DESIGN AND ANALYSIS OF A COMPRESSION MOLDED CARBON COMPOSITE WHEEL CENTER

By

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To my dear parents Dhananjayan and Padmavathi Dhananjayan and to my brother Hemananthan Dhananjayan for their support throughout my life

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ABSTRACT

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Importance of closed mold and short fibers in the manufacture of carbon composite parts was realized based on a study of existing manufacturing processes for thermoset resins as these can improve production volumes, cost reduction of the part, production of near net shape parts eliminating secondary operations and production of parts with near isotropic properties due to random fiber orientation. Compression molding process is the most preferred process as this addresses the problems of fiber damage effectively because of the minimal flow in the material. A brief study was done on the compression molded carbon composite parts in the industry. Identification of part manufacturers, process types, raw material suppliers are the key findings of the study. Compression molding process depends on three key areas such as geometry of the part, raw material used and the process conditions for producing a desired part.

This thesis will demonstrate the advantageous carbon composite compression molding process by developing a high strength part for the racing team. A comparative study was done between wheel center and wheel hub for the existing process and areas for improvement. Wheel center was identified as the most suitable part for development based on scope of weight Reduction in team's goal and need for improvement in functional aspects. A detailed market study was done on the material suppliers and their compounds.

Compounds are compared in relation to the existing aluminum grade. Three compounds are selected based on the strength and modulus values which are closer to the aluminum values. Modifications are made to the design to address the functional issues and to suit the process. Stress and deformation values are compared for existing and proposed designs. The proposed design promised over 20 % reduction in weight, stress and deformation. Detailed design for the mold is done based on the proposed design. Heating and cooling systems are studied and positions in the mold are analyzed in ansys and solidworks for the thermal distribution in the cavity. Detailed engineering drawings are made for the part and the mold. Process parameters like cure temperature, process pressure, press tonnage required are identified based on the selected raw material. This thesis will provide an approach for developing high strength parts by compression molding process.

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CHAPTER 1

INTRODUCTION

1.1 Composites overview

Improving performance is a key challenge enforced to all manufacturers to meet customer demands and to maintain a dominant place in competition driven market. Manufacturers have decoded this art by introducing new technologies, improving the process, introduction of lightweight materials. All of them lead to a single goal of increasing product performance envelope. Introduction of lightweight materials led to the development of composites. Composites fare better when compared to steel and aluminum in terms of weight, thermal expansion, specific stiffness, specific strength and fatigue strength. Replacing steel with composite can save from 60% to 80% in weight and can save up to 50% when composites are used in place of aluminum [1].

Composites possess several distinct advantages that the metal counter parts could not offer. They are extremely lightweight, offer tailor made properties and provides parts consolidation. There are quite some disadvantages which remains a key question in adapting a composite structure for the application. Cost, lack of proven design criteria, long lead time for development, manufacturing difficulties are some of the negative aspects of composites. The usage is on consistent rise because of the extensive research in the design, analysis and manufacturing of composite parts. The manufacturing processes had been greatly developed for the composites since its inception.

1.2 Composites constituents

The concept of composites is not invented by human beings. It is found in nature. Wood is a nice example for composite; it consists of cellulose fibers found in matrix glue called lignin. Husk, straw are mixed with clay to build houses in countries like India several hundred years ago. Mixing of husk with clay is a particulate composite and mixing of straw with clay is a short fiber composite [1]. Composites are defined as

“Composite materials are those solid materials composed of a binder or matrix that surrounds and holds in place reinforcements” [1].

The two main constituents of a composite material are matrix and reinforcement. Superior strength is obtained when two different materials are combined together than they exist separately. The properties of the constituent materials are still retained. Constituents of a composite are shown in figure 1.

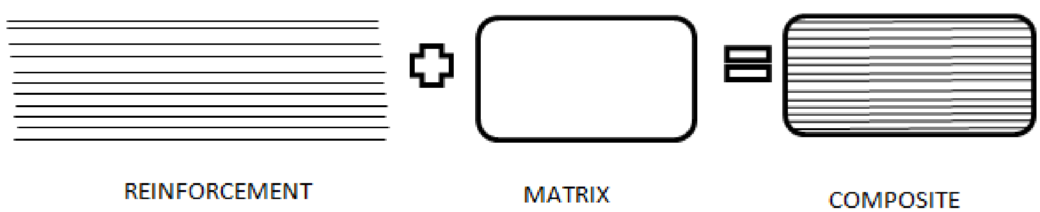

Figure 1 Composite constituents

As the name implies the reinforcement supports the matrix to improve strength. Matrix is a medium in which the reinforcements are placed. Composites are classified based on the matrix and reinforcement in the structure.

