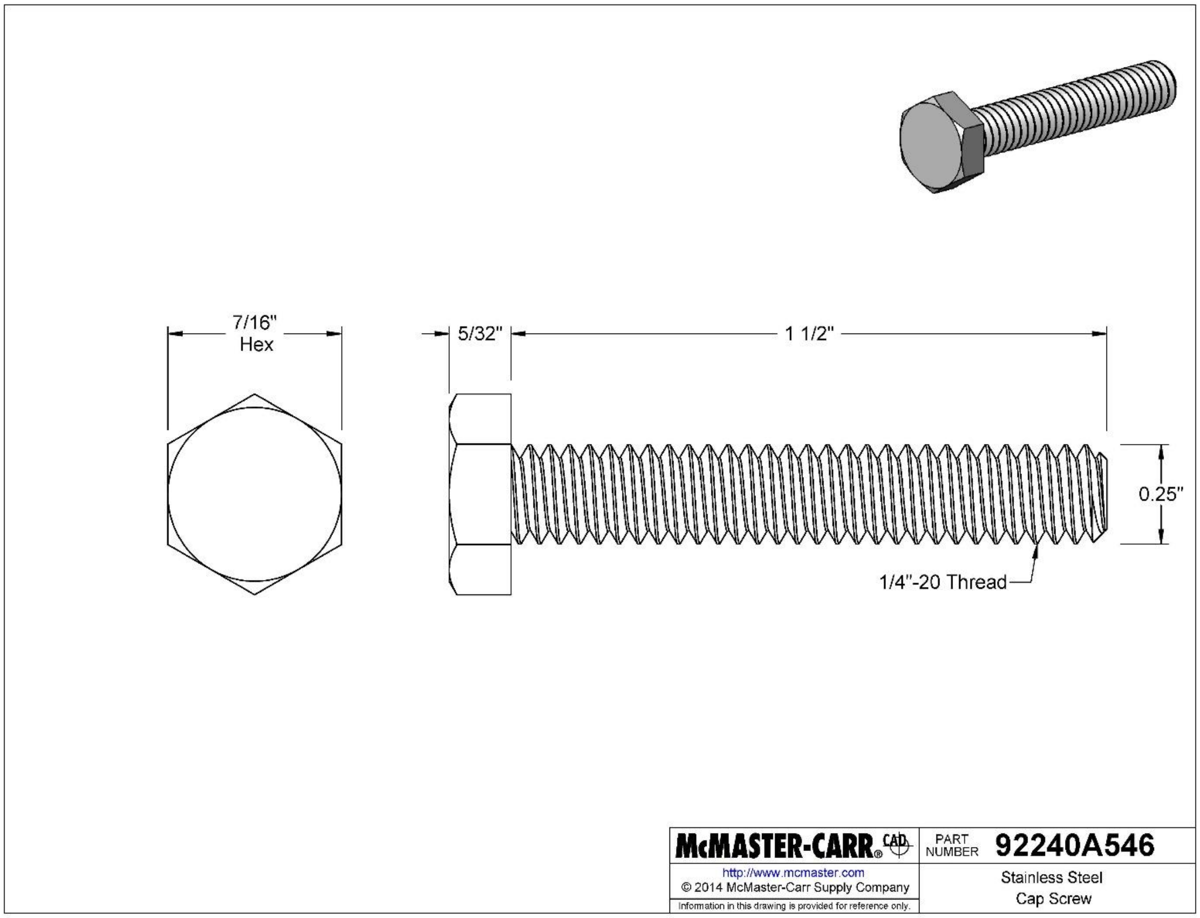
Cal Poly Mechanical Engineering			Title: COUPON MOLDEXPLODED VIEW	Drwn. By: JONAH LEVIS
ME 429 - WINTER 2019			Date: 3/17/19 / Scale: 1:4	Chkd. By: JOSH WARNER

SOLIDWORKS Educational Product. For Instructional Use Only.


4.00
2.00
4X R.20
1.50
NOTES:
ALL DIMS IN INCHES
UNLESS OTHERWISE SPECIFIED ALL DIMS ±.005
THE 1.50 DIMENSION IS ONLY ONE OF FOUR THICKNESSES: 1.5, 1.25, 1, .75
Cal Poly Mechanical Engineering
ME 429 - WINTER 2019
Title: SILICONE COUPON
Drwn. By: JONAH LEVIS
Date: 3/17/19
Scale: 1:1
Chkd. By: JOSH WARNER


1.995
B
1.375
A
C
1/4-20 TAPPED HOLE
1.998
3.995
.998
NOTES:
ALL DIMS IN INCHES
UNLESS OTHERWISE SPECIFIED ALL DIMS ±.005
THE 1.375 DIMENSION IS ONLY ONE OF FOUR THICKNESSES: 1.375, 1.125, .875, .625
Cal Poly Mechanical Engineering
ME 429 - WINTER 2019
Title: SILICONE COUPON
Drwn. By: JONAH LEVIS
Date: 3/17/19
Scale: 1:1
Chkd. By: JOSH WARNER


