

Formula SAE Cast Magnesium Wheels

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Abstract

The University of Michigan MRacing Formula SAE team is interested in improving the performance of their race car, specifically through reducing weight. The wheels have been targeted as an area for weight reduction, as they are unsprung rotating mass and have the highest inertia condition on the car. As members of the MRacing team, we have identified various design options for reducing the weight of the wheels, and have settled on designing and manufacturing a set of cast magnesium wheels. Through the use of these wheels, we will reduce the unsprung mass of the car and greatly improve performance. The wheels were designed with the aid of 3D modeling software and finite element analysis, and cast out of magnesium using a sand-casting process. The tooling was made using rapid prototyping, which greatly reduced production time and cost. They were also physically tested on an Instron machine and will be run on the 2007 MRacing vehicle for design validation.

Introduction

Formula SAE (FSAE) is an international competition that challenges teams of students to finance, design, build, and race a small open-wheel racecar. The University of Michigan team has consistently been one of the top teams in the competition. In order to meet our 2007 goal of winning both the US competition and the World Cup, each area of the car needs to be optimized. A smaller frame has been designed to decrease weight, and a turbocharger has been added to the engine to increase power. Another area where large improvements can be made is the wheels. The wheels are one of the heaviest components on the car, and as unsprung rotating mass they have a dramatic effect on all facets of dynamic performance.

The goal of our project was to design a set of wheels lighter than those currently being used without sacrificing stiffness. Several other FSAE teams currently produce their own wheels in an effort to save weight. Some of them use three piece wheels featuring an aluminum center and carbon fiber shells, and one team produces full carbon fiber wheels. We manufactured a set of one piece cast magnesium wheels which are significantly lighter than the three piece aluminum wheels we currently use, while improving stiffness under critical loading conditions. We were also the first FSAE team to manufacture a set of cast magnesium wheels using 3D rapid prototyping as tooling.

Information Search

The wheels currently used on the Uof M FSAE car are a 10 inch diameter, three piece aluminum design consisting of a machined aluminum center and spun aluminum shells. The three sections are bolted together using twelve 3/16 inch bolts and cost roughly \$120

a piece. The primary problem with these wheels is their weight. At over five pounds per wheel there is a significant amount of weight which can be removed.

In an effort to reduce the weight of their wheels, several other FSAE teams currently design and manufacture their own wheels or wheel centers. One particularly common solution is a machined aluminum center with a carbon fiber shell. This design is easy to manufacture because it is a three piece assembly, thus the complexity of the machining and carbon fiber molds is reduced. It is also easy to repair if damage occurs because the damaged component can be replaced without replacing the entire wheel. The drawbacks of such a design are in its weight and stiffness. The bolts used to hold the three sections together increase weight and localize stresses. This results in more deflection during cornering and increased inertia values.

Another common design is a one piece wheel, where the shell and center are either manufactured from one piece of material or the center and the shells are permanently bonded together. This design has the inverse benefits of a three piece wheel: it is extremely light and stiff, but very difficult to repair and manufacture. Currently the one piece designs seen in Formula SAE are aluminum centers bonded to carbon shells, forged magnesium, or complete carbon fiber. No team however currently makes a one piece cast magnesium wheel with a 10 inch diameter. There is also currently not a commercially available 10 inch magnesium wheel.

Magnesium has been used in the automotive industry for many years, in applications ranging from engine blocks, transmission housings and structural members, [1] to brackets and wheels. Many motorsports use magnesium for its high specific stiffness and low weight. Currently it is used to make Formula One wheels, Moto GP wheels, and the engine cradle in the 2006 Corvette Z06 [2].

Other benefits of magnesium are its cost and versatility. Of the primary light alloy metals magnesium is one of the cheapest, and currently costs less to cast than aluminum [3]. It is also applicable to many manufacturing processes. Unlike other metals, magnesium can be cast, machined, laser cut and welded. This makes it very appealing to any situation where several machining processes are required.

Research has also been conducted in the manufacturing processes required to make the wheel. CNC machining, forging, and casting were considered. CNC machining a solid wheel from a large piece of billet material is extremely inefficient. During the machining process, approximately 80% of the material would be removed. This would result in large manufacturing times and costs. Forging is a process in which metal is formed under pressure to the desired shape. Forging has great material properties, but the tooling required for the process is extremely expensive and is far beyond the budget of this project. Green sand-casting is relatively inexpensive and requires less robust tooling, which makes it appealing for one-off projects such as this.

Traditional tooling for sand casting is machined out of metal, typically steel, and is expensive and takes a relatively long time to make. Therefore we have looked into using

rapid prototyping (RP) materials to make our tooling. RP is a process in which successive layers of powder are built up using a resin binder or laser sintering. It is often used as a quick way to create a non-structural proof-of-concept. Recent advances in rapid prototyping have led to powders which can be used in the casting process, making tooling development much faster. In 2006 the MRacing team successfully cast a small magnesium throttle body using this rapid prototyping process and believes this technology to be extremely important to the development of the 2007 vehicle.

Additional design considerations were also taken into account due to the casting process. During the casting process, the material tends to shrink as the part is cooled. From talking with our sponsor, we found we could expect a linear shrinkage of 5/32 of an inch for every 12 inches of material. We also had to maintain a minimum wall thickness of 0.1 inches to prevent excessive porosity in the casting. The design also had to have large enough radii so the molten magnesium could flow easily through the mold. Large changes in the thickness of the material were also undesirable since the magnesium would cool down at different rates, resulting in inconsistent material properties. According to an SAE paper regarding the reliability of castings, "...cooling rate difference in turn can lead to variation in the mechanical properties between geometrically different portions of a die cast component." [4]

The design of the casting had to factor in post-machining considerations. Machining bosses also had to be cast to be used as locating points. The locating points were used to machine datum that will define the part. After speaking with our sponsor, faces that were post-machined would have 1/8 inch of extra material to account for the inaccuracies of the casting.

Customer Requirements and Engineering Specifications

To organize the specifications of the customer, we completed a Quality Function Deployment (QFD). This involved determining a set of customer requirements and engineering specifications, as well as benchmarking similar designs.

Customer Requirements

The requirements of the customer can be broken down into three basic areas: mechanics, manufacturing, and aesthetics. The main customer for our design is the Formula SAE team. The requirements of manufacturing sponsors must also be met for the design to be successful.

The most important requirements to the customer are the mechanics of the design since they directly affect the performance of the racing vehicle. The wheel was required to be lightweight in order to reduce rotating unsprung mass. The wheel needed to be stiff as to not induce compliance into the suspension system. The wheel also needed to exhibit high strength, both in fatigue and impact loading. The design could not fail catastrophically, for this would result in damage to many other systems on the vehicle.

Another area of requirements that is also important to the customer is the manufacturing of the design. Since the customer is a non-profit student organization, the design needed

to be cost-effective. It also had to be able to be produced with the capabilities currently available to our manufacturing sponsors. The manufacturing process of this design is also a chance to expand the manufacturing knowledge and business contacts of the MRacing team.

The last customer requirement is that the wheel design is aesthetically pleasing. The Formula car represents the University of Michigan and our sponsors in multiple competitions and publications. The Formula team competes with over 100 universities around the globe at the US competition and will also be traveling to compete in Europe. The Formula car has also been featured in multiple publications including *Road & Track* magazine, *Racecar Engineering* magazine, and the Mechanical Engineering yearly bulletin at the University of Michigan.

Engineering Specifications

A number of engineering specifications were made in order to fulfill the customer requirements explained above. Target values were also made in order to achieve our goals. These specifications along with respective target values can be seen in Table 1 below.

Table 1: Engineering Specifications and Target Values.

| Engineering Specification | Target Value | Unit of Measurement |
|----------------------------------|---------------------|----------------------------|
| Width | 7.5 | Inches |
| Diameter | 10.0 | Inches |
| Weight | 4.0 | Pounds |
| Stiffness | 105.0 | Percent of Kodiak |
| Fatigue Life | 3.0 | Years |
| Cost | 500.0 | US Dollars |
| Cracks in Wheel | 1.0 | Percent of Volume |

Benchmarking

We benchmarked the Kodiak wheels currently used on the car using FEA software. The wheels were first laser scanned to accurately model their geometry, and then several different loading conditions were simulated in FEA to find the maximum stresses and strains as well as their locations and distributions, so that these numbers could be compared to the FEA model of the wheel being designed, as well as the physical test data on the new wheel.

Organization of QFD

To organize the needs of the customer, a QFD was created and can be found in Appendix A. The QFD helped us determine which engineering specifications should be focused on in order to fulfill the customer's specifications.

The importance of each customer specification was discussed as a group and then assigned a corresponding weight between 0 and 10, with 10 representing a very strong importance. The correlation between the engineering specifications and the customer requirements were then discussed as a group. These correlations were assigned one of

four values: 0 representing no correlation, 1 representing a weak correlation, 3 representing a mild correlation, and 9 representing a strong correlation. The correlations were then combined with the weights to determine the importance rating of each engineering specification.

From the results of our QFD, we determined that the number of cracks in the wheel is the most important engineering specification. Since the number of cracks will have a large impact on the structural integrity of the wheel as well as the safety of the racing vehicle and driver, we agree with the QFD result. The second and third most important specifications were weight and stiffness. Based on these results, our design will focus on a wheel that will be free from defects, light, and stiff.

Concept Generation

From a design perspective, a wheel is a very simple mechanical system. It has no linkages and has a very clear purpose: transmit the torque delivered from the studs to the tires, which then grip the ground and provide a motive force on the car. The simplicity of its function can be seen in the FAST diagram, shown below in Figure 1.

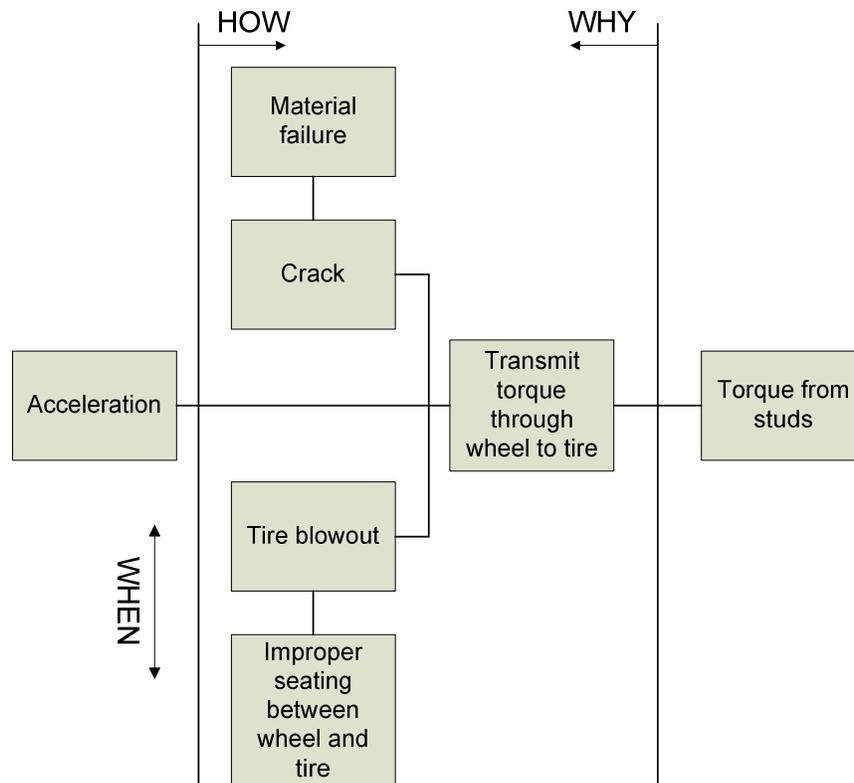


Figure 1: FAST Diagram

The input to the wheel is torque from the studs, which is then transmitted through the wheel to the tire. As the torque is being transmitted through the wheel, three things can happen: the wheel can crack due to material failure; the tire can blowout due to improper

seating between the wheel and the tire; or everything can function as designed and a force can be placed on the ground, leading to acceleration of the car.

After carefully considering the failure modes of catastrophic material failure and tire blowout as well as the customer requirements and engineering specifications for the wheels, we began to sketch both on paper and using CAD some possible wheel designs (Figure 2). There were two general design types considered. One possible style for the wheels was a design similar to the Kodiak wheels currently used on the car. This design features a few large spokes (Concept 4). The second possible style for the wheels was a design which features many smaller spokes (Concepts 1-3). The design of the wheel shell was also considered, and several different configurations seen below in Figure 3 on page 7 were considered in order to optimize the wheel.