1.2.1 Constituents comparison

Differences between matrix and reinforcement are tabulated in Table 1.

Table 1 Composites constituent's comparison

Attributes	Matrix	Reinforcement
Function	Transfer loads to reinforcement and protects it from environmental conditions	Load bearing members
Secondary functions	Gives shape to the part, contributes to specific properties like toughness, failure is primarily dependent on matrix	Contributes to the mechanical properties of composite
Types	Polymers, ceramics, metals	Fibers, particles
Sub category classification	Polymers - thermoset, thermoplastics	Fibers - glass, carbon, organic
Focus area	Thermoset polymers	Carbon fibers
Focus area properties	Cross linking formed when curing, cannot be re melted once cured	Properties depend on rovings and form of carbon fiber. It can be unidirectional, chopped, woven mat.
Example	epoxy, vinyl ester, unsaturated poly ester, phenolic compounds	continuous fibers, discontinuous or chopped fiber

1.3 Applications

Aircraft industry is the first one who realized the importance of composites. Composites are used in boeing 757 in doors, fairings, elevators, rudders, spoiler and flaps [4]. Rise of composite usage is evident from the recent trends. The composite consumption has increased greatly in aerospace, automotive and construction industry. With the introduction of newer manufacturing methods for processing carbon fiber, the cost of carbon fiber is steadily decreasing. This is a primary reason for the increase in composite usage as the overall cost is constantly reducing. Automotive market is a cost driven market where fiberglass reinforcements plays a vital role. Composite parts are used in hood, seat floor, radiator support and bumper beams. Composites are used in sporting industry in tennis racquets, golf clubs, fishing rods, bicycle frames and snow skis. Composites are used in general appliances like tables, chairs, bath tub, doors, computers and printers. Composites are used in construction industry to improve corrosion resistance, enhance strength and perform repair.

1.4 Manufacturing methods

Processing of composites is based on the matrix material and the form of reinforcement. We are concerned on the polymer reinforced composites, so thermoset and thermoplastic are the two categories which fall under composites processing. Based on the form i.e., short fiber or continuous fiber the processing techniques varies. Brief classification of the processes is described in the Table 2.

Table 2 Composites manufacturing process

Thermoset composites		Thermoplastic composites	
Short fiber	Continuous fiber	Short fiber	Continuous fiber
Compression molding	Filament winding	Blow molding	Thermoforming
SRIM	Pultrusion	Injection Molding	Tape winding
Wet layup	RTM		Compression molding
Injection molding	Hand layup		Autoclave process
BMC molding	Autoclave process		Diaphragm forming
	Roll wrapping		

RTM- Resin Transfer Molding; SRIM – Structural Reaction Injection molding

Process selection plays a key role in developing a composite part for an application. It depends on several factors such as production rate, cost, performance, size and shape.

1.5 Importance of closed mold and short fibers

Composite manufacturing has four basic criteria which affects the cost and application of the process. They are material cost, labor skill requirement, volume capability, complex shapes capability. Processes are screened based on these four factors in table 3. Closed mold processes address these criteria effectively. Closed mold process either employs pellets or chopped fibers. In addition to the above advantages intricate shapes and parts with ribs, bosses can be molded.

Table 3 Thermoset process evaluation

Thermoset processes	Low raw material cost	Less labor	High volume	Complex shapes
Prepreg layup				
Wet layup				
Spray layup	Spray layup			
FW	FW	FW	FW	
Pultrusion	Pultrusion	Pultrusion	Pultrusion	
RTM	RTM	RTM		
SRIM	SRIM	SRIM	SRIM	SRIM
IM	IM	IM	IM	IM
CM	CM	CM	CM	CM
Roll wrapping				

FW – Filament winding; IM- Injection Molding; CM- Compression molding

The strength of the parts produced by closed mold processes which utilizes short fibers are less than the continuous fiber parts but can match or even surpass the aluminum counterparts. So short fiber molded parts find application in areas where high strength aluminum is used. Several papers have been published to study the characteristics, notch behavior, modulus measurement, failure initiation and damage analysis of short fiber molded parts. Refer Appendix A Literature review on short fibers and compression molding process.

1.6 Compression Molding

In this thesis we are trying to build a metal part in composite for the formula SAE team which would reduce weight and benefit the team. A process should be selected which is capable of reducing the lead time and capable of producing intricate parts with strength properties matching the existing grade aluminum. Refer Appendix B for detailed process review available for thermoset composites.

Compression molding process is a suitable process for the defined requirements. Compression molding primarily utilizes short fibers. Continuous fiber also can be molded but a perform is made prior to the process in order to avoid fiber damage. Compression molding process lead to quicker cycle times and intricate shapes can be processed along with ribs and bosses.