7/16"
Hex
5/32"
5/8"
0.25"
1/4"-20 Thread
McMASTER-CARR
CAD
PART NUMBER
92240A539
http://www.mcmaster.com
© 2014 McMaster-Carr Supply Company
Information in this drawing is provided for reference only.
Stainless Steel
Cap Screw

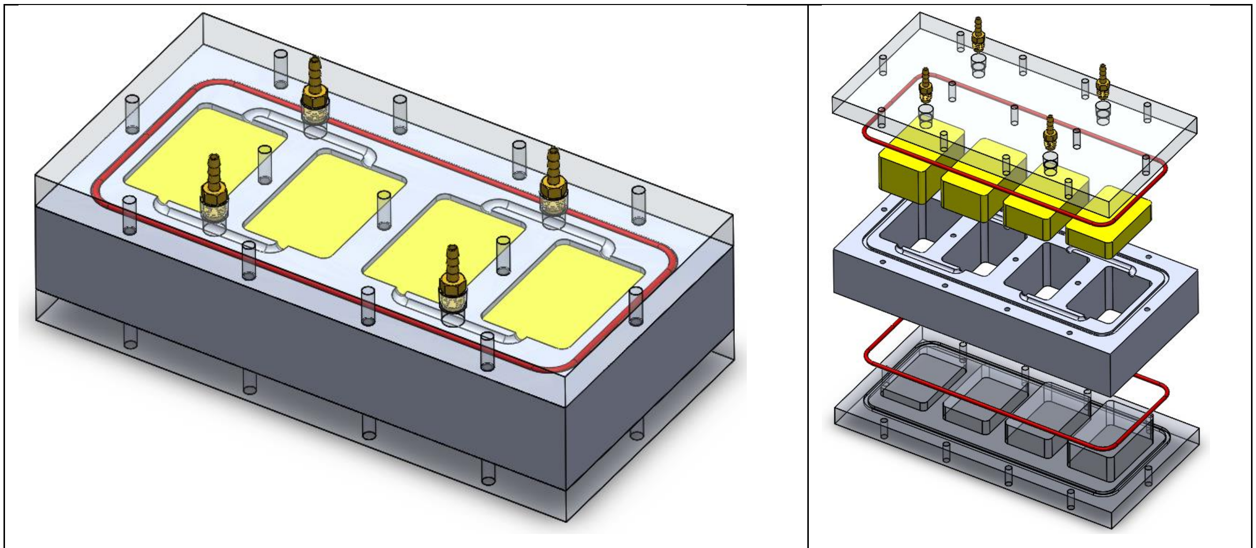


Appendix J: Mold and Test for Resin Infusion (Seriforge Design)

The trapped rubber concept simplifies some areas of the molding process and complicates others. It eliminates the need to infuse the carbon at a partially expanded mold state, then compress the mold to compact out excess resin. That process involves shims and other complications that this trapped rubber concept circumvents. However, this concept complicates the mold assembly and the achievement of vacuum for resin infusion, compared to a more standard infusion process like vacuum bag infusion. The process of assembling a dry, delicate preform within the components of the mold is challenging. The Silicone to carbon interface has friction and consequently a shear force. This could be mitigated by using plastic sheet to slip in between the two layers during assembly that could be slipped out. Another area of concern is the O-ring to O-ring interface “T” shaped seal when the vertical O-ring stock in between the female mold sections meets the circular portion on the male mold. This area needs to seal well for the mold to hold vacuum. This could be accomplished by clever machining of the end pieces into a U-shape.

As shown below a molding plan for testing variable silicone thicknesses includes a three-piece aluminum mold. Four thicknesses of Silicone will be tested: .75in, 1.0in, 1.25in, and 1.5in.

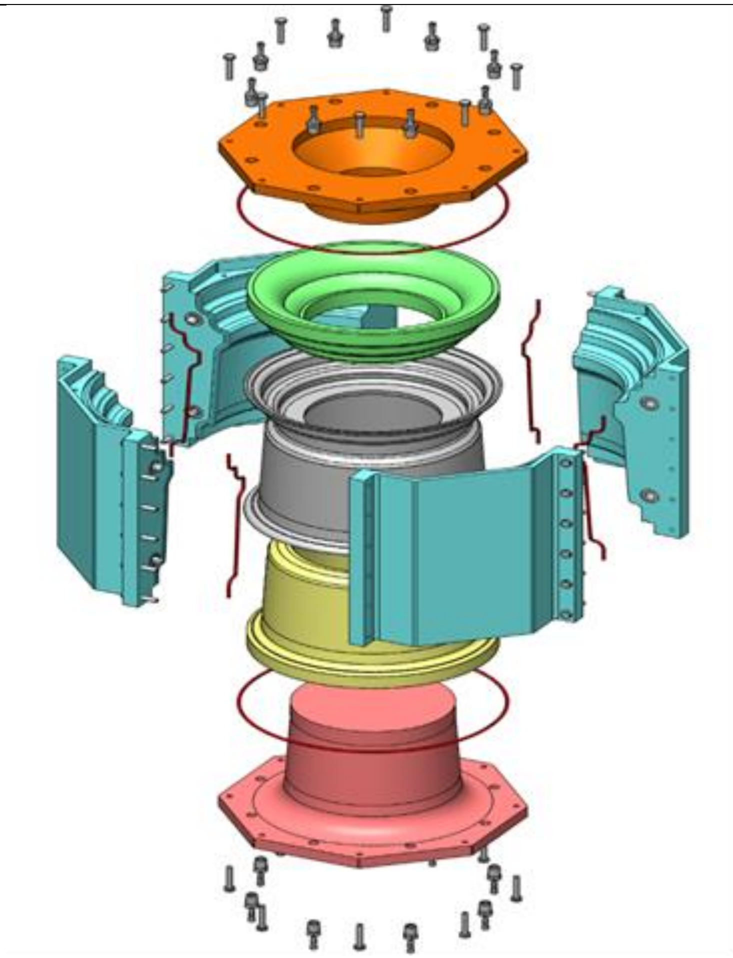
The base has four different height reliefs that allow the silicone coupons to sit level when assembled. It is very important for all carbon coupons to start at the same height to achieve valuable test results. The base also has a groove machined out for O-ring stock to sit and supply a seal. The center portion has four 2 x 4 inch slots which will hold the reliefs from the base, silicone and carbon coupons, and will join the three mold pieces together. The center also has two inlet and outlet resin channels machined, each connecting two coupons. These channels equally position resin ports above, allowing for equal infusion of all four coupons. An O-ring will sit in the groove machined on the top surface of the center mold piece to seal top and center pieces during infusion. After infusion the mold will be tightened with ¼-20 machined screws and baked at 350 F for 120 min to cure and the results will validate the thickness of Silicone required to achieve a 70% FVF.