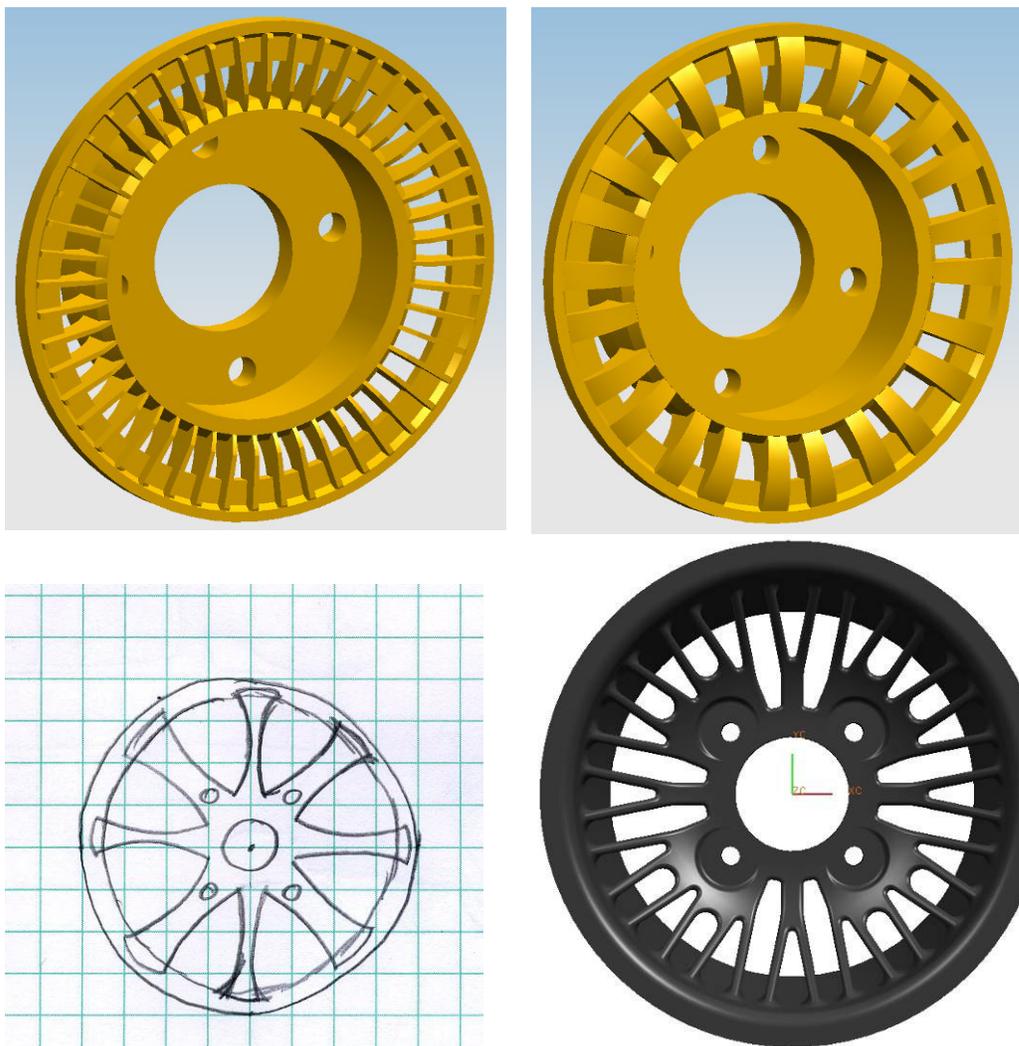


Figure 2: Wheel Concepts 1, 2, 3, and 4 (Clockwise from Top Left)

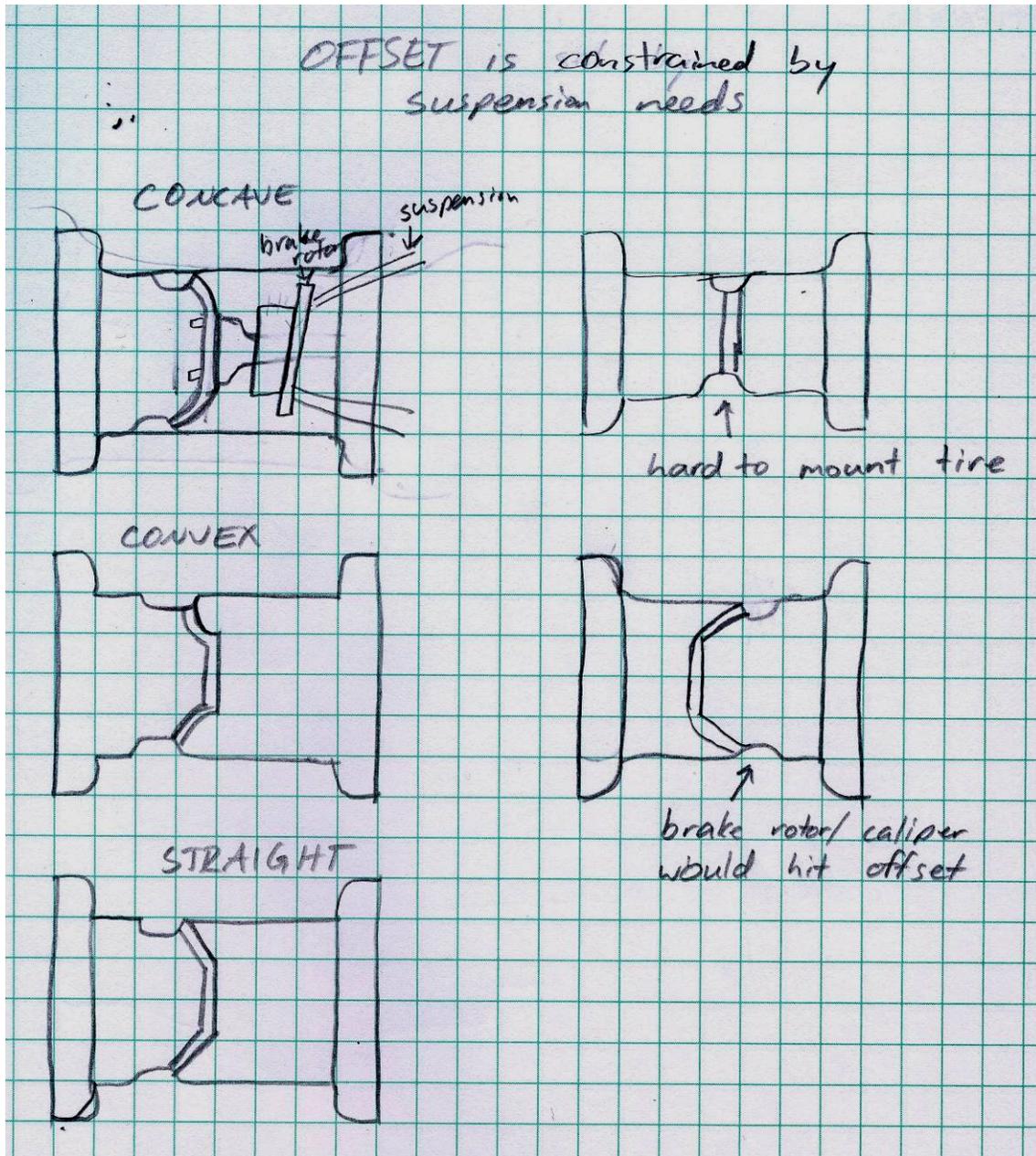


Figure 3: Wheel Shell Concepts

Concept Evaluation and Selection

Each of the four possible wheel designs was evaluated using a Pugh chart. The results from the Pugh chart (Table 2) showed that the design shown in sketch 3 was the best possible design. It received a 'plus' for nearly each of the customer requirements and had the highest weighted total. After selecting our final concept, small changes were made to improve the design. These changes were made to improve the weight, reliability, and manufacturability of the design.

Table 2: Pugh Chart

| Customer Requirement | Weight | Sketch 1 | Sketch 2 | Sketch 3 | Sketch 4 |
|---|--------|-------------|-------------|-------------|-------------|
| Lightweight | 10 | - | - | + | - |
| Improved or maintain stiffness | 8 | + | + | + | + |
| Low probability of catastrophic failure | 8 | + | + | + | + |
| Long fatigue life | 7 | + | + | + | + |
| Expand MRacing manufacturing techniques | 6 | + | + | + | + |
| Low cost | 8 | + | + | + | + |
| Aesthetically pleasing | 5 | - | - | + | + |
| Total + | | 5 | 5 | 7 | 6 |
| Total - | | 2 | 2 | 0 | 7 |
| Total | | 3 | 3 | 7 | 5 |
| Weighted total | | 22 | 22 | 52 | 32 |

Finite element analysis was used both to validate and optimize the design. Similar models were created for our design as well as the Kodiak wheel. Both models were then run with identical forces and constraints so the results could be directly compared. The models were run under four different loading conditions: 1. 1000 lb torsion load; 2. 1000 lb lateral load; 3. 1000 lb longitudinal load; and 4. 100 lb mounting load. The relative strength and stiffness of our design was then compared to the Kodiak wheel. We calculated worst case loads for each loading condition using the information below.

Table 3. Properties of 2007 FSAE Car

| Property | Symbol | Value |
|--|-----------------|-----------|
| Max Acceleration | a | 2.5 g's |
| Weight of Vehicle with Driver | W | 600.0 lbs |
| Center of Gravity in x-axis | CG _x | 35.8 in |
| Center of Gravity in y-axis | CG _y | 0.6 in |
| Center of Gravity in z-axis | CG _z | 9.1 in |
| Average Track (front and rear) | t | 51.5 in |
| Wheel Base | L | 63.0 in |
| Coefficient of Friction (dry pavement) | μ | 2.2 |
| Weight Distribution (Front/Rear) | d | 0.43/0.57 |

$$W_a = d W \quad (\text{Eq. 1})$$

$$\Delta W_{long} = \frac{CG_z \cdot a}{L} W_{stat} \quad (\text{Eq. 2})$$

$$\Delta W_{lat} = \frac{CG_z \cdot a}{t} W_{stat} \quad (\text{Eq. 3})$$

$$W_{max,a} = W_{stat} + \Delta W_{long} \quad (\text{Eq. 4})$$

$$W_{\max,t} = \frac{W_{\max,a}}{2} + \frac{\Delta W_{lat}}{2} \quad (\text{Eq. 5})$$

$$F_T = \mu W_{\max,t} \quad (\text{Eq. 6})$$

$$F_L = \mu W_{\max,t} \quad (\text{Eq. 7})$$

$$F_B = a W_{\max,t} \quad (\text{Eq. 8})$$

Table 4. Calculated Values for 2007 FSAE Car

| Property | Symbol | Front | Rear |
|------------------------------|--------------------------|--------------|-----------------|
| Static Axle Weight | W_{stat} | 259 lbs | 341 lbs |
| Longitudinal Weight Transfer | ΔW_{long} | 217 lbs | 217 lbs |
| Lateral Load Transfer | ΔW_{lat} | 265 lbs | 265 lbs |
| Max Axle Load | $W_{\max,a}$ | 476 lbs | 558 lbs |
| Max Tire Load | $W_{\max,t}$ | 371 lbs | 411 lbs |
| Torsion Load | F_T | 815 lbs | 905 lbs |
| Lateral Load | F_L | 815 lbs | 905 lbs |
| Bump Load | F_B | 926 lbs | 1028 lbs |

After calculating the loads, the tire contact patch was physically tested by loading a tire on a piece of contact paper. The loads were assumed to transfer from the tire contact patch to the wheel. The loads were evenly distributed throughout the tire contact patch.

By running several iterations in FEA, we were able to cut 0.82 lbs out of our original design as seen in Table 5 below. We started with a center that was 0.625" thick and two groups of spokes, each a different length. In the second iteration, we took away material from the spokes and the center. This area had smaller stresses than the surrounding material. The third iteration again made the center and spokes thinner, and also cut out material from the center, making some spokes longer. This iteration resulted in stresses that were too high in the center. The fourth iteration took geometry from iteration two, and cut .050" out of the shell. Our final design combines geometry from all three iterations and includes smooth radii and transitions that are difficult to model using FEM. The final design has a center that is 0.4375" thick, equal spoke sizes, and 0.150" typical thickness in the shell. The FE models can be seen in Figures 4 and 5 on page 10, and in Appendix D.

Table 5. Weight Estimates of Various Design Iterations

| | Weight Estimate (lbs) | |
|------------------|-----------------------|------|
| | CAD | FEA |
| First Design | 4.75 | 4.54 |
| Second Iteration | - | 3.98 |
| Third Iteration | - | 3.78 |
| Fourth Iteration | - | 3.30 |
| Final Design | 3.93 | - |

After completing the design for strength and durability, we had to make some small modifications for manufacturing. Several factors had to be taken into account to meet the casting requirements. First, we had to make sure that all surfaces had at least 2 degrees of draft. This allows the cores and patterns to be easily removed from the sand. Second, the foundry requested a minimum wall thickness of 0.1” and a minimum radius of 0.125”. Also, the cross-section of the wheel has to have smooth transitions without large jumps in thickness. This allows the metal to flow into the cavity smoothly and also maintains a relatively even solidification rate. The last casting effect we had to consider was shrinkage. During casting, the metal shrinks as it cools down and solidifies. The foundry told us to expect a 2% linear shrinkage. We simply scaled our model by 2 percent to account for the shrinkage. Since all critical dimensions will be post-machined, this approximation was deemed appropriate.

Design considerations were also made for post-machining after casting. A large flat surface was designed into the back of the wheel so it could be used to clamp or otherwise jig the wheel on a milling or turning machine. The holes in the wheel were also designed with standard drill sizes for ease of manufacturing.