1.6.1 Process description

Compression molding is a closed mold process. It consists of matched die molds. Two molds (Male and Female) are provided with heating and cooling sources. Ejector pins are placed in the bottom mold to facilitate the component removal. Sheet molding compound also called as charge is the raw material for this process. Charge is cut in predetermined shapes and placed in the mold. Compression molding employs a heated mold for curing the sheet molding compound in the mold. Charge which is in semi cured stage is placed in the mold and the mold is closed by bringing down the male mold and female mold together. The charge is squeezed and allowed to flow inside the cavity. Due to the heat source in the mold the charge gets heated and the viscosity drops thereby starts flowing inside the cavity. The molding process requires high pressures so the molds are mounted in big presses. The presses enable rapid curing cycles and high production volume. Because of this advantage this is highly used in automotive industry where there is a need for high volume process. Part repeatability is better than the other composite processes. Process repeatability and parts quality depends on part design, mold design, raw material selection, process conditions and charge placement. A simple compression mold process setup is shown in figure 2.

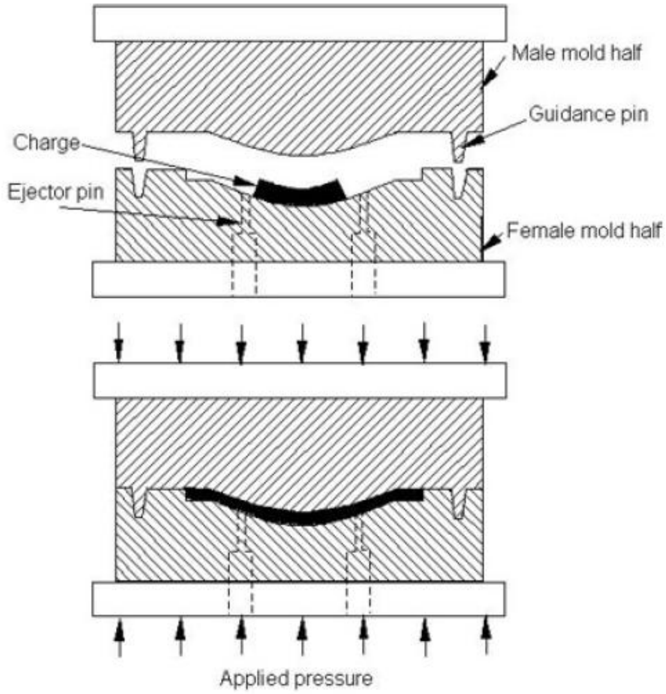

Figure 2 Compression molding setup [1]

1.6.2 Advantages

1. Low labor cost and shorter lead time
2. Holes, flanges, non uniform thickness can be created in the part thereby reducing additional processes like welding and drilling.
3. Produces near net shape parts eliminating secondary operations

1.6.3 Disadvantages

1. High initial investment in the form of mold is needed, but a high volume part can compensate this investment
2. Lack of simulation facilities for the process
3. Knowledge about the process and controlling parameters

1.6.4 Applications

Applications include roof panels, doors, hood, radiator support, oil pans, bath tubs, switches and fuses. Lamborghini has developed a new technology called forged composite which is an advanced compression molding process. This technology is utilized in making parts for its concept car sesto elemento in parts like passenger tub which is shown in figure 3 and suspension arms [2]. Parts made of Hexcel HexMC compound and parts made by Carbone forge are shown in figure 4.

Figure 3 Lamborghini sesto elemento passenger cell [2]

Figure 4 Carbon composite compression molded parts [4,5]

Callaway has utilized this technology to manufacture carbon golf head in its latest series of golf clubs. Dodge viper was the first mass produced vehicle which utilized compression molded carbon fiber sheet molding compound. Study findings on compression molded parts are tabulated in table 4.

Table 4 Compression molding parts market study

OEM	Model	Parts	Part Manufacturer	SMC Manufacturer	SMC Model
Dodge [7]	Viper	right and left fender systems, windshield section	Meridian systems	Quantum composites	AMC series
Boeing	787	Window frames, highly loaded gussets, pressure pans, clips, brackets	Nordaam group interiors and structures division	Hexcel	HexMC
Lamborghini [2]	Sesto elemento	Passenger cell, suspension arms	Lamborghini	Quantum composites	AMC series
Callaway golf [8]	Diablo octane	Golf head	NA	Quantum composites	NA
Airbus [6]	A340	fitting	Duqueine	NA	NA
Carbone forge [5]	NA	Aerospace parts	NA	NA	NA
DUC helices [9]	NA	Propeller hubs	NA	NA	NA
Audemars Piguet [10]	Royal oak	Watches	Audemars Piguet		NA

1.6.5 Challenges

Fiber orientation in the part determines the strength of the part. Fiber orientation is decided by the material flow during mold closing. The quality of a compression molded part is dependent on numerous factors unlike the other process. The challenges include good part design, material selection, mold design, thermal system design, charge placement, process parameters etc.