Isometric views of the silicone coupon test mold.

The four-piece outer shell will be sealed for resin transfer with O-rings and O-ring chord. The 1/8 in nominal diameter silicone O-rings and O-ring chord will be purchased from McMaster Carr. A half dovetail O-ring gland will be machined into one vertical surface of each female shell piece. This will retain the O-ring chord during mold assembly. The top and bottom O-rings will be fit to more traditional rectangular cross-sectioned glands machined into the top and bottom of the female pieces. The O-ring glands are sized based on the design guides from Bay Seal Company and Parker.

The central resin inlet will be sealed for resin transfer with a small vacuum bag and tacky tape. This will allow the use of resin dispersion materials such as spiral tubing and breather mesh to distribute the resin evenly at the inlet. A shutoff valve will be incorporated at the outlet of the upper section of the mold for use during infusion to ensure resin is directed into the deeper section of the mold after the upper portion has been infused.



Detailed, exploded view of trapped rubber mold designed for resin transfer molding

PRODUCT DATA SHEET

TENCATE

TENCATE ADVANCED COMPOSITES

RS-50

PRODUCT TYPE

350°F (177°C) Curing Epoxy RTM Resin

PRODUCT FORMS

Resin

SHELF LIFE

Pot Life

4 hours @ 200°F (93°C), 270 cps

Frozen Storage Life

12 months @ <0°F (-18°C)

PRODUCT DESCRIPTION

RS-50 is a toughened low viscosity epoxy RTM resin. It features a long four hour pot life and a low minimum viscosity for excellent RTM and VARTM processing. It can also be used in wet winding applications.

PRODUCT BENEFITS/FEATURES

- One Part Resin System
- Low Minimum Viscosity of 23 cps
- Long 4 Hour Pot Life
- High Hot/Wet Tg of 388°F (189°C)
- 2 Hour Cure Cycle
- Low 190°-200°F (88°-99°C) Injection Temperature

NEAT RESIN PHYSICAL PROPERTIES

Density .... 1.16 g/cc
Tg (Dry) .... 397°F (203°C)
Tg (Wet) .... 388°F (197°C)
Minimum Resin Viscosity .... 23 cps (by DMA, 4°F/min; 2°C/min ramp rate)
Moisture Absorption .... 2.1% (after 48 hour water boil)
Resin Viscosity
  180°F (82°C) .... 365 cps
  200°F (93°C) .... 193 cps
  250°F (121°C) .... 56 cps
Gel Time (at 350°F/177°C) .... 32 minutes

NEAT RESIN PHYSICAL PROPERTIES

Fracture Toughness .... 186 J/m² (G1C)
Flexural Strength .... 21 ksi (145 MPa)
Flexural Modulus .... 0.58 Msi (4.0 GPa)
Tensile Strength .... 11 ksi (76 MPa)
Tensile Modulus .... 0.52 Msi (3.7 GPa)

LAMINATE DATA USED T300, 5HS FABRIC, 370 GSM FAW.

Properties	Condition	Method	Results	
Flexural Strength 0°	RTD	ASTM D7264	135 ksi	930.8 MPa
Flexural Modulus 0°	RTD	ASTM D7264	8.5 Msi	58.6 GPa
Open Hole Comp. Strength*	RTD	ASTM D6484	40 ksi	275.8 MPa
Open Hole Comp. Strength*	ETD	ASTM D6484	32.3 ksi	222.7 MPa
Short Beam Shear Strength	RTD	ASTM D2344	10.5 ksi	72.4 MPa
CAI*	RTD	ASTM D7136/7137	34.8 ksi	239.9 MPa

** 3rd Party Generated Data*
ETD: 220°F (104°C)

TYPICAL CURE PARAMETERS

2 hours at 350°F/177°C

Revised 1/2017

All data given is based on representative samples of the materials in question. Since the method and circumstances under which these materials are processed and tested are key to their performance, and TenCate Advanced Composites has no assurance of how its customers will use the material, the corporation cannot guarantee these properties.