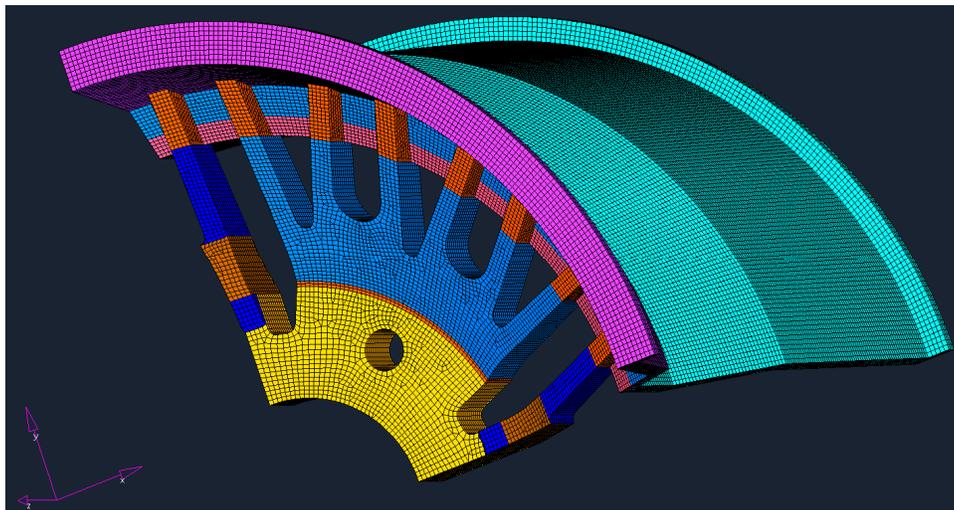


Figure 4. FEM of Design Iteration One

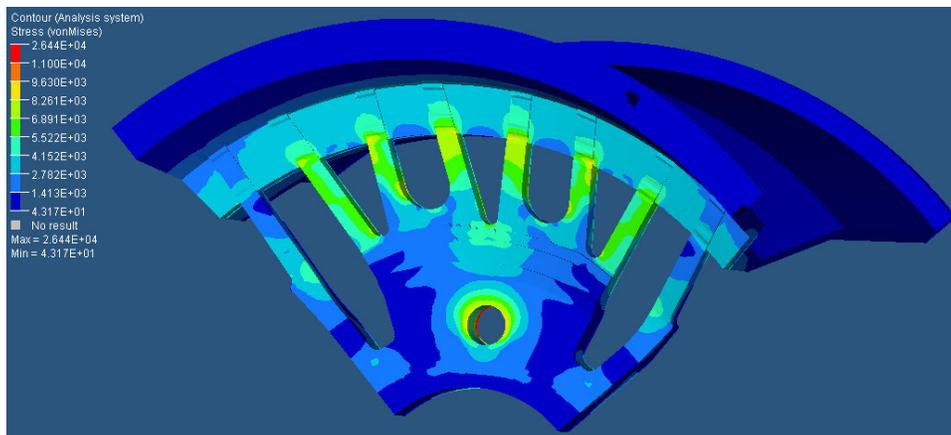


Figure 5. FEA Stress Analysis of Design Iteration Three

Selected Concept

The selected design will fit 10 inch tires ranging in width from 6 to 8 inches. It is roughly 25% lighter and 20% stiffer than the current wheel (10 inch Kodiak). This is attributed to its one piece construction and its higher spoke count, both of which reduce stress concentrations.

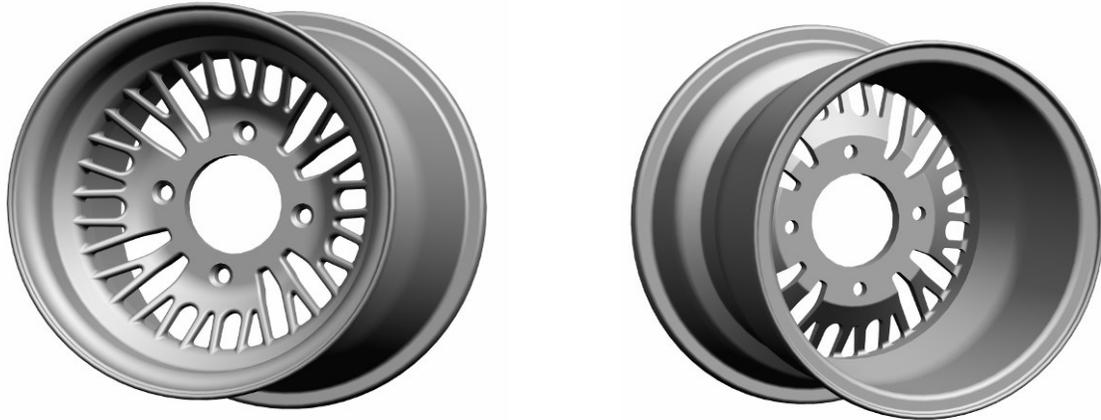


Figure 6: Final Wheel Design

Several packaging constraints were addressed in the final design in order to insure that there were no integration issues with the car. Primarily the vehicle track width was not changed, meaning that the distance from the inside face of the center section to the outside lip of the rim was kept the same as the Kodiaks. Also, the shell could not be any smaller in diameter than the Kodiak's due to interference with the car's front brake calipers.

The last issues to be addressed with the wheels were material related. Of the two choices of magnesium available at the foundry, AZ91C-T6 and AZ91C-T4, we chose AZ91C-T4. Despite the fact that this material has a lower yield stress, its lower temper means that it has increased ductility, and therefore failure will be more progressive. This then makes fracture less likely and improves the overall safety of the wheel.

Tooling

In addition to designing the wheels, we are also responsible for designing and manufacturing the tooling that will be used to create the sand molds for casting the wheels. We chose to use rapid prototyping to create the necessary tooling because of the huge savings in both time and cost over traditional tool making methods. One case study showed that using RP to create tooling resulted in a 54.0% time savings and 49.6% cost savings over traditional aluminum tooling [6]. Specifically, we used an RP technique called 3D printing to create the tools. 3D printing is one of the fastest and most cost effective RP methods available. The downsides to 3D printing however are that the parts can be less accurate than other RP methods and they are also somewhat fragile, with an ultimate tensile strength of only 13MPa at nearly immeasurable amounts of strain. [7], [8].

3D printing works by spreading a layer of plaster powder from a feed bin over a build bin. A resin is then printed across the layer in the shape of the part cross-section. The build bin then moves down slightly, and the next layer of powder is spread across, and the process begins again until the entire part has been created. Once the part has dried for at least an hour, it is then coated with a layer of epoxy to give it extra strength, and once the epoxy dries the part is sanded smooth. The machine we will be using is shown below, in Figure 7.

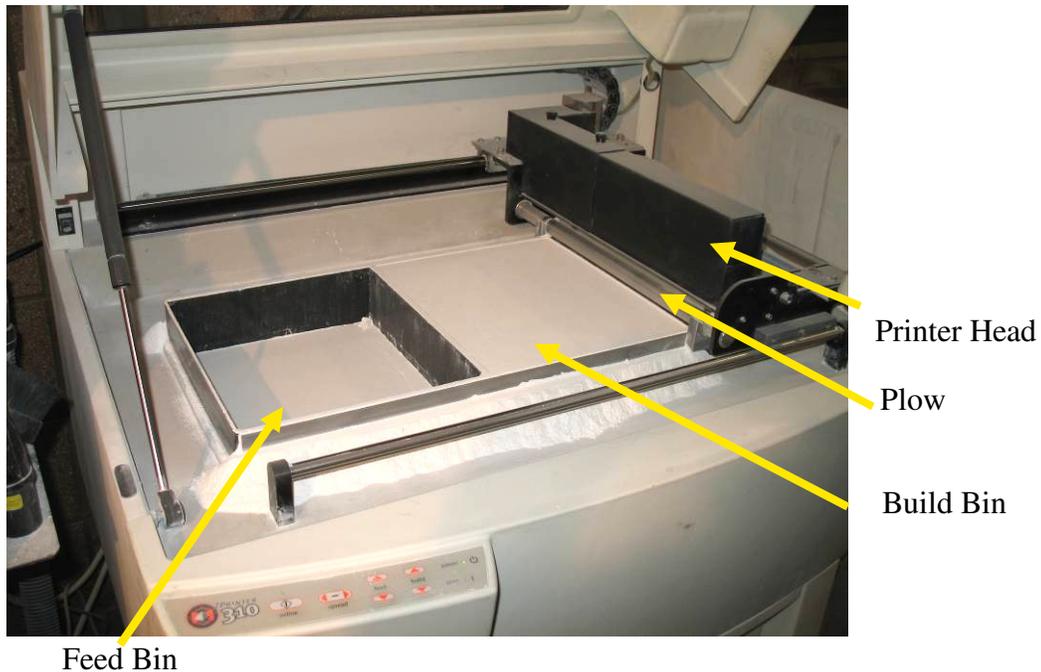


Figure 7: ZCorp ZPrinter310 3D Printer

When creating the tooling for the wheels, several factors had to be taken into consideration. First, the tooling needed to be scaled larger than the wheels to account for shrinkage during cooling. In the case of the alloy the wheels will be cast in, AZ91C-T4, a 2% linear shrinkage was quoted from our foundry [9]. The tooling also needed to provide extra material on surfaces which will be post-machined. Another consideration was that all of the tooling for the wheel is significantly larger than the 8" x 10" x 8" build volume of the ZCorp ZPrinter 310 we used [10]. We therefore had to break up each section of the tooling into four parts to be joined later using epoxy. Photographs of the production process can be seen in Appendix F.

Engineering Analysis

Finite Element Analysis

The finite element models described above were used to analyze both the Kodiak wheel and our design. The results of the stress analysis are summarized in Table 6 on page 13. The safety factor was determined by dividing the yield strength by the maximum stress. The yield strength of our magnesium design was 11 ksi. This was determined by conducting tensile tests of cast samples at Lite Metals. It can be seen that the safety

factor for each loading condition is lower for the magnesium design. This was needed to accomplish our weight savings goal. However, the safety factor for lateral loading on the magnesium wheel is within 15% of the Kodiak wheel since this is the most common condition for wheels to fail. A safety factor of at least 1.1 was maintained to guarantee protection against yielding. It should be noted that a safety factor of about 2 was also used to calculate the loading conditions.

Table 6. FEA Stress Results

| Loading Condition | Max Stress (psi) | | Safety Factor | |
|-------------------|------------------|-----------|---------------|-----------|
| | Kodiak | Magnesium | Kodiak | Magnesium |
| Lateral | 28520 | 9630 | 1.3 | 1.1 |
| Bump | 4322 | 3648 | 8.8 | 3.0 |
| Torsion | 7966 | 6701 | 4.8 | 1.6 |
| Mounting | 7672 | 6023 | 5.0 | 1.8 |

The finite element models were also used to characterize the stiffness of the Kodiak and magnesium designs by calculating the maximum displacement under various loading conditions. The results of displacement calculations are summarized in Table 7 below. The magnesium design has a smaller displacement in the largest loading condition, lateral loading. The magnesium wheel also has a smaller deformation under tire mounting, which is important to prevent air leaks at the tire/wheel interface. Some stiffness was lost in bump and torsion loading conditions. We feel that the performance of the wheel will not be hindered by this small change in stiffness.

Table 7. FEA Displacement Results

| Loading Condition | Max Displacement (1e-3 in) | |
|-------------------|----------------------------|-----------|
| | Kodiak | Magnesium |
| Lateral | 11.4 | 9.1 |
| Bump | 3.2 | 5.6 |
| Torsion | 23.5 | 83.2 |
| Mounting | 7.7 | 5.7 |

Failure Mode and Effects Analysis

To identify the potential failures and try to prevent them, a failure mode and effects analysis was conducted, the results of which can be seen in Appendix G. From our FMEA we can conclude that no further actions need to be taken to prevent failure.

Cost Analysis

The cost of the prototype was also analyzed. The bill of materials as well as the service and labor costs to manufacture the prototypes can be seen below on page 14. The total project cost is calculated for six wheels.

Table 8. Bill of Materials

| Item | Quantity | Supplier | Discount | Total Cost |
|--------------------|-----------------|-----------------|-----------------|-------------------|
| ZCorp ZB56 Binder | 2 gallons | UM3D Lab | Free | \$0.00 |
| ZCorp ZP401 Powder | 55 gallon drum | UM3D Lab | Free | \$0.00 |
| Hapcast 3732 | 8 gallons | Hapco | None | \$544.00 |
| ½” Plywood | 8’ x 4’ sheet | Home Depot | None | \$22.00 |

Material Cost \$564.00**Table 9. Bill of Services**

| Service | Provider | Discount | Total Cost |
|-----------------------|------------------------|-----------------|-------------------|
| Cast Magnesium Wheels | Lite Metals | \$1200 | \$2100.00 |
| Casting Setup Fee | Lite Metals | \$1050 | \$150.00 |
| Post-Machining | Liberty’s Gear | Free | \$0.00 |
| Structural Testing | University of Michigan | Free | \$0.00 |

Service Cost \$2250.00**Total Project Cost \$2814.00****Design for Environment**

Environmental impact was important to the design of our wheel. The amount of magnesium used is minimized by distributing the stress throughout the wheel. Using a one piece wheel also makes the design easy to recycle. There is no disassembly needed at the end of the product’s life and 100% of the material can be recycled. The manufacturing process is also eco friendly. Casting a wheel takes less energy than machining it out of a solid piece of billet magnesium. The casting process also recycles most of its materials. The sand from the molds is recycled, as well as the extra metal that is removed from the parts. The RP tooling for the casting is also better for the environment than traditional methods. The RP tooling takes less energy to manufacture than machining out of tool steel. Also, the RP material is water soluble, so there is no waste sent to the landfill.