1.7 Objective of Thesis

This thesis will focus on developing a high strength part for the racing team using compression molding process. The part development must lead to significant weight savings and additional benefits to the team. Three key areas had been identified which significantly affect the compression molding process. They are part geometry, raw material and process conditions. The influencing parameters will be studied and the parameters will be identified for the wheel center development.

1.8 Outline of the Thesis

Chapter 1 describes about composites and brief introduction to compression molding process

Chapter 2 talks about identification of a high strength part and raw material for compression molding

Chapter 3 explains the structural analysis of the existing design and the proposed design.

Chapter 4 details about the mold design and process parameters identification and prediction for the wheel center development

Chapter 5 summarizes the results and scope for future work

CHAPTER 2

IDENTIFICATION OF PART AND RAW MATERIAL SELECTION

2.1 Expectations from the part development

Formula Society of Automotive Engineers team (FSAE) is functioning in our university which involves a group of students in building a formula style race car towards the yearly competition. The team has won several times in the competitions because of the competitive car built by the students. Weight reductions in parts play a vital role in deciding a championship. The car should be extremely light but powerful. This paves the way for carbon composite materials usage in the structures used in the car. Every year the formula SAE team is revising its target goal in achieving the performance in order to stay competitive in the competition. This part development process by using composite was aimed at benefitting the team's performance. Weight reduction will be the main goal of this development process without compromising strength and other requirements. The alternate manufacturing method will ease the way in which the part is manufactured today. The new process should address the following aspects such as adaptability, cost, quality output parts and reduction of skilled labor requirement.

2.2 Part Identification

A part needs to be selected such that it reaps in maximum benefits from the development. Aluminum and metal casting parts are the main focus here as they consume a lot of weight in the car. Part selection must address the following criteria

1. Weight of the part and influence of weight reduction in target goal
2. Addressing existing functional issues
3. Reduction in manufacturing lead time

Some of the heavy weight parts are wheel center, wheel hub, control arms etc. Of these based on the above set of criteria wheel center and wheel hub are identified for compression molding process. The most suitable part will be selected based on existing process study, weight reduction scope and effect.

2.2.1 Wheel center

Wheel center is a critical functional part which connects the wheel rim and the wheel hub. It is a critical load bearing member which experiences high stress during cornering and braking. Existing wheel center which is used by the team is shown in figure 5. Loads are transmitted from the ground through the tire and to the wheel center. Identical wheel centers are used for all four wheels. Each wheel center weighs around 1.98lb which makes 7.92lb for the entire car. Wheel center is made of Al 6061 T6 material. It is manufactured by machining a solid aluminum block.

Figure 5 Existing wheel center

The main constraints of the present wheel center are high machining time and high material wastage as it is machined from a solid block. Present design has complicated profiles in the form of a radial pattern. Every year the team manufactures two sets of wheel centers for the competition. Each set consist of four wheel centers. Deflection in the part was found to be high. For weight reduction the hollow spaces are created in between the patterns which give rise to the stress concentrations in the arms. The component has not failed as of now in any circumstances. Weight reductions, stiffness increase, reducing manufacturing lead time are the key areas which are identified for the compression molding process. Wheel center is subjected to racing driving conditions. It involves dry and wet track racing conditions. It is also subjected to high temperatures. Heat generated in the tires will be dissipated through the wheel rims and to the wheel center.

2.2.2 Wheel hub

Wheel hub is a structural load bearing member. Wheel hub connects the wheel center and the stationery axle through bearings. Wheel hub is mounted to wheel center on one side and it's positioned over the stationery axle though two tapered roller bearings. Brake disc is mounted to the wheel hub. It experiences severe load in the form of torsion when the disc brakes are applied and also a considerable load from cornering which is transferred from the wheel center. Wheel hub is made of Al 6061 T6 alloy. Wheel hub weighs at 0.98lb. Each car utilizes two identical wheel hubs which sums the total weight of 1.96 lbs. Each year the team manufactures two sets of wheel hubs for the competition use. Existing wheel hub which is used by the team is shown in figure 6.