TENCATE ADVANCED COMPOSITES

18410 Butterfield Blvd.
Morgan Hill, CA 95037 USA
Tel: +1 408 776 0700

2450 Cordelia Road
Fairfield, CA 94534 USA
Tel: +1 707 359 3400

Amber Drive, Langley Mill
Nottingham, NG16 4BE UK
Tel: +44 (0)1773 530899

www.tencateadvancedcomposites.com
info@tcac-usa.com (USA)
tcacsales@tencate.com (Europe)

Appendix K: DVP&R

Senior Project DVP&R

Date:	Team: C6 Wheels	Sponsor: Formula	Description of System: Carbon Fiber Wheel Mold	DVP&R Engineer: Sam Pizot, Jonah Levis

TEST PLAN										TEST REPORT			
Item No	Specification #	Test Description	Acceptance Criteria	Test Responsibility	Test Stage	SAMPLES		TIMING		TEST RESULTS			NOTES
						Quantity	Type	Start date	Finish date	Test Result	Quantity Pass	Quantity Fail	
1	Compaction	Use coupon test mold to cure carbon fiber coupons with varying silicone thicknesses and process gaps. Observe coupons for voids or overcompaction	Visual inspection	Sam, Jonah	CP	18	C	5/7/2019	5/30/2019	.75"-1" silicone w/ no process gap	4	14	Failures due to change of variables
2	Strength	3-point bend test of coupons to determine strength	Maximum ultimate tensile strength	Sam, Jonah	CP	6	C	5/7/2019	5/30/2019	.75"-1" silicone w/ no process gap	2	4	
3	45-end mill proofing	Machine multi-level angled face, show whether the cutter produces a flat enough face to datum from	Visual inspection	Josh, Luke	FP	1	Sub	5/21/2019	5/30/2019	End mill can be used reliably for manufacture	1	0	

Appendix L: Project Spending Receipts

McMASTER-CARR.

Order Confirmation

562-692-5911
562-695-2323 (fax)
la.sales@mcmaster.com

Ship to

Warner Consulting
2690 Northview Ave
Arroyo Grande CA 93420-6506

Attention Josh Warner

Order Date
5/14/19

Ordered By
Josh Warner

McMaster-Carr Number
4373072

Line		Product	Ordered	Delivers	Price	Total
1	8936A979	Uncoated High-Speed Steel Tapered End Mill, 4 Flute, 45 Degree Taper, 1/8" Mill Diameter, 5/16" Long Cut	1 each	May 15	55.11 each	55.11

Merchandise $55.11

Applicable shipping and tax will be added.

McMASTER-CARR.

Order Confirmation

562-692-5911
562-695-2323 (fax)
la.sales@mcmaster.com

Ship to

Sam Pizot
338 San Miguel Avenue
San Luis Obispo CA 93405

Attention Josh Warner

Order Date
4/11/19

Ordered By
Josh Warner

McMaster-Carr Number
2854451

Line		Product	Ordered	Delivers	Price	Total
1	92240A546	18-8 Stainless Steel Hex Head Screw, 1/4"-20 Thread Size, 1-1/2" Long, Fully Threaded, packs of 50	1 pack	Apr 12	7.91 per pack	7.91

Merchandise $7.91

Applicable shipping and tax will be added.

McMASTER-CARR

Order Confirmation

562-692-5911
562-695-2323 (fax)
la.sales@mcmaster.com

Order Date
4/5/19

Ship to

Warner Consulting
2690 Northview Ave
Arroyo Grande CA 93420-6506

Ordered By
Josh Warner

McMaster-Carr Number
2571703

Attention Josh Warner

Line		Product	Ordered	Delivers	Price	Total
1	88815A36	Uncoated Carbide Square-End End Mill, 3 Flute, 3/8" Mill Diameter, 2-1/2" Overall Length	2 each	Apr 8	33.82 each	67.64
2	8975K235	6061 Aluminum, 3/4" Thick x 6" Wide, 1 Foot Long	1 each	Apr 8	44.26 each	44.26

Merchandise $111.90

Applicable shipping and tax will be added.