Final Design

The final design iteration of the wheel before coating will weigh approximately 4 pounds and can be seen above in Figure 6 on page 11.

One additional design consideration was the corrosion properties of magnesium. ASTM B117 testing predicts 0.0008 inches of penetration of corrosion per year at standard atmospheric conditions. [13] This corrosion rate is fairly low considering our target life of three years. Magnesium also reacts with ferrous metals, resulting in galvanic corrosion. [13] In order to prevent corrosion at the interface between the hub and the wheel, aluminum lug-nuts will be used to clamp the wheel. Also, the wheel will be painted to prevent metal-to-metal contact.

In order to inhibit corrosion, different coatings were studied. Anodizing, powder coating, and painting were all considered. The appearance of an anodized part is highly dependent on the part's surface finish. The appearance of anodizing will vary due to the variation in surface finish between cast and post-machined surfaces on the wheels. Powder coating was also considered because it is very durable, but the coating is also relatively heavy. We are seeking to reduce the weight of the wheels as much as possible so this added weight is undesirable. Painting is the simplest and cheapest coating method available and weighs approximately 70% less than powder coat [11,12]. There is a high likelihood of damage to the paint due to tire mounting and road debris, but chips and scratches can be easily touched-up. Considering all of the benefits and drawbacks to each of the coating methods, it was determined that painting would be the best coating method.

Manufacturing

The first step in manufacturing the wheels was to make the tooling that was used to form the patterns and cores for casting. This tooling was created using a rapid prototyping machine. The two parts that would be used to create the patterns in the cope and drag were divided into four pieces each and printed on the RP machine. The pieces were then coated with a layer of epoxy and sanded smooth. The four pieces for each of the two patterns were then glued together. After the glue had dried, any gaps in the joints between pieces were filled in using a body filler and sanded smooth. This process was also repeated with the two parts which form the core. Once the core parts were glued together and sanded smooth two core boxes were built of plywood, and coated in wax. The RP parts were then coated in mold release and centered in the boxes. Hapco 3237 aluminum resin was then poured around the RP parts and allowed to cure in order to create a negative mold for the core to be formed in. This step was necessary because the RP material is not strong enough to withstand the forces of packing the core sand. Once the tooling resin cured the RP material was chipped and sanded out and body filler was used to fill in any damaged areas.

After the tooling was manufactured it was delivered to the foundry where the wheels were cast. The two RP pieces are used to form the patterns which define the shape of the wheel center and spokes as well as the inside portion of the shell. One pattern each is placed in the top and bottom halves of the mold, the cope and the drag (as shown in Appendix I). Patterns for gates and risers are also inserted, and sand mixed with a binding agent is poured in and packed around the patterns. After the sand hardens, the patterns are removed and used to create the next mold. The tooling made of resin is used to create a core which defines the outside of the wheel shell. The three pieces of the core box are assembled together and aligned and then core material is poured and packed in. After the core hardens, the tooling is disassembled and the core and two pattern halves are assembled. Molten magnesium is then poured into the mold. After the magnesium has had sufficient time to cool and harden the sand is broken off, and any remaining sand is burned away from the wheel using a large torch. The wheels are then heat treated to obtain the correct material properties. Finally an x-ray of the wheel is taken to ensure there is no porosity. A dye penetrant inspection checks for surface defects and cracks.

After the wheels have been cast, it is necessary to post-machine any of the critical dimensions. The area of the wheel which contacts the hub, the wheel stud holes, and the bead area all needed to be machined. Detailed drawings of all areas which needed to be machined were created for the machinist to follow and can be seen in Appendix J. A detailed manufacturing plan can be found in Appendix H.

Testing

In order to validate our FEA predictions one wheel was physically tested. The wheel was subjected to a lateral load. This loading condition was chosen because our FEA results showed that failure would most likely occur during a high lateral acceleration corner. Also visual accounts of wheel failures have shown that this loading condition is the most likely to cause failure. Rim and spoke displacements were measured using nine strain gauges and the load was controlled using an Instron 8516 testing machine. The wheels were initially loaded to 700 lbs at a rate of 0.005 inches per minute. Once it was determined that no yielding had occurred all further tests were conducted to a maximum of 1000 lbs at 0.001 inches per minute. In all, four tests were done at 1000 lbs, monitoring three strain gauges per test. Once these tests were completed we attempted to destructively test the wheel by increasing the load to 2000 lbs. The wheels showed roughly 0.06% elongation during these tests, approximately a third of the projected elongation at yield for AZ91C-T4. We were unable to increase the load any further because the maximum load for the load cell is 2000 lbs. A picture of the test setup can be seen below in Figure 8. Results from the 1000 lb. test can be found below in Table 10 on page 17, and a plot of the 1000 lb. test can be seen below in Figure 9 on page 17. Further test setup pictures, and a plot from the 2000 lb. test can be found in Appendix K.



Figure 8. Instron Test Setup

Table 10. Results of Physical Test Compared to FEA Results

| Location on Spoke | Predicted Strain (Micro Strain) | Actual Strain (Micro Strain) |
|--------------------------|---------------------------------|------------------------------|
| Top Edge, Outside Face | 450 | 150 |
| Inside Face | 220 | 150 |
| Transition (One-Two) | 100 | 25 |
| Bottom Edge, Inside Face | 260 | 75 |
| Top Edge, Inside Face | 200 | 300 |

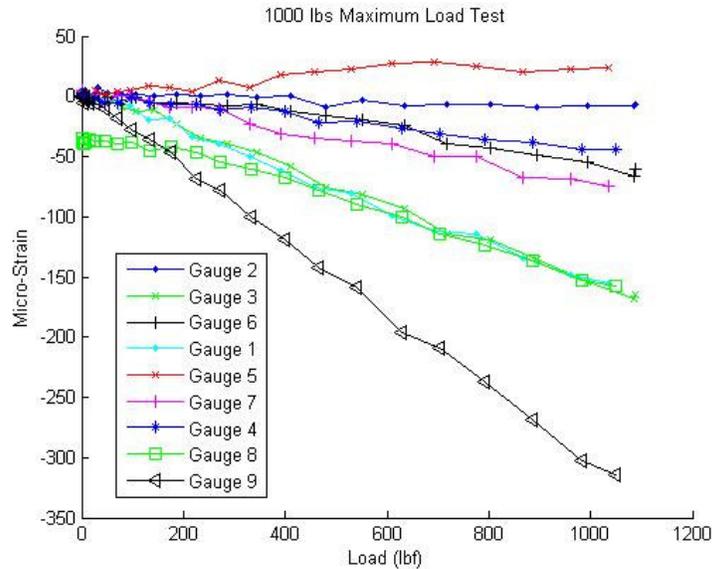


Figure 9. Plot of 1000 lbs. Maximum Load Test

Initial plans for testing involved building a custom designed test rig (Figure 10 on page 18). Several iterations were considered and a final design was chosen however this approach was deemed impractical as material costs would have exceeded \$200 and load increments would have needed to be fairly large. Also the ultimate amount of load which we could safely add would not be enough to properly test the wheel. Costs for the Instron were considerably less, and the degree of control and safety were significantly greater. The only materials required to test the wheel were a thick steel plate to mount the wheel, and the strain gauges, both of which were donated.

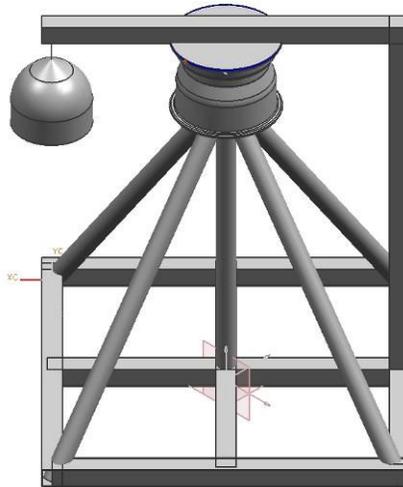


Figure 10. Initial Testing Fixture Design

Discussion for Future Improvements

The largest future improvement for the wheel is that it could be made even lighter. For example, the wheel was able to withstand a thrust load much larger than should ever be seen. Further physical testing of the current design as well as further FEA modeling would allow us to better determine the needed safety factors and minimize the weight of the wheel.

The most immediate work that needs to be done on these wheels is fatigue testing. After the wheels are run on the car in testing for several weeks, they will be returned to the foundry to be x-rayed again, to check for any cracks that may have developed. The wheels will also be periodically x-rayed throughout their life to check crack development and better understand wheel fatigue for future designs.

Conclusions

The goal of our project was to design and manufacture a set of wheels lighter than those currently in use on the University of Michigan Formula SAE car without sacrificing stiffness. Other FSAE teams have designed their own wheels, typically using a three piece design. To achieve our design goal, we intended to be the first FSAE team to design and manufacture a set of one piece cast magnesium wheels. The design needed to satisfy requirements in three areas: mechanics, manufacturing, and aesthetics.

The current wheels are a three piece aluminum design, with a 10 inch diameter. They have a machined aluminum center with spun aluminum shell, and weigh 5 pounds. Magnesium was chosen as the desired material for a few reasons: it has been used in the automotive industry for many years, and motorsport uses it for its high specific stiffness; it is currently one of the cheapest primary light alloy metals available; and it is a very versatile metal.

In considering the requirements in the areas of mechanics, manufacturing, and aesthetics, the chosen design concept has many smaller spokes, as opposed to the larger-spoke

design of the wheels currently in use by the team. The FSAE car was parameterized using Equations 1-8 on pages 8-9, enabling the necessary loads to be determined. Using FEA software and the determined loads, the design was validated and optimized, netting a weight of approximately 4 lbs (25% reduction), and similar stiffness values. We also designed and manufactured the tooling for the casting process using rapid prototyping methods.

The wheels were cast and physically tested. The testing revealed that the design was able to withstand larger than expected forces in the most critical loading condition. The maximum strain due to a 2000 lbs. lateral load, the most critical loading condition, was found to be 6×10^{-4} . This is only around a third of the yield strain of AZ91C-T4. The wheels are currently being post-machined, and should be on the car within two weeks

Acknowledgements

Brett Lyons and the UM3D Lab: For all his valuable knowledge in rapid prototyping and casting.

Craig Liberty and Liberty's Gears: For his generous post-machining sponsorship, knowledge, and continued support of the Formula team.

Department of Mechanical Engineering: For supporting the team throughout their undergraduate careers.

Mike Clancy and Lite Metals: For his generous casting sponsorship, knowledge, and continued support of the Formula team.

MRacing Formula SAE Team: For providing resources and support.

Tom Bress: For providing testing knowledge, support, and time.

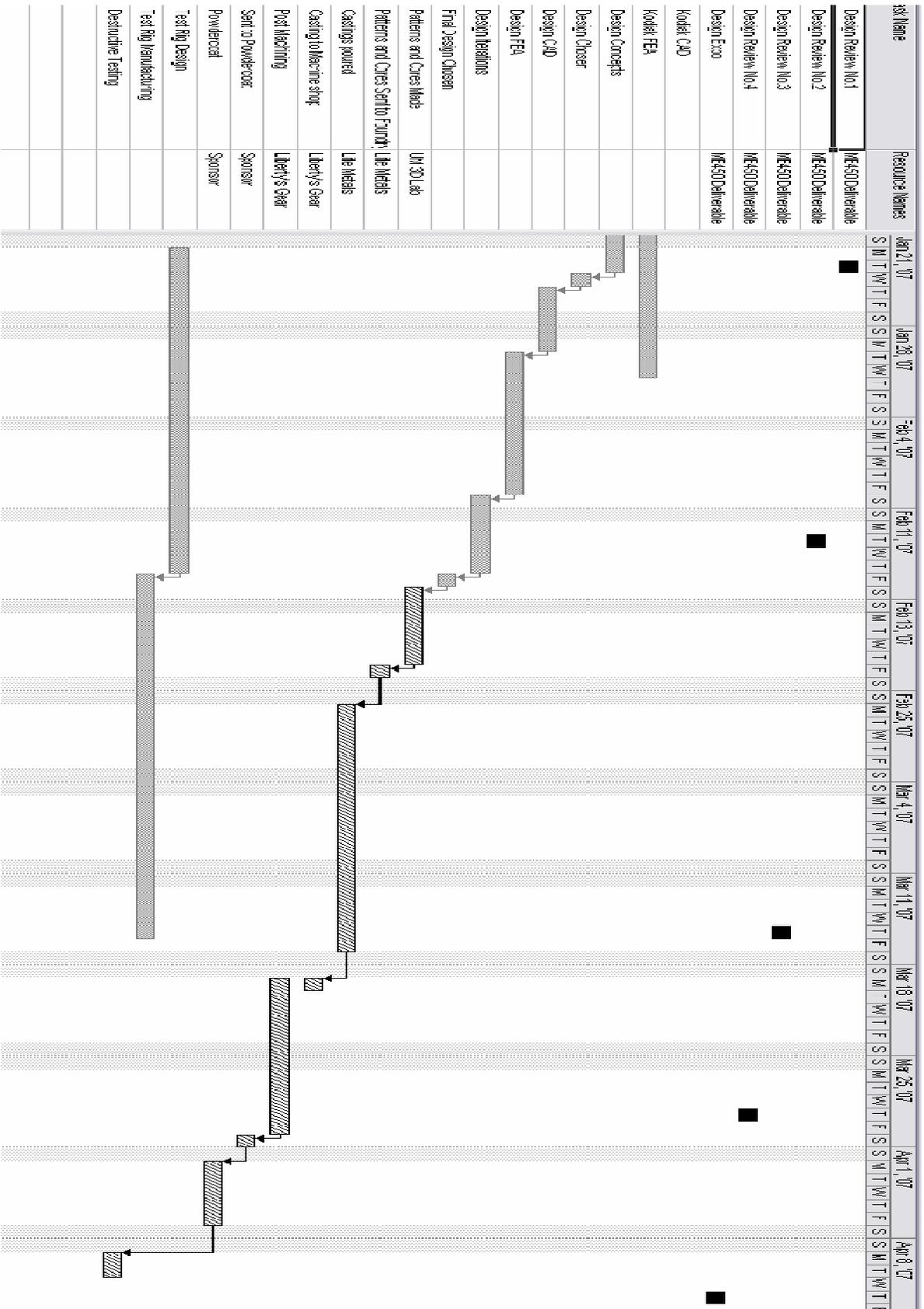
Volker Sick: For his continued support of the Formula team.