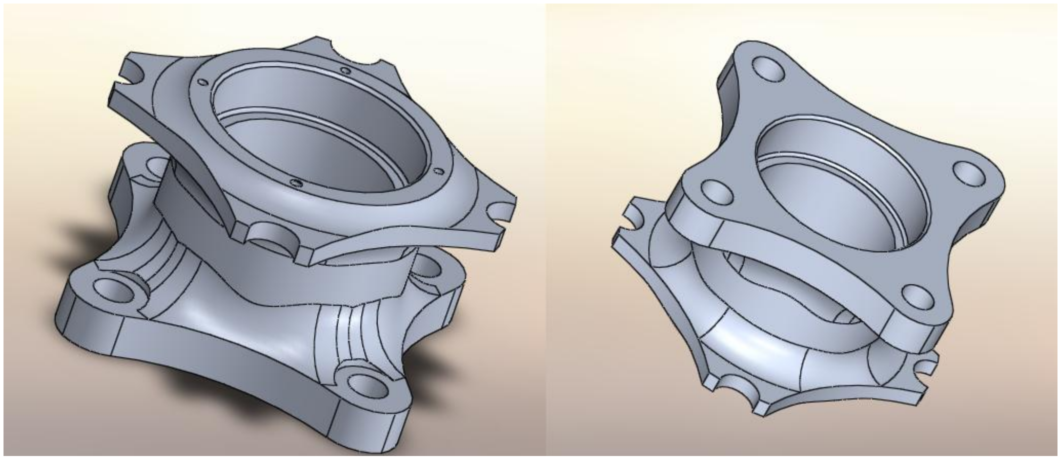

Figure 6 Wheel hub

It is manufactured by machining a solid block of aluminum. It involves numerous machine setups because of the profile complexity in the part. The component is very rigid and has high FOS. This component has not failed in the past since its inception. The areas where it is mounted with brake disc and the wheel center are the high stressed areas. Wheel hub is subjected to high temperatures. The heat generated from the brake disc is dissipated in the wheel hub.

2.2.3 Comparison

The following criteria are considered before the selection

2.2.3.1 Influence of improvement in teams goal

Our target of 20% weight reduction will impact wheel center greatly than wheel hub. Total weight reduction of 1.58 lbs can be achieved by wheel center against 0.392 lbs through wheel hub. Each year the team revises the weight of the car to be 25 lbs lighter than the previous year. With that goal into consideration the influence of weight reduction through wheel center will be significant than the wheel hub.

2.2.3.2 Existing process study

Both the parts are manufactured by machining solid aluminum. The number of machining setups is high in wheel hub when compared to wheel center. But the material wastage will be higher in wheel center because of the part size. Wheel center is 10.5” in diameter. Solid blocks of aluminum are required for machining. Wheel hub is 5” in diameter. Either bars or solid blocks can be used because of the smaller size. Material wastage can be greatly reduced in wheel center when compared to wheel hub.

2.2.3.3 Issues to be addressed

Wheel center has greater deflection under cornering. Wheel center bears less lateral stiffness. On the other hand wheel hub has not got any significant issues to be addressed.

From the above comparison criteria wheel center will be the best suitable choice for development through alternate process by composite.

2.3 Material selection

2.3.1 Raw material

Sheet molding compound (SMC), Bulk molding compound (BMC), Thick molding compound (TMC) are the initial raw materials used for compression molding. Sheet molding compound comes in the form of sheets of thickness ranging up to 0.236” whereas Thick molding compound which is a thicker version of SMC has a thickness up to 2”. Bulk molding compound comes in the form of logs or ropes which is extruded after mixing resin, fibers and fillers and then cut to small lengths. Fiber content varies from 30% to 50%. Depending on the fiber volume fraction the strength of the component is determined. Nowadays high strength raw materials are being developed with fiber volumes greater than 50%.

All compounds utilized for compression molding process consists of 10% additives of the total weight. Additives include initiators to start the chemical reaction, Inhibitors to retard the reaction and low profile additives to control shrinkage.

2.3.2 Manufacturing

Sheet molding compound is prepared by dispersing chopped carbon fiber over resin sheet and compacted after placing another resin sheet for impregnation. Fillers and curing initiators are mixed with the resin to start curing. Curing starts once the resin wets out fibers after compaction. Initiators such as heat activated peroxide will cause minimal curing in the manufacturing stage. Furthermore to avoid premature curing it is stored in refrigerator under sub zero conditions thereby extending the shelf life of the material. Typical shelf life of SMC material will be in the order of 6 - 8 weeks when stored at room temperature 23 deg C. Normally SMC requires a week to be used in compression molding from the time of sheet preparation. This phase is called maturation phase.

2.3.3 Types

Sheet molding compound can be either

1. SMC-R for randomly oriented short fibers.
2. SMC-CR for continuously oriented fibers.
3. XMC represents mixture of short fibers and continuous fiber reinforcement.