Order Confirmation

COAST ALUMINUM and ARCHITECTURAL

Order #: 4464658
Date: 05/03/19
Page: 1

Sold-To: 111149
Attn: Luke Martin
CAL POLY STATE UNIV.
1 GRAND AVE
41A COURTYARD
SAN LUIS OBISPO, CA 93407

Ship To:
CAL POLY STATE UNIV.
1 GRAND AVE
41A COURTYARD
SAN LUIS OBISPO, CA 93407

T) 805 756-2341
c6wheels@gmail.com

F) 805 756-5439

Date Ordered	Ship Date	Ship Via	Freight Terms	Salesman 208	Ordered By	Customer PO	Terms
05/03/19	05/09/19	OUR TRUC	PREPAID	Teneshia H	Luke Marti	VERBAL- LUKE	COD * C

Ln #	Pcs	Lbs	Part Number/Description	UM	Unit/Ext Price
1	4	224	4PL61 4.000 X 11" X 12" PLATE 6061 T651 C/T +.030/-.000	EA	169.3000 677.20
2	1	11	512PL61D 5.50 X 2.75" X 6" PLATE 6061 T651 C/T +.030/-.000 PAID W/CC AUTH# 03088D	EA	58.3500 58.35
999	1		SURCHARGE SURCHARGE	EA	10.0000 10.00

Total Lbs: 235

PAID W/CC

Subtotal:	745.55
7.750% Tax:	57.78
Freight:	0.00
Total:	803.33

VT-IT-03-F01

Quotation

COAST ALUMINUM and ARCHITECTURAL

1360 EAST NORTH AVENUE
FRESNO, CA 93725
U.S.A.
559 495-6061
FAX: 559 444-1790

Quote #: 169261
Date: 02/27/19
Page: 1

Sold-To: CAL POLY STATE UNIV.
1 GRAND AVE
41A COURTYARD
SAN LUIS OBISPO, CA 93407
111149

Ship To: CAL POLY STATE UNIV.
1 GRAND AVE
41A COURTYARD
SAN LUIS OBISPO, CA 93407
805 756-2341

Date Quoted	Lead Time	Ship Via	Freight terms	Territory
02/27/19		OUR TRUCK	PREPAID	216

Salesperson	Quoted For	Tax	Terms	Whse
208 Teneshia Hackett	Luke Martin	48	COD * COD *	200

Ln #	Pcs	Lbs	Part Number/Description	UM	Unit/Ext Price
1	2	29	26B61 2.000 X 6.000 BAR 6061 T6511 12" c/t +.030/-.000	EA	55.0000 110.00
2	1	5	346B61 .750 X 6.000 BAR 6061-T6511 12" c/t +.030/-.000 **4 DAY LEAD TIME**	EA	40.0000 40.00
			A $10 SURCHARGE APPLIES TO EACH PURCHASE ORDER		

COD***COD***COD***COD***COD***
CODCOD***COD***COD***COD
****

Subtotal:	150.00
Tax:	11.63
Freight:	0.00
Total:	161.63

02/27/19 10:25AM

McMASTER-CARR.

Order Confirmation

562-692-5911
562-695-2323 (fax)
la.sales@mcmaster.com

Ship to

Luke Martin (C6WHEELS@GMAIL.COM)
C/O Cal Poly Mustang 60 Machine Shop
1 Grand Avenue
San Luis Obispo CA 93407

Order Date
5/3/19

Ordered By
Luke Patrick Martin

McMaster-Carr Number
3937980

Line		Product	Ordered	Delivers	Price	Total
1	5190A31	Aluminum Load-Rated Pull Handle with Unthreaded Holes, Anodized, 5-3/16" Center-to-Center Width	2 each	May 6	17.21 each	34.42
2	92240A546	18-8 Stainless Steel Hex Head Screw, 1/4"-20 Thread Size, 1-1/2" Long, Fully Threaded, packs of 50	1 pack	May 6	7.91 per pack	7.91
3	92185A542	Super-Corrosion-Resistant 316 Stainless Steel Socket Head Screw, 1/4"-20 Thread Size, 1" Long, packs of 10	1 pack	May 6	3.91 per pack	3.91
4	31335A54	Hole Liner for 1/2" Diameter Diamond and Round-Head Mating Locating Pin	4 each	May 6	8.55 each	34.20
5	31335A14	Mating Locating Pin, 1/2" Diameter Round Head	2 each	May 6	9.36 each	18.72
6	31335A34	Mating Locating Pin, 1/2" Diameter Diamond Head	2 each	May 6	15.77 each	31.54

Merchandise $130.70

Applicable shipping and tax will be added.

Note: $150 of Silicone was purchased using the Pro-Card and rainy day fund, but the receipt was unavailable.

Appendix M: Machining manual

Machining manual

There are six operations for machining the female mold pieces. The first three operations will be done using a standard 6” vise with parallels for work holding, and the last three will be done using the fixture block in conjunction with a standard 6” vise.

This manual assumes the fixture block has already been machined and locating pins press fit in place. The stock for the female mold pieces is cut to 12”x11”x4”. Before machining, ensure the vise is square to the machine and that the jaws close in the Y machine coordinate.