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Appendix B: Gantt Chart



Appendix C: Bios

Steven Coons

Steven is originally from Hartland, Michigan, a small town about 30 miles north of Ann Arbor. He decided that he wanted to pursue a degree in engineering while in high school after taking a physics class. He first came to U of M to major in chemical engineering before going to medical school. During his freshman year however, he began to rethink medical school and his interest in automobiles led him to major in mechanical engineering. Steve will graduate with a Bachelor of Science degree in Mechanical Engineering in April 2007, and would like to continue on to graduate school at U of M to obtain a Masters degree in Mechanical Engineering and then work in the automotive industry. While at U of M, Steve has had two internships. The first was at Dana Corporation working in a test lab for the Fluid Systems Group. There he tested automotive hose and tubing assemblies for air conditioning, braking, and power steering systems. His second internship was for Eaton Automotive, where he worked at the Fuel Vapor Systems Group, helping to design and test valves for fuel systems. He joined the Formula SAE team at the beginning of his sophomore year, and enjoys working on and riding his vintage Honda motorcycle in his spare time.

Raymon Gallé

Raymon was originally born in the Netherlands. His family moved to the United States in 1991. After living in Grand Rapids for about a year, his family moved to the small town of Middleville, about 30 miles south of Grand Rapids. Ray was always interested in math and science and came from a family of 'do-it-yourselfers'. His grandfather was a mechanic and his father is a quality engineer. He decided to be an engineer simply because he could not see himself doing anything else. Ray has been a part of the Formula SAE team at the university since he was a freshman. Ray claims that Formula is the reason he stayed in engineering. He would like to go into the automotive or aerospace industry, anything that is fast-paced with lots of engineering challenges. Ray enjoyed a fulfilling internship at Williams International last summer. He would also like to return to school to earn a master's degree after working in industry for a few years. Ray also enjoys being outdoors, he frequently goes mountain biking and has started playing with photography.

Bryan GilroySmith

Bryan is originally from Worcester, Massachusetts about 60 miles west of Boston. His interest in mechanical engineering began as a child and was fostered throughout high school. He began attending the University of Michigan in the fall of 2003. His competitive attitude and interest in motorsports immediately found a home on the university's formula SAE team. During the 2003-2004 season his interests primarily focused on engine related topics. The next year he took over design of the cooling and fuel systems during which time he learned valuable lessons in thermodynamics, engine management and engineering principles. He continued his involvement in the 2005-2006 season where he was in charge of the entire engine and its supporting systems. Due to the efforts of himself as well as others the car won 3rd place that year in both the U.S. and in Japan. Following the success of the 2006 car he took on an internship working for IAV

Inc. where he and one other engineer developed a turbocharged engine package for the 2006-2007 car. Currently in his fourth and final year on the team he is working on a very competitive engine package, as well as traction control calibration and this magnesium wheel project. When he graduates he hopes to work for one of several companies, namely Bosch, Borg Warner, or IAV Inc.

John Nanry

John hails from the beautiful Metro Detroit suburb of Beverly Hills, MI. He has a lifelong interest in cars and graduated from Birmingham Groves High School in 2003 and enrolled in the College of Engineering that fall. He took a variety of classes and considered many majors before deciding on Mechanical Engineering because of the emphasis on physical and mechanical systems understanding. He has also greatly enjoyed being a member of the MRacing Formula SAE team. This past year he was the Business Group Leader and was able to secure a second-place finish in the business competition at the Formula SAE World Cup in September. He has enjoyed internships at Roush Industries and Productos Casado. At Roush he worked on powertrain calibration for the 2007 Ford SVT Mustang Cobra and received a lot of education on the automotive industry. This past summer at Productos Casado he worked in a processed foods manufacturing facility. It was during this internship that he developed a strong interest in manufacturing, and he plans to pursue a summer project with the Tauber Manufacturing Institute this summer. He will finish up with his Bachelors degree in Mechanical Engineering in December, 2007 and plans to immediately pursue a Masters degree in Industrial and Operations Engineering.