2.3.4 Curing process

Curing of the material is directly related to the viscosity of the material. Viscosity of the material is constantly changing throughout the lifecycle of SMC. During molding operation the sheets are placed in the heated mold which causes the resin viscosity to decrease once it absorbs the heat and starts flowing in the mold. Preheating of the charge outside the mold can be done for quicker processing. Flow of the material is associated with the viscosity and that is related to the fiber content and the resin compatibility with the fibers. Viscosity increases and the curing reach a maximum. Too many fibers will reduce the flow and high viscosity will also inhibit flow. The art lies in finding a balance with the fibers and causing the material to flow along with the fibers. Minimal flow is a typical feature of SMC molding as the charge already covers 80% of the mold during initial placement. The material is stored in rolls or stack form.

They should be used within a limited period as they have a limited shelf life. Various curing models have been developed in order to define the complex curing process. Barone and Caulk was the first who developed an analytical cure model for SMC [12].

2.4 SMC materials market study comparison

A raw material which is suitable for the compression molding process and also should possess stiffness similar to existing aluminum 6061 T6 is required for our development. Availability and usage of this compound in the industry is also considered.

A study was made on the list of available SMC in the market matching the properties of existing grade. Hexcel, Quantum composites and Tencate are the most dominant manufacturers of sheet molding compound in the market. Around 15 compounds in the market are taken into the study. Compounds belong to epoxy, vinyl ester, unsaturated poly ester and phenolic resin types. Epoxy and vinyl ester resins can be used in thick regions. Unsaturated polyester is the most commonly used but molding thick regions will be an issue. Phenolic resins are used in place of fire resistance. Thickness of the wheel center ranges up to 1" in certain areas. Epoxies and vinyl esters will be suitable for the purpose. Common differences between epoxy and vinyl ester are tabulated in table 5.

Table 5 Epoxy resin and vinyl ester resin comparison

Epoxy resin	Vinyl ester resin
Excellent adhesion, good thermal stability, good mechanical properties	High chemical resistance
Expensive than vinyl ester	Less expensive than epoxy but expensive than unsaturated polyester
Slow curing	Fast curing
Most commonly used	Only used in places of chemical resistance applications and corrosion requirements

Refer Appendix C for the detailed comparison of properties of all compounds taken for the study. Properties of all the compounds are tabulated in table 15 and 16.

Hexcel [4]

HexMC is a proprietary sheet molding compound developed by Hexcel. It is one of the high strength compounds available in the market. It is made of short fibers chopped from a unidirectional prepreg. Each chopped fiber prepreg measures around 2” in length and 0.3” in width. It has high shelf life time of 18 months. Cure time is relatively quicker than the others. It is used in structures of Boeing, Lamborghini. Modulus value is slightly lower than aluminum but the tensile strength equals aluminum values.

Quantum composites [7]

Lytex series and AMC series are the sheet molding compounds which are mainly used in compression molding systems. Lytex is a carbon epoxy compound whereas AMC is carbon vinyl ester compound. It is used in structures of Lamborghini. Complete properties of the compound was not available to us.

Tencate YLA [13]

It is one of the fast curing intermediate modulus category compounds from Tencate. Excellent moldability, good strength and stiffness are the key features. MS4A has almost equal modulus values in all directions.

Properties of selected compounds are tabulated in table 6.

Table 6 SMC properties comparison

Manufacturer	Aluminum[14]	Hexcel	Tencate	
Properties/Material name	Al 6061 T6	HexMC® / C / 2000 / M77	MS 1H	MS 4A
Type	-	carbon epoxy	carbon epoxy	carbon epoxy
Material density lb/in^3	0.098	0.056	0.055	0.054
Fiber length in	-	2	1	1
Fiber width in		0.31	0.13	0.13
Fiber volume %	-	up to 57	52	52
Cure temp °f	-	302	280-309	280-309
Tensile modulus msi	10	5.5	10	9
Compressive modulus msi	10	5.5	9	8
Flexural modulus msi	10	4.35	10	7
Press pressure psi	-	725-2175	2000	2000

HexMC, MS4A, MS1H are the three compounds which are selected for the analysis and based on the analysis results final compound will be chosen for the manufacture of wheel center.

CHAPTER 3

ANALYSIS AND DESIGN OF EXISTING AND PROPOSED WHEEL CENTER

3.1 Software introduction

Software used for the analysis is Ansys 14 workbench. Static structural analysis is performed for the wheel center. The components are modeled in solidworks and imported to ansys and the analysis was performed as an assembly.

3.2 Analysis of existing design

3.2.1 Wheel center assembly

Wheel center is mounted to wheel hub on one side and wheel rim on the other. Wheel hub is fastened to wheel center by four titanium lugs and nuts. On the other side, the flat face at the periphery of the wheel center is butted on the wheel rim inside and riveted at the points where the wheel center arms meet the rims. From the assembly the load transfer path is predominantly in the rivet points which hold the components together. Wheel center assembly is shown in figure 7.