Tooling Recommendations – with DOC (depth of cut) and WOC (width of cut)

Tool	Reason	Feeds (IPM), Speeds (RPM), DOC (in), WOC (in)
3” face mill	Fastest way of clearing large volume of material on the TM, best surface finish for flat surfaces	25, 2900, 0.100, 2.5
45 deg tapered end mill	Fastest way of making flat 45 degree faces	30, 2600, 0.010, 0.200
3/4" square end mill, 2" length of cut	Need at least 2” for establishing reference faces for subsequent operations	17.5,
3/8” square end mill	Need a tool small enough to machine locating pin bores, less than 1/2" diameter recommended	33, 2400, 0.375, 0.095
1/4" ball end mill	Needed to reach certain internal radii	90, 4000, 0.250, 0.050
0.201" drill	Needed to make tap holes for 1/4-20 screws	30, 4000, 0.125 (peck)
0.252" drill	Needed to make clearance holes for 1/4-20 screws	30, 4000, 0.125 (peck)
1/2" or 3/4" ball end mill	Larger ball end mill for most of the surfacing	

Op 1: Outer geometry and fixturing features

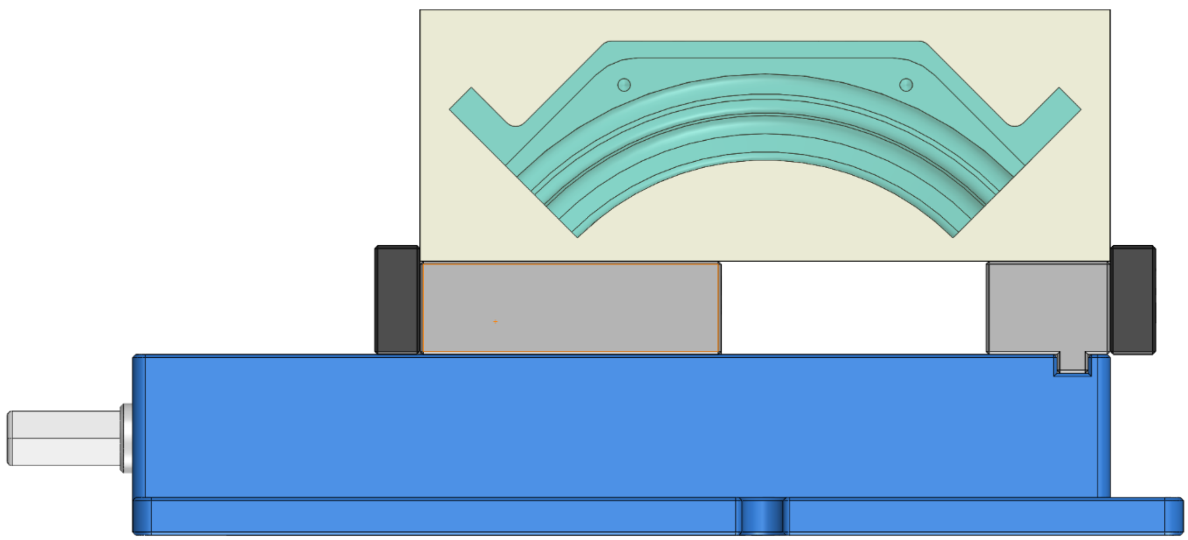


Figure 1 – Side view of setup for Op 1. Stock is shown here in yellow.

For the first operation, move the vise jaws to the outer position in order to be able to grip around the 11” dimension of the stock. Orient the stock in the vise such that the 12” dimension is in the X direction, the 11” dimension in the Y direction, and the 4” dimension in the Z direction. Figure 1 above shows a side view of the stock located in the vise. Locate the coordinate system on the top of the stock centered in X and Y. This ensures even cutting forces at the edge of the stock without precise measurement of the stock size.

The features machined in this operation will mate with the fixture block later and will be used for locating subsequent operations.

Face the stock to establish the face that mates with the fixture block. This also establishes the B datum for the next 2 operations. Then machine the locating pin bores and drill the 1/4-20 tap holes. Make sure to measure the bores with pin gages to ensure they will be a light press fit for the alignment pin sleeves (recommended diameter range is 0.7505” – 0.7509”). Also ensure that the lip of the alignment pins sits below the surface of the aluminum to ensure proper mating of components. Next, profile the vertical faces normal to the Y direction as deep as the tool allows (recommended 1.95” with the 3/4" square end mill). These faces will be used to touch off the part in the X direction in the next 2 operations (C datum). Then the 45-degree faces are roughed and finished. Finally, profile the faces normal to the X coordinate as deep as the tool allows (recommended 1.95” with the 3/4" square end mill). This establishes the A datum for the next two operations.

Figure 2 below shows how the part should look after Op 1.