Appendix D: Finite Element Analysis of Wheels

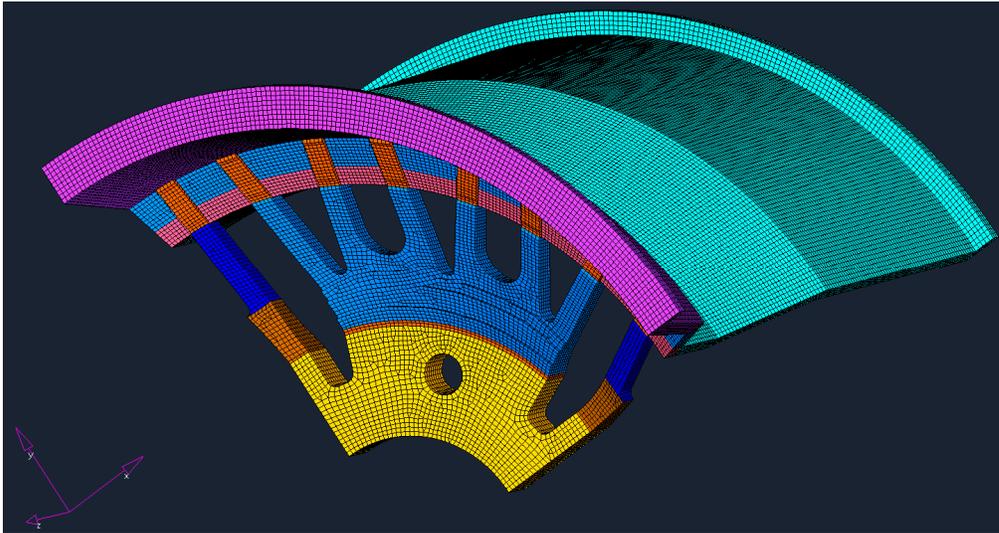


Figure D1. FEM of Design Iteration Two

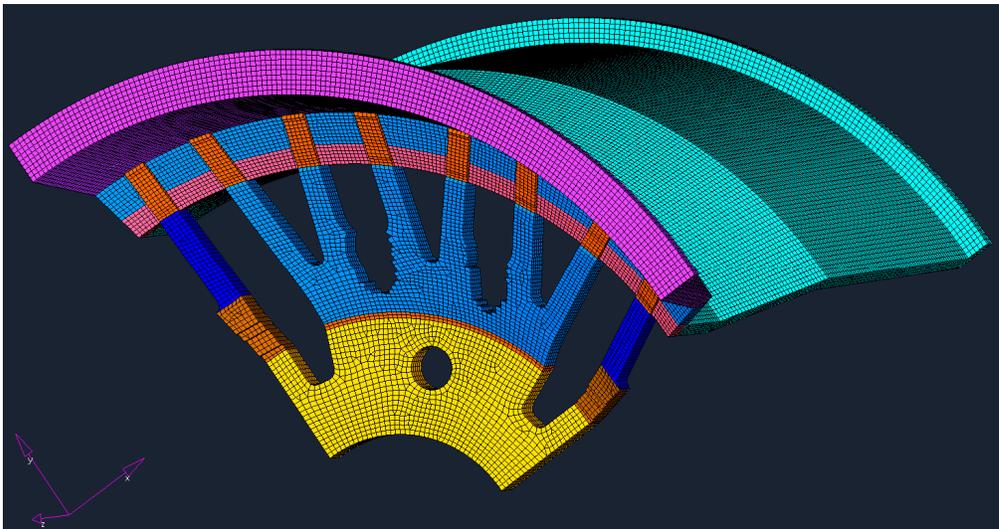


Figure D2. FEM of Design Iteration Three

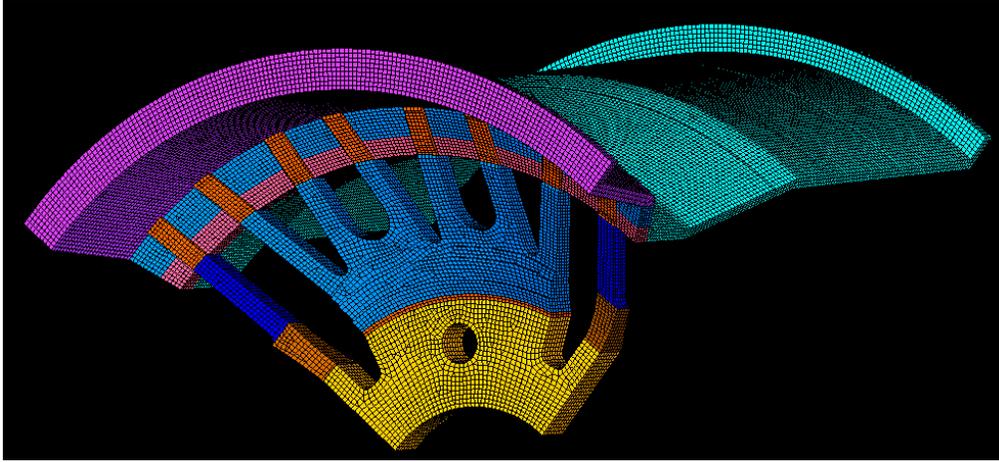


Figure D3. FEM of Design Iteration Four

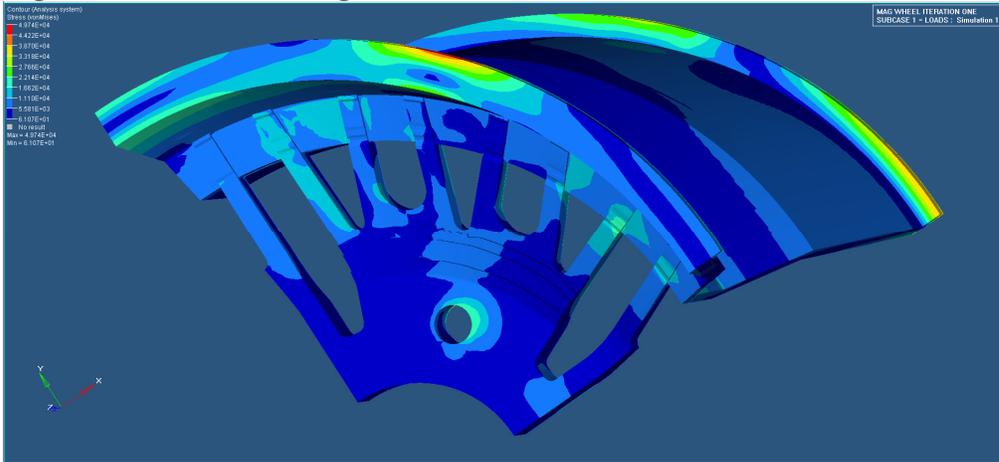


Figure D4. FEA Stress Analysis of Design Iteration 4

Appendix E: Detailed Drawings

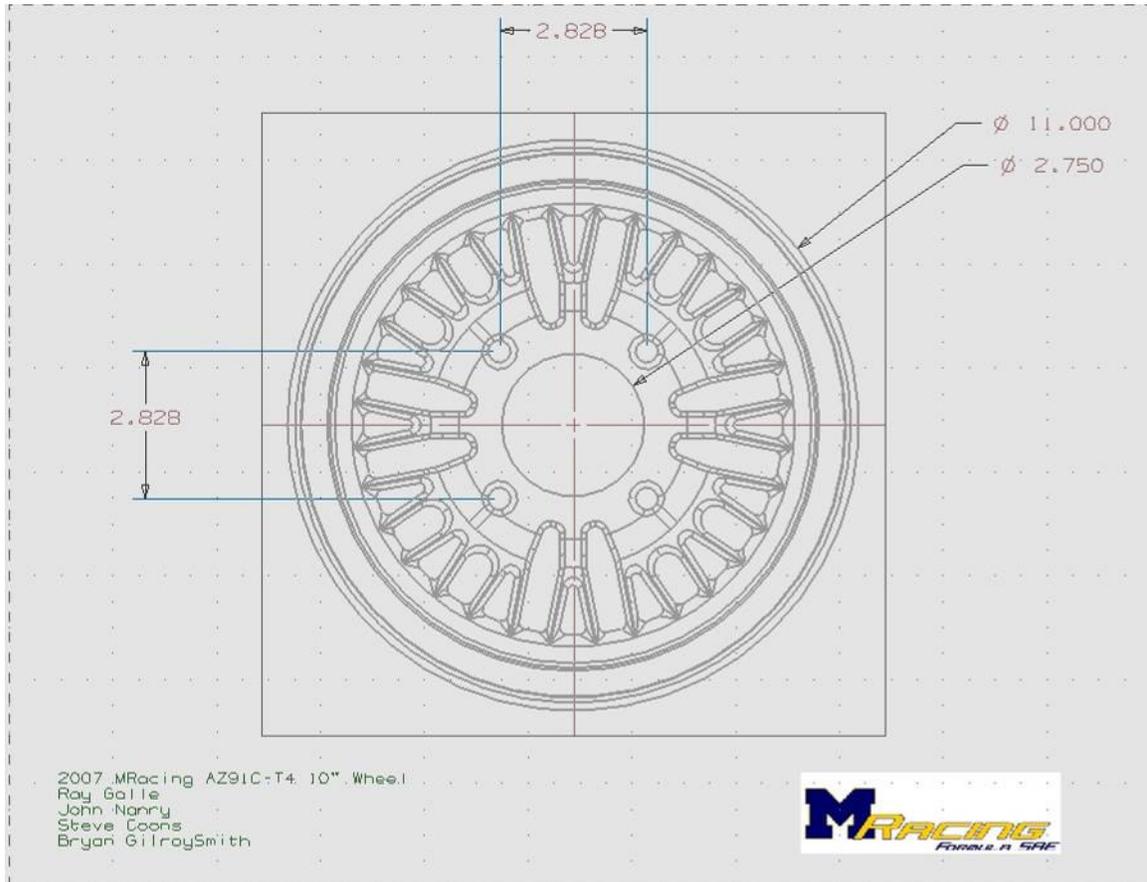


Figure E1. Front View of Final Design

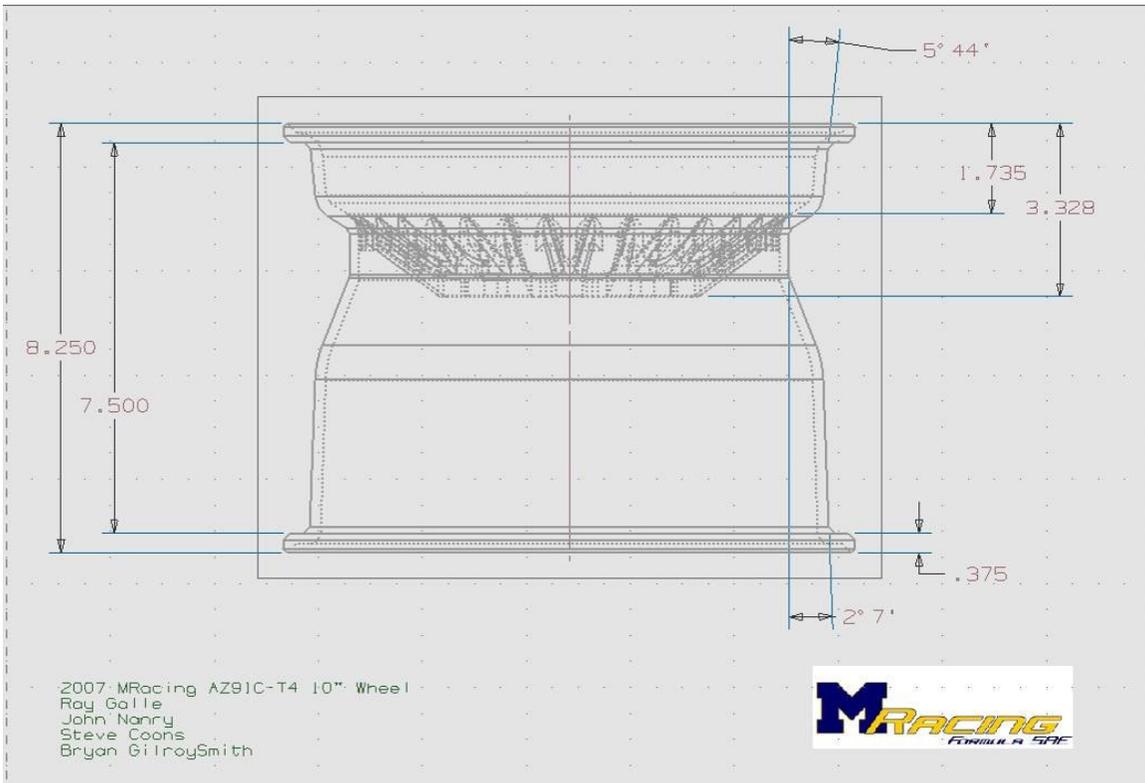


Figure E2. Side View of Final Design

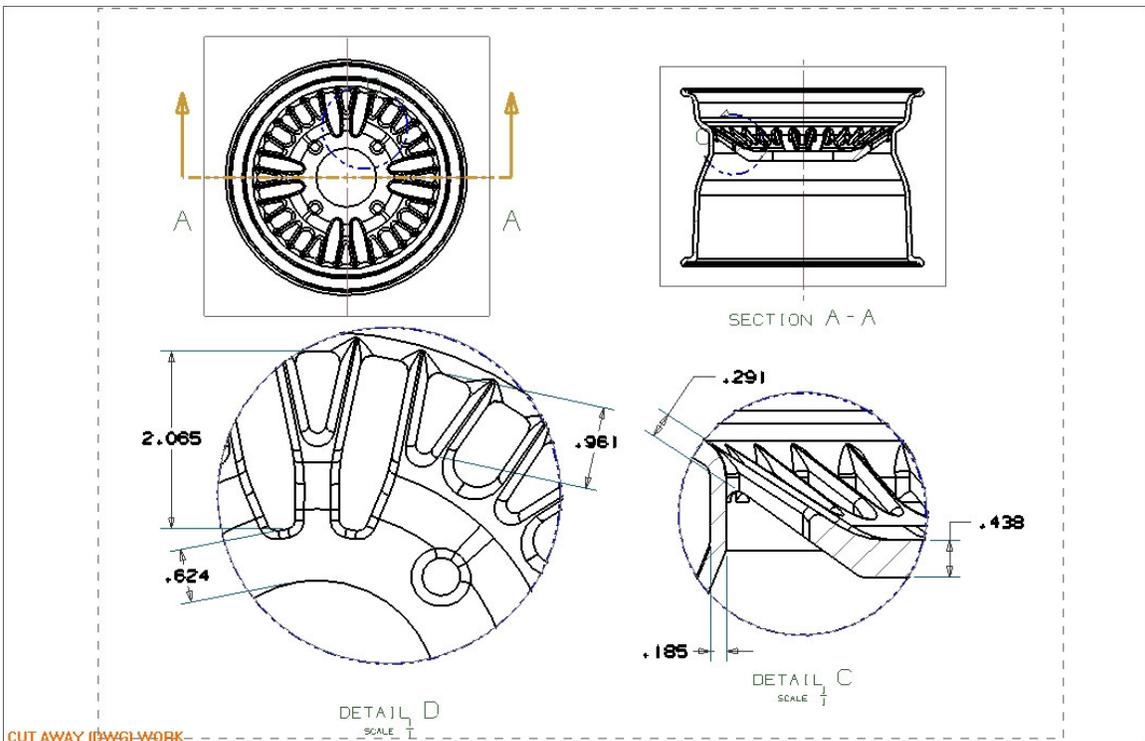


Figure E3. Detailed View of Final Design

Appendix F. Pictures of RP Tooling Production



Figure F1. Finished Part Being Removed from 3D Printing Machine



Figure F2. Example of RP Tooling

Appendix G. Failure Mode and Effects Analysis

DESIGN FAILURE MODE AND EFFECTS ANALYSIS

Product Type: Wheels
Design Responsibility: Team 9
Prepared by: S. Coons
DFMEA Origination Date: 3/12/2007

Revision Prepared by: S. Coons
Rev. Date: 3/12/2007

| Row # | Item/Function | Potential Failure Mode | Potential Effect(s) of Failure | 12 Sev | 14 Potential Cause(s)/ Mechanism(s) of Failure | 15 Occur | 16 Current Design Controls | 17 Detect | 18 RPN | 19 Recommended Actions | 20 Responsibility & Target Completion Date | Action Results | | | |
|-------|---|--|---|-----------|---|-------------|---|--------------|-----------|---------------------------|---|----------------|-----|-----|-----|
| | | | | | | | | | | | | Actions Taken | Sev | Occ | Det |
| 1 | Wheel Center/ Point where wheel attaches to the hub | Wheel stud holes too small. | Wheels will not mount on car. | 9 | Holes are drilled too small. | 1 | Holes can be drilled larger. | 1 | 9 | NONE | | | | | |
| 2 | | Wheel stud holes too large. | Wheels mount loosely on the car. | 10 | Holes are drilled too large. | 1 | Hole size is specified on wheel drawing. | 2 | 20 | NONE | | | | | |
| 3 | | Bolt circle for wheel stud holes is too large or small | Wheels will not mount on car. | 9 | Bolt circle is machined wrong. | 1 | Bolt circle size is specified on wheel drawing. | 1 | 9 | NONE | | | | | |
| 4 | | Contact area with the hub is not flat. | Wheel does not mount as intended to car | 9 | Area is improperly machined. | 1 | Control frame for surface on the wheel drawing. | 2 | 18 | NONE | | | | | |
| 5 | | Area fractures. | Wheel fails catastrophically. | 10 | Cracks in area | 2 | X-ray of wheels after casting. | 2 | 40 | NONE | | | | | |
| 6 | | | Wheel fails catastrophically. | 10 | Fatigue strength of the wheel is too low. | 1 | Fatigue strength calculations. | 2 | 20 | NONE | | | | | |
| 7 | | Area yields | Wheel bends and becomes unusable. | 9 | Area is designed too thin. | 1 | FEA analysis of wheels. | 2 | 18 | NONE | | | | | |
| 8 | | | Wheel bends and becomes unusable. | 9 | Casting process results in lower than expected material properties. | 1 | Tensile test of material sample during casting. | 1 | 9 | NONE | | | | | |

| | | | | | | | | | | | | | | | | | | |
|----|--|---|--|----|---|---|------------------------------------|---|----|------|--|--|--|--|--|--|--|--|
| 9 | Spokes/ Connect wheel center to wheel shell. | Spokes fracture. | Wheel fails catastrophically. | 10 | Cracks in area | 2 | X-ray of wheels after casting. | 2 | 40 | NONE | | | | | | | | |
| 10 | | | Wheel fails catastrophically. | 10 | Fatigue strength of the wheel is too low. | 1 | Fatigue strength calculations. | 2 | 20 | NONE | | | | | | | | |
| 11 | | Spokes yield. | Wheel bends and becomes unusable. | 9 | Area is designed too thin. | 1 | FEA analysis of wheels. | 2 | 18 | NONE | | | | | | | | |
| 12 | | Spokes contact brake calipers | Wheels are unusable. | 9 | Wheels improperly designed | 1 | CAD modeling on wheels on the car. | 1 | 9 | NONE | | | | | | | | |
| 13 | | | Wheel and calipers destroyed. | 10 | Spokes deform too much during loading. | 1 | FEA analysis of wheels. | 1 | 10 | NONE | | | | | | | | |
| 14 | Wheel Shell/ Contact area with tires | Shell Fractures | Wheel fails catastrophically. | 10 | Cracks in area | 2 | X-ray of wheels after casting. | 2 | 40 | NONE | | | | | | | | |
| 15 | | | Wheel fails catastrophically. | 10 | Fatigue strength of the wheel is too low. | 1 | Fatigue strength calculations. | 2 | 20 | NONE | | | | | | | | |
| 16 | | Shell yields | Wheel bends and becomes unusable. | 9 | Area is designed too thin. | 1 | FEA analysis of wheels. | 2 | 18 | NONE | | | | | | | | |
| 17 | | Shell contacts brake calipers. | Wheels are unusable. | 9 | Wheels improperly designed | 1 | CAD modeling on wheels on the car. | 1 | 9 | NONE | | | | | | | | |
| 18 | | | Wheel and calipers destroyed. | 10 | Spokes deform too much during loading. | 1 | FEA analysis of wheels. | 1 | 10 | NONE | | | | | | | | |
| 19 | | Bead area causes improper seat with tire. | Wheels and car are damaged or destroyed. | 10 | Improper surface finish causes wear on tire bead. | 2 | Area will be machined. | 2 | 40 | NONE | | | | | | | | |
| 20 | | | Tires do not hold air. | 9 | Area is not machined correctly. | 1 | Detailed drawings of bead area. | 1 | 9 | NONE | | | | | | | | |
| 21 | | | Tires do not hold air. | 9 | Area is damaged during tire mounting. | 4 | FEA analysis of wheels. | 1 | 36 | NONE | | | | | | | | |