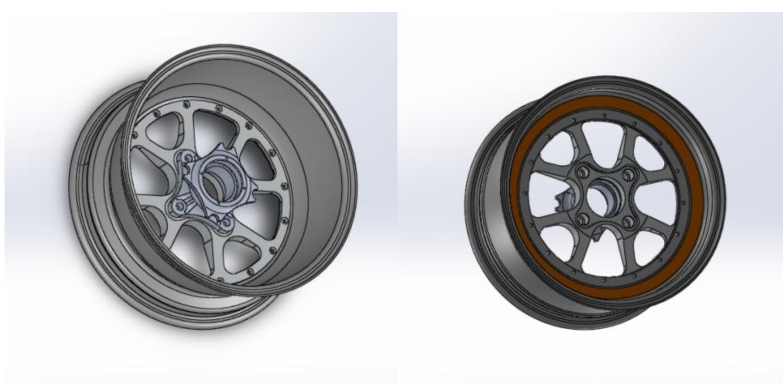

Figure 7 Wheel center assembly

3.2.2 Loading conditions

Wheel center is subjected to two loading scenarios during the race. They are cornering load and braking load conditions.

3.2.2.1 Cornering load

The car weight is supported on four tires touching the ground. These are the only contact points with the ground. The vertical weight will push the tire towards the ground whereas the lateral force acting towards the tire pushes the tire laterally. When the race car approaches a turn the lateral load will act on the tires forcing the car out of the racing line. Higher the speeds higher the cornering forces acting on the tires. During high speeds based on the acceleration g's the car weight is distributed between the tires. When the car is stationery the car weight is equally loaded in the four tires but during motion the weight acting on the tire is proportional to the acceleration g and also whether it is cornering or braking. During braking in straight line, front tires will be loaded heavily and during cornering, the outside tires will be loaded heavily. Forces acting on the wheel during cornering are shown in figure 8.

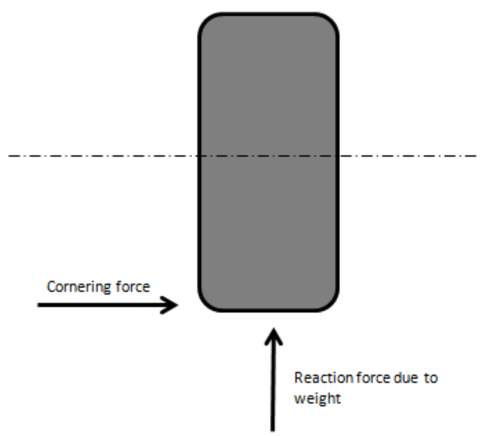

Figure 8 Cornering forces

The car is subjected to 3g acceleration at the maximum. The analysis should be done for the extreme condition. During 3g acceleration in the corners the car will be subjected to 750 lb of lateral force and 600 lb of normal force (car weight). Diameter of the wheel center is 10.5 ".

3.2.2.2 Braking load condition

During braking the car will be subjected to 2g's at the maximum and the force acting on the wheel center is 600 lbs in addition to the car weight.

3.2.3 Analysis conditions

Wheel center is analyzed with wheel rim and wheel hub in place simulating the on track conditions. The entire assembly models are obtained from the formula SAE team and analyzed for the above load conditions. The car is loaded on four tires and only a small portion of the tire which is really making contact with the ground. All the forces generated are transferred through this small portion. A small contact patch was identified in the rim and the loads are applied. The loads are given as remote forces from the point in the ground. The model is constrained in the bearing seating faces of the hub. Bonded connection is used between the wheel rim and wheel center and also between wheel center and hub. Stress and deformation in the part are our prime interest in the analysis. Wheel center is also analyzed by rotating the wheel center in the assembly by 45 deg. Results are found to be less than the normal assembly conditions. Hence the analysis results of the normal condition is discussed and compared with the proposed design. For other results refer Appendix D

3.2.4 Analysis results of the existing design

3.2.4.1Lateral load

The component is deformed at the bottom portion. Stress profile and deformation profile of the wheel center under lateral load are shown in figure 9 and 10.High values of stress are found in the arms which connect the wheel center periphery and the central mounting holes. The corners along the arms are subjected to high stresses. Because of the reduced cross section the stresses are concentrated in the small arms. Maximum value of stress is observed to be 41.598 ksi and the maximum deformation is observed as 0.049". For detailed analysis conditions and settings refer Appendix D.