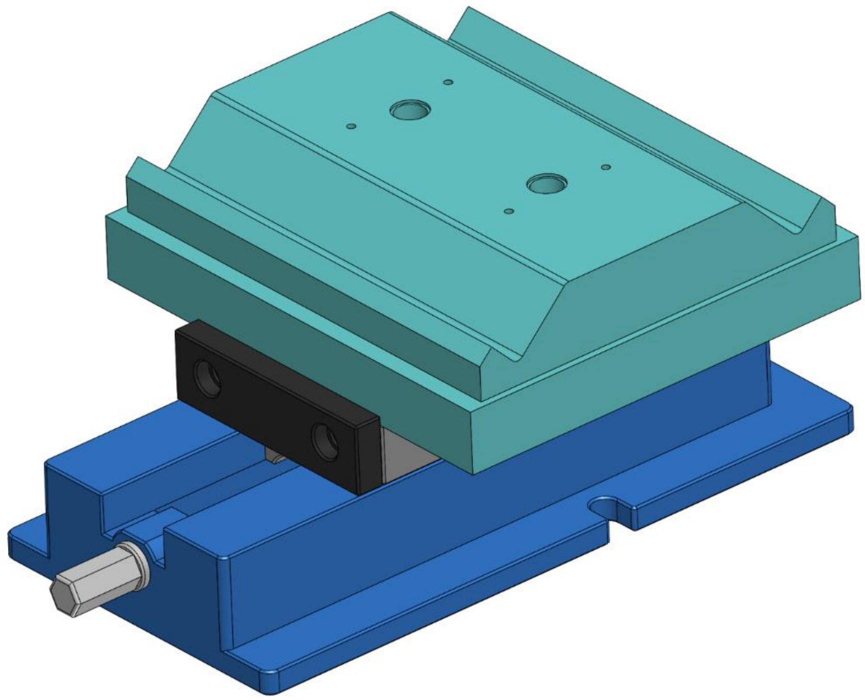


Figure 2 – This is how the part should look after Op 1 has been completed.

Op 2: Upper geometry

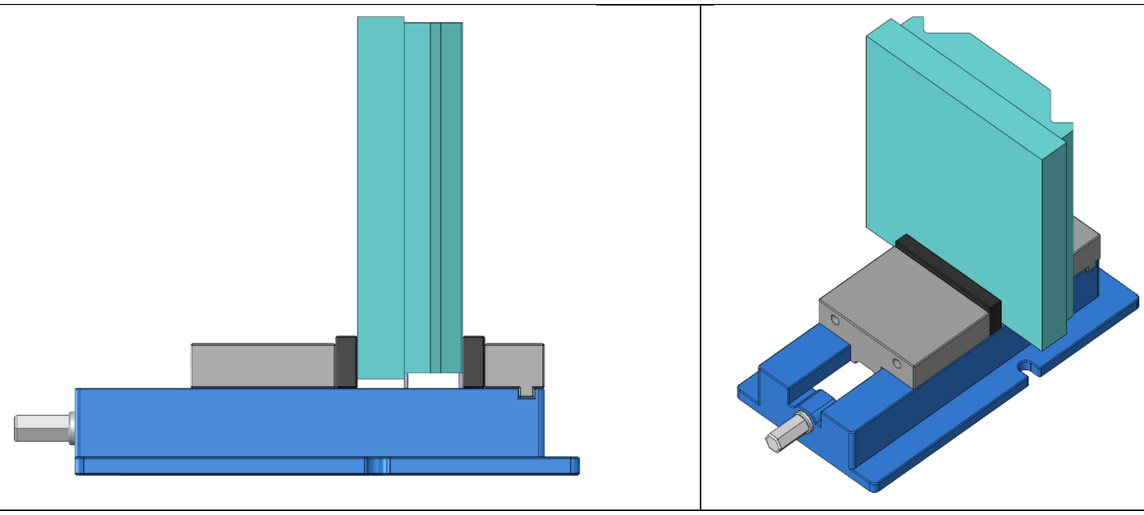


Figure 3 – Side view (left) and isometric view (right) of setup for Op 2.

For the second operation, the jaws on the vise need to be moved to the normal inner position. Orient the part in the vise such that one of the faces that was normal to X in the previous operation is resting on the shortest parallels available. Place the face that was up, which has the pin bores, against the fixed jaw. Locate the coordinate system on the top of the parallels in Z, centered in X and along the fixed jaw of the vise in Y. Figure 3 above shows the part in the vise as described.

Face the top of the part, and pocket out the material down to the face with the 1/4"-20 tap holes. Profile the wall of this face and drill the holes.

Op 3: Lower geometry

For Op 3, flip the part in the vise 180° about the Y axis, such that the face which was just machined in Op 2 with the 1/4"-20 tap holes now rests on parallels. Use taller parallels such that the face with the 1/4"-20 tap holes is the one resting on the parallels. Set the origin in Z on the top of the parallels. Run the same toolpaths as Op 2 after adjusting the Z.

Op 4: Molding surface

To set up for Op 4, the locating pins must be pressed into the bores made in Op 1. Before pressing in the pins, freeze them to make pressing easier. Next attach the fixture block to the part using the 1/4-20 socket head cap screws. Locate the coordinate system on the bottom of the vise in Z. Load the fixtured part into the vise such that the faces machined in Op 2 and Op 3 are normal to the X axis and the fixture block is clamped in the vise, resting on the bottom. Locate the coordinate system centered in X and Y. Figure 4 below shows a side view of the part attached to the fixture block held in the vise.