Figure G1. FMEA

Appendix H. Prototype Manufacturing Plan

| Prototype Manufacturing Plan | | | | | | | | | |
|--------------------------------------|----------------------|--------------|---------------------|---------|---------------------------------|--------------|------|------|-------|
| Op. # | Operation | Machine | Tool | Fixture | Parameters | Time (hours) | | | |
| | | | | | | Set-up | Run | Cure | Total |
| <i>Patterns</i> | | | | | | | | | |
| 1 | 3D Print | 3D Printer | - | - | ZP401 Powder/ZB56 Resin | 0.5 | 6 | 4 | 10.5 |
| 2 | Epoxy | Hand | Brush | - | West Systems 105 resin | 0.1 | 0.25 | 6 | 6.35 |
| 3 | Sand | Hand | Sandpaper | - | 80,400,600 grit | 0.1 | 0.5 | 0 | 0.6 |
| 4 | Assemble | Hand | Brush | - | 5 minute epoxy | 0.25 | 0.25 | 1 | 1.5 |
| 5 | Sand | Hand | Sandpaper | - | 80,400,600 grit | 0.1 | 2 | 0 | 2.1 |
| <i>Core</i> | | | | | | | | | |
| 1 | 3D Print | 3D Printer | - | - | ZP401 Powder/ZB56 Resin | 0.5 | 6 | 4 | 10.5 |
| 2 | Epoxy | Hand | Brush | - | West Systems 105 resin | 0.1 | 0.25 | 6 | 6.35 |
| 3 | Sand | Hand | Sandpaper | - | 80,400,600 grit | 0.1 | 0.5 | 0 | 0.6 |
| 4 | Assemble | Hand | Brush | - | 5 minute epoxy | 0.25 | 0.25 | 1 | 1.5 |
| 5 | Sand | Hand | Sandpaper | - | 80,400,600 grit | 0.1 | 2 | 0 | 2.1 |
| 6 | Cut Wood for Box | Circular Saw | Wood Saw Blade | - | 16"x16"x8"and5" | 0.5 | 0.5 | 0 | 1 |
| 7 | Assemble Box | Hand | Hand Drill | - | | 0.1 | 0.5 | 0 | 0.6 |
| 8 | Seal Box | Hand | Caulk Gun | - | Silicon caulk | 0.1 | 0.25 | 0 | 0.35 |
| 9 | Assemble Core in Box | Hand | Brush | - | 5 minute epoxy | 0.25 | 0.1 | 1 | 1.35 |
| 10 | Pour Tooling Resin | Hand | - | - | Hapcast 3732 Aluminum Resin | 0.5 | 0.1 | 24 | 24.6 |
| 11 | Sand Core | Hand | Sandpaper | - | 80,400,600 grit | 0.1 | 4 | 0 | 4.1 |
| <i>Casting - Done by Lite Metals</i> | | | | | | | | | |
| 1 | Mount Patterns | Hand | Hand Drill/Resin | Board | Pattern halves mounted to board | 0.5 | 3 | 0 | 3.5 |
| 2 | Mount Gating/Risers | Hand | Hand Drill/Resin | Board | Gating/Risers attached to board | 0.5 | 3 | 0 | 3.5 |
| 3 | Make Sand Mold | Sand Hopper | Air Hammer | Flask | Green Sand | 1 | 1 | 0 | 2 |
| 4 | Pour Magnesium | Hand | Hopper | - | AZ-91C-T4 alloy | 1 | 0.1 | 24 | 25.1 |
| 5 | Burn Out Mold | Hand | Oxy-Asedaline Torch | - | - | 0.5 | 0.5 | 0 | 1 |
| 6 | Remove Gating | Hand | Power Saw | - | Leave 1/8" of material | 0.5 | 1 | 0 | 1.5 |

| | | | | | | | | | |
|--|---------------------------|------------------|-----------------|--------|--------------------------------|-----|------|----------------------------------|------|
| 7 | Fix porosity as necessary | Welder | Tig-Welder | - | X-ray for porosity | 0.5 | 1 | 0 | 1.5 |
| <i>Post-Machining - Done by Liberty's Gear</i> | | | | | | | | | |
| 1 | Machine Hub Face | Mill | Facing End Mill | Clamp | Face off to create datum plane | 0.5 | 0.1 | 0 | 0.6 |
| 2 | Machine Center Hole | Mill | Solid End Mill | Clamp | Pocket to create datum axis | 0.1 | 0.1 | 0 | 0.2 |
| 3 | Machine Stud Pattern | Mill | Solid End Mill | Clamp | Pocket radial pattern | 0.1 | 0.25 | 0 | 0.35 |
| 4 | Machine Outside Profile | Lathe | Profiling | Chuck | Turn profile with CNC lathe | 0.5 | 1 | 0 | 1.5 |
| 5 | Machine Inside Profile | Lathe | Profiling | Chuck | Turn profile with CNC lathe | 0.1 | 1 | 0 | 1.1 |
| 6 | Machine Valve Stem Hole | Mill/Drill Press | Drill | Clamp | Clocking does not matter | 0.5 | 0.25 | 0 | 0.75 |
| <i>Finishing</i> | | | | | | | | | |
| 1 | Sand | Hand | Sandpaper | - | 1000 grit wet sand | 0.1 | 2 | 0 | 2.1 |
| 2 | Prime | Paint Gun | - | Hanger | Metal primer | 0.5 | 0.5 | 2 | 3 |
| 3 | Paint | Paint Gun | - | Hanger | Gold automotive paint | 0.5 | 1 | 24 | 25.5 |
| 4 | Clear | Paint Gun | - | Hanger | Automotive clear-coat | 0.5 | 0.5 | 24 | 25 |
| 5 | Mount Valve Stem | Hand | Screwdriver | - | Valve stem supplied by Hoosier | 0.1 | 0.25 | 0 | 0.35 |
| | | | | | | | | Total Time (hours) 172.65 | |

Figure H1. Prototype Manufacturing Plan

Appendix I. Casting Pictures

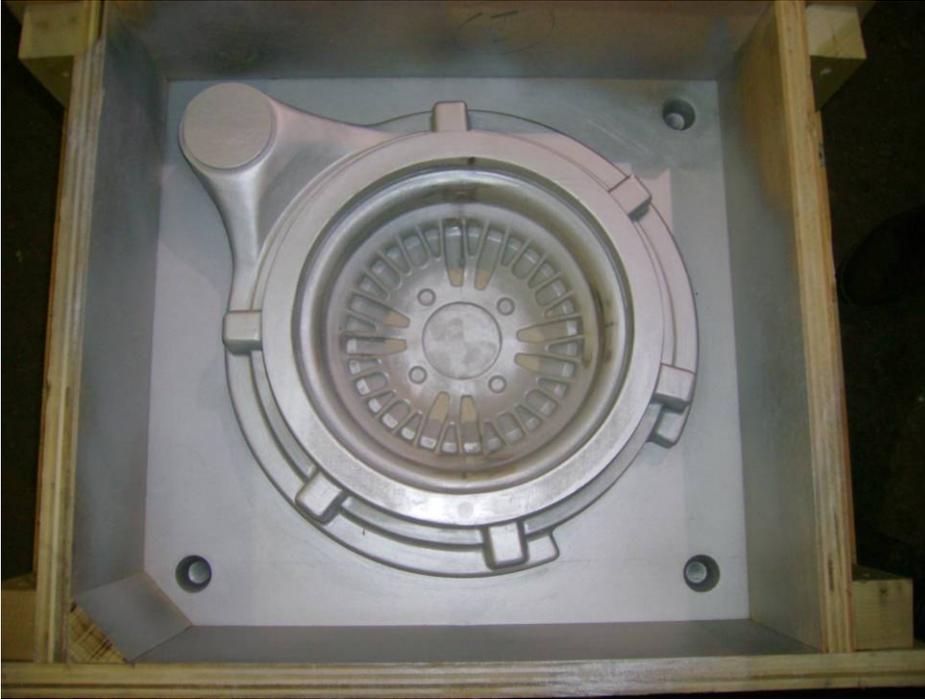


Figure I1. Cope

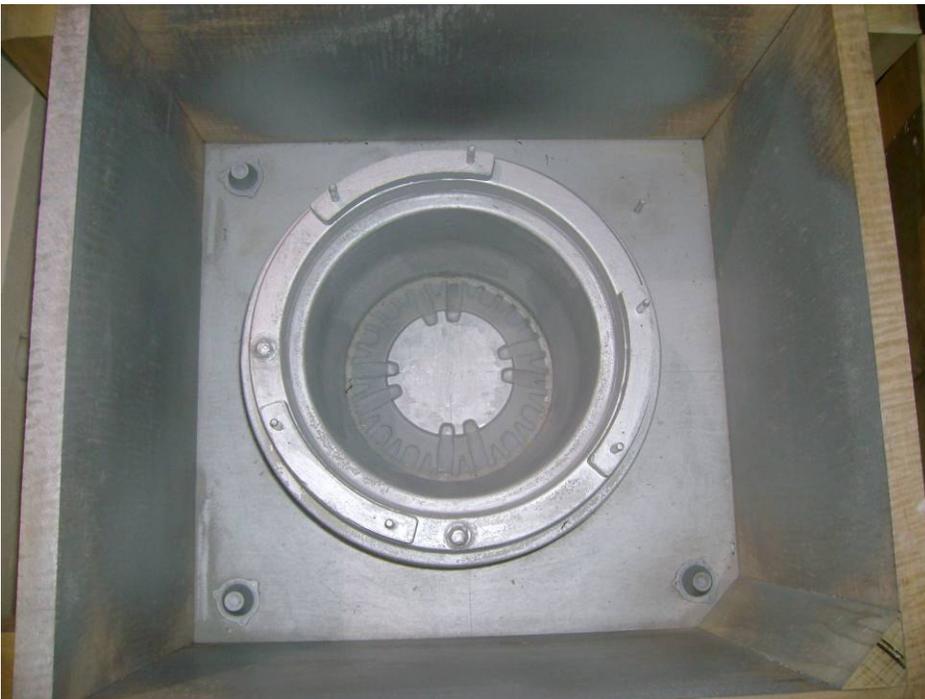


Figure I2. Drag

Appendix J. Detailed Drawings for Post-Machining

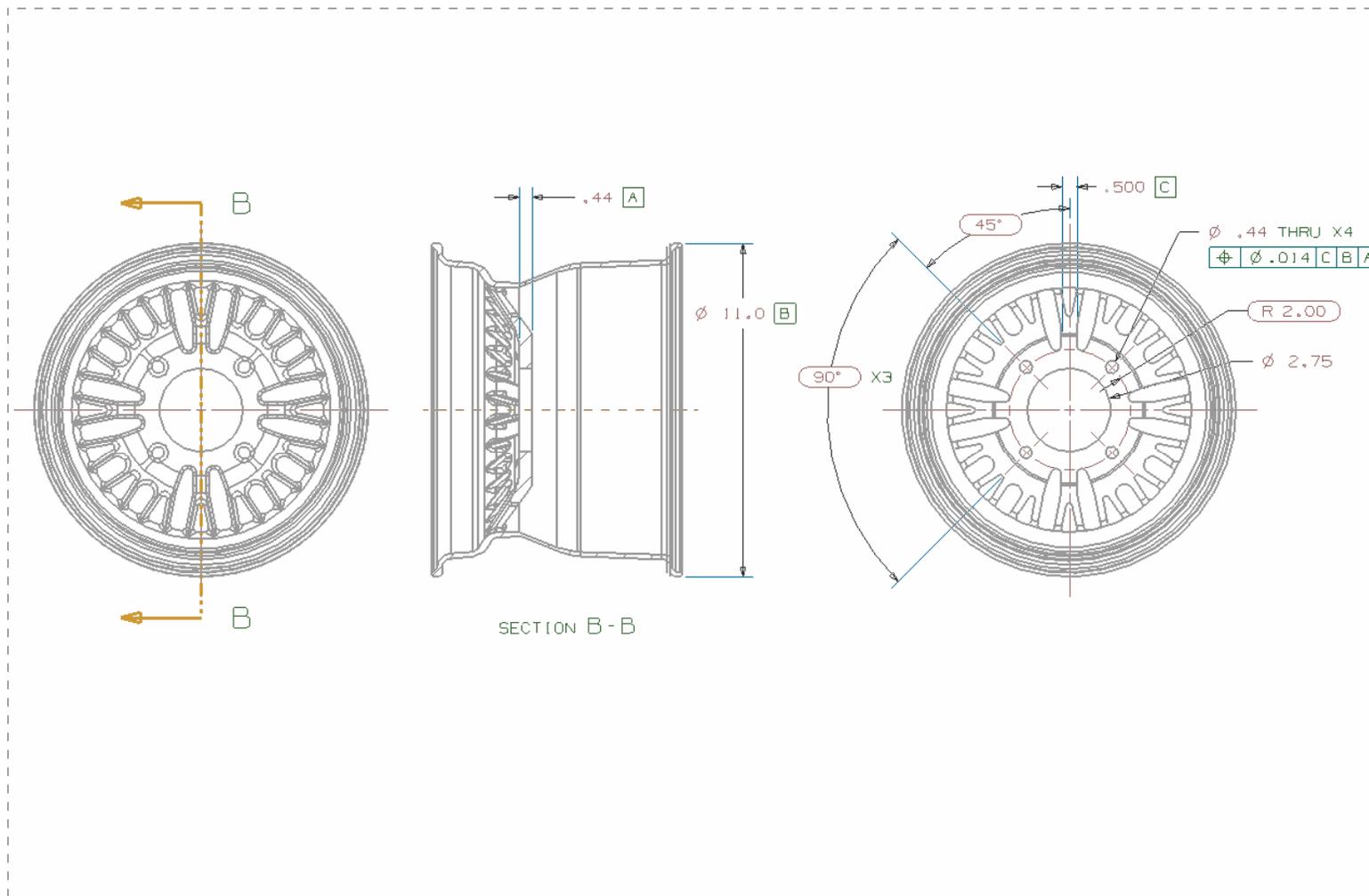


Figure J1. Detailed Drawing of Wheel Center

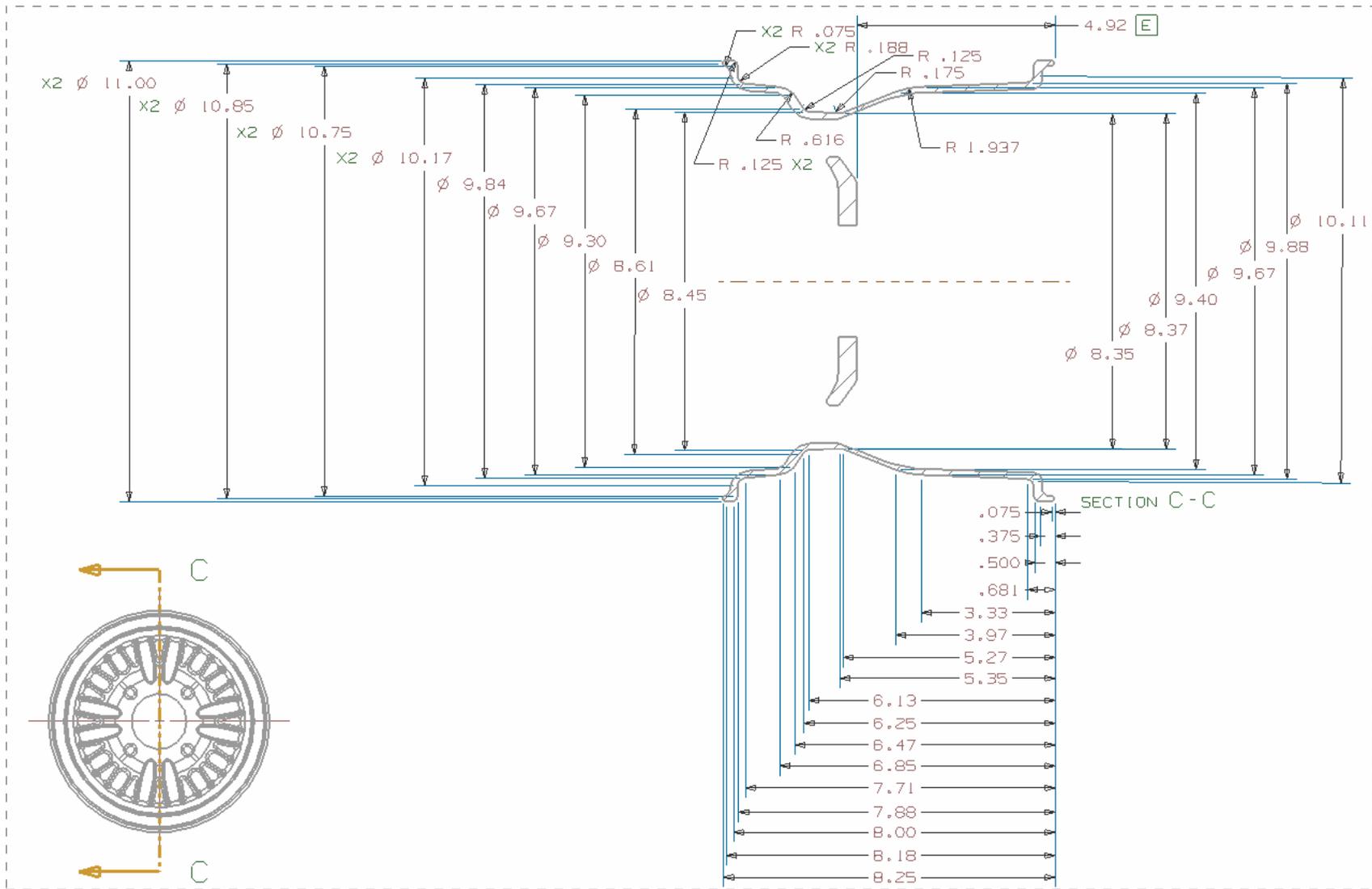


Figure J2. Detailed Drawing of Outside of Wheel Shell

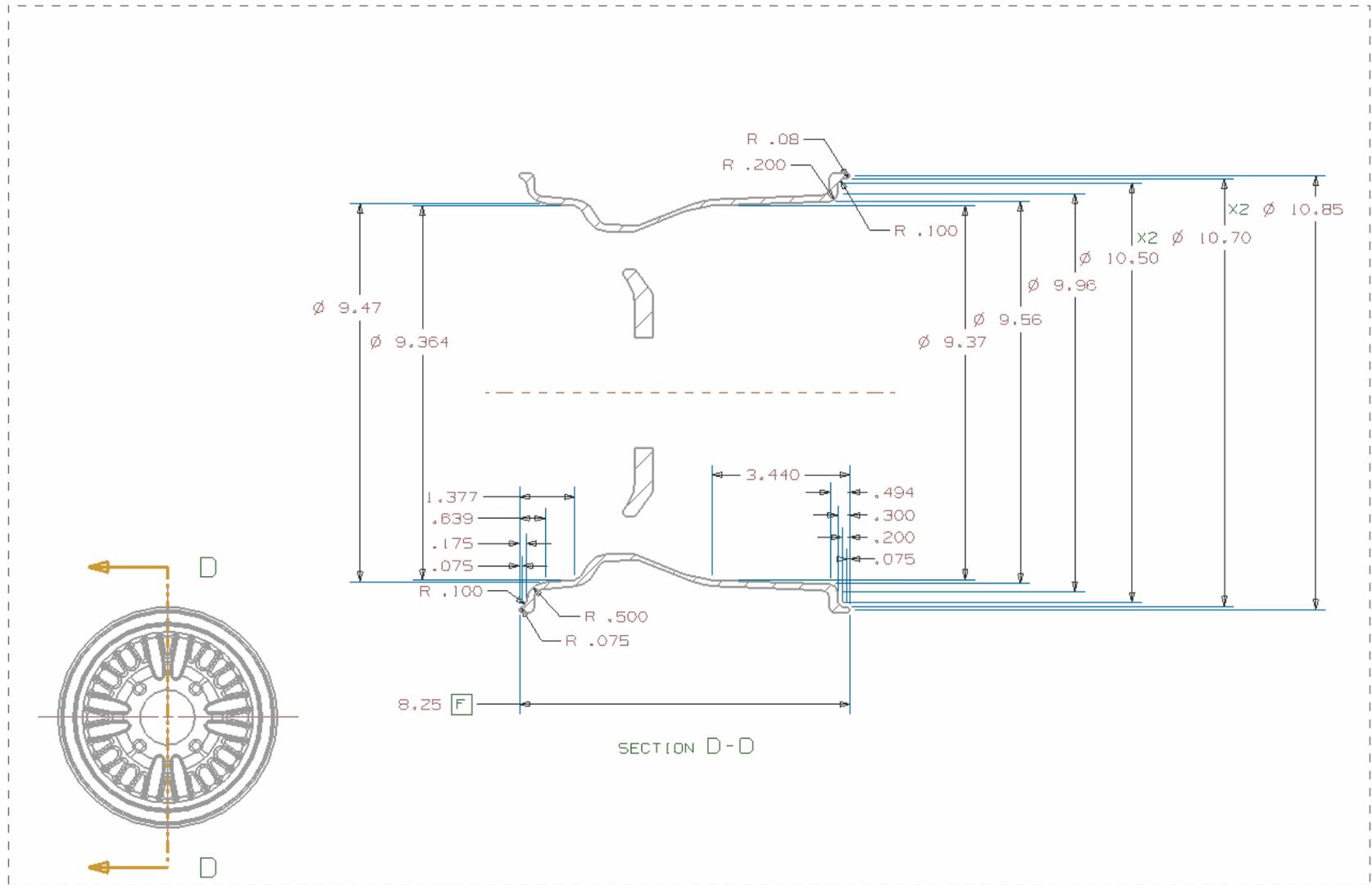


Figure J3. Detailed Drawing of Inside of Wheel Shell

Appendix K. Physical Test Setup and Results



Figure K1. Instrumented Wheel

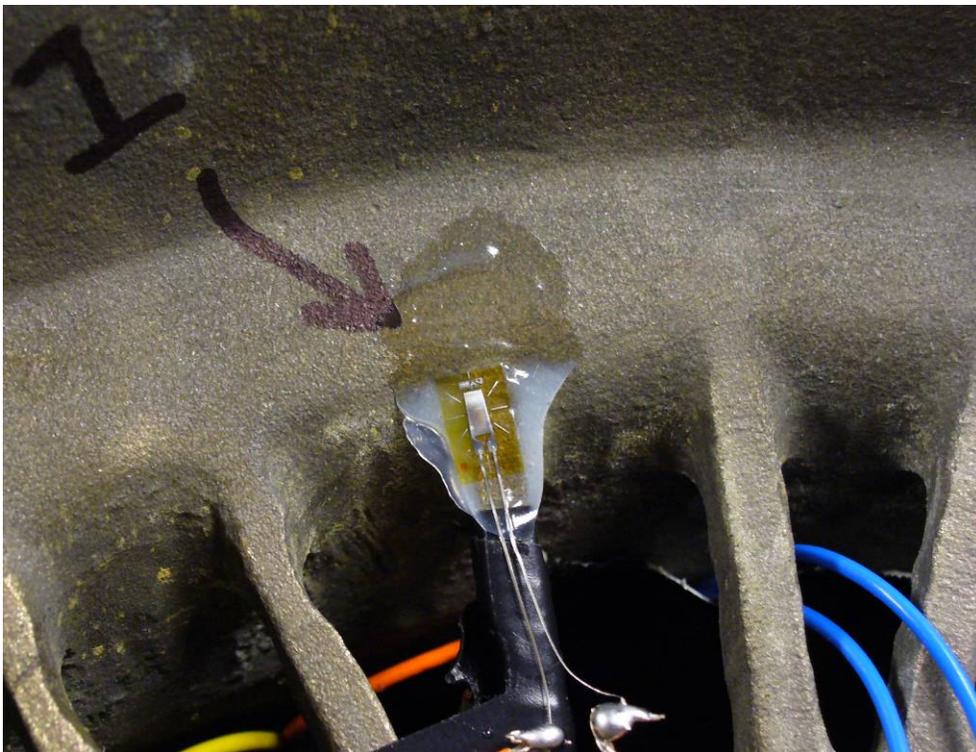


Figure K2. Strain Gauge on the Wheel

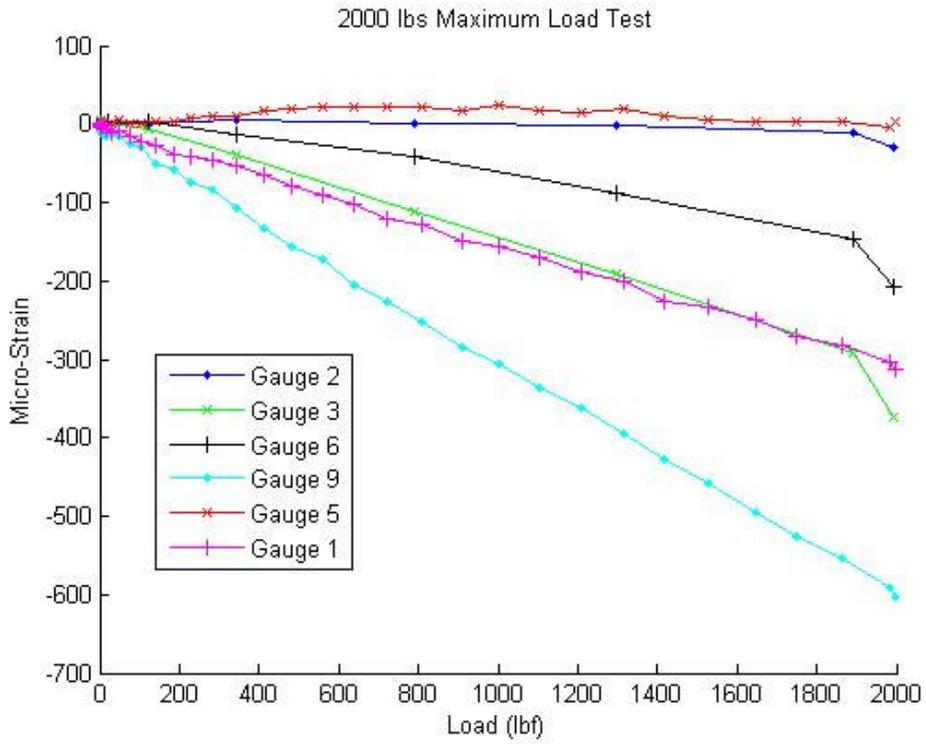


Figure K3. Plot of 2000 lbs. Maximum Load Test