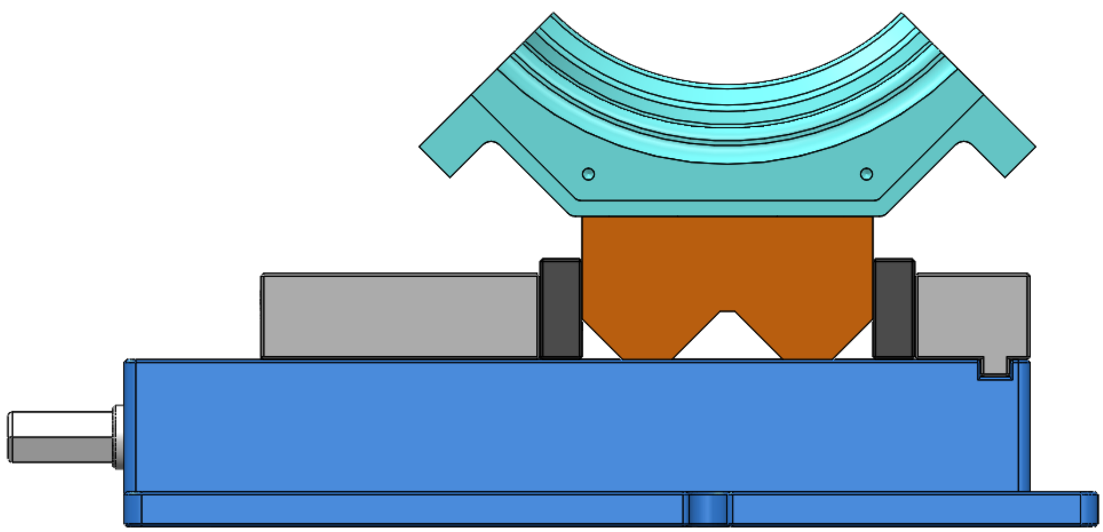


Figure 4 – Side view of setup for Op 4.

Machine the bulk of the material away using a combination of the face mill, and square end mills. Machine the mold surface with a combination of the ball end mills, working from largest diameter to smallest using rest machining to ensure the smaller cutters only cut where necessary.

Ensure that the 45° surfaces have at least 0.010" stock remaining to be cleaned up in the next operation using the face mill.

Op 5: Angled mating surface

For Op 5, rotate the part 45° about the X axis, such that the front angled surface machined in Op 4 is against the moveable jaw of the vise, and one of the angled surfaces of the fixture block is against the fixed jaw of the vise. Locate the coordinate system on the bottom of the vise in Z, centered in X and against the fixed jaw of the vise in Y. See figure 5 below.

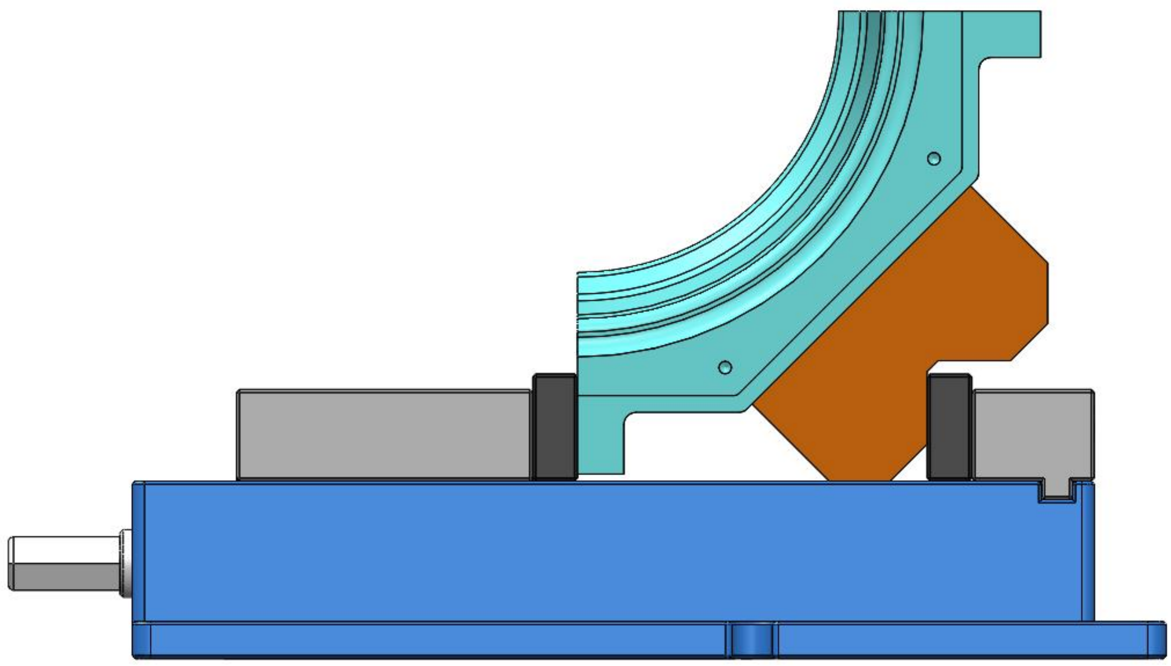


Figure 5 – Side view of the setup for Op 5 and Op 6. Note that Op 5 and Op 6 only differ in that Op 6 drills through holes for 1/4" screws and Op 5 drills tap holes.

Face the surface with the face mill and bore the alignment pin bores with the 3/8" square end mill. Again, check with gage pins for proper fit. Drill the holes.

Op 6: Second angled mating surface

Rotate the part 180° about Z and 90° about X such that the angled face machined in Op 5 is against the moving jaw and the other angled face is positioned like the previous operation. The coordinate system remains in the same location as Op 5, but will need to be re-centered in X. Repeat the operations from Op 5 except that the drill for this op should be for through holes, not tap holes.