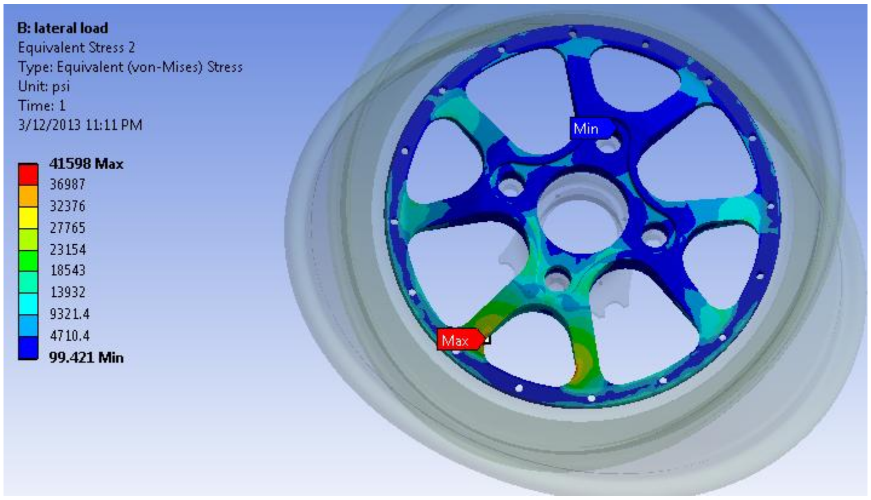

Figure 9 Stress plot in lateral load condition for existing wheel center

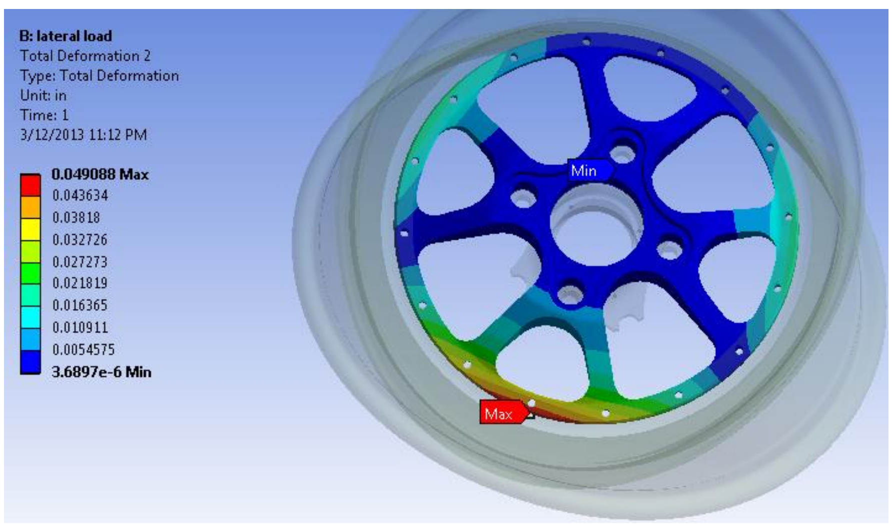

Figure 10 Deformation plot in lateral load condition for existing wheel center

3.2.4.2 Braking load

High stresses are found at the bottom radius of the arms. Peak value is found to be 9.034 ksi and the maximum deformation is found to be 0.0044808”. Stress plot and deformation plot under braking load are shown in figure 11 and 12.

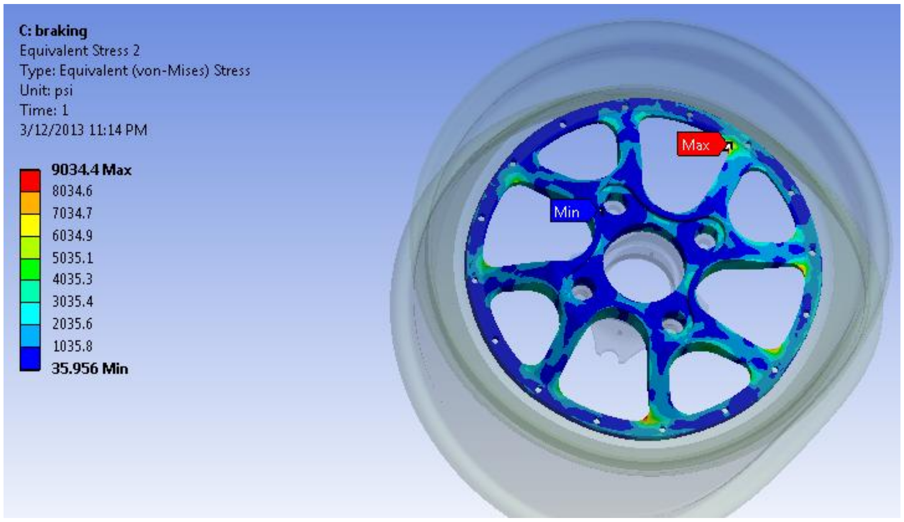

Figure 11 Stress plot under braking load in existing wheel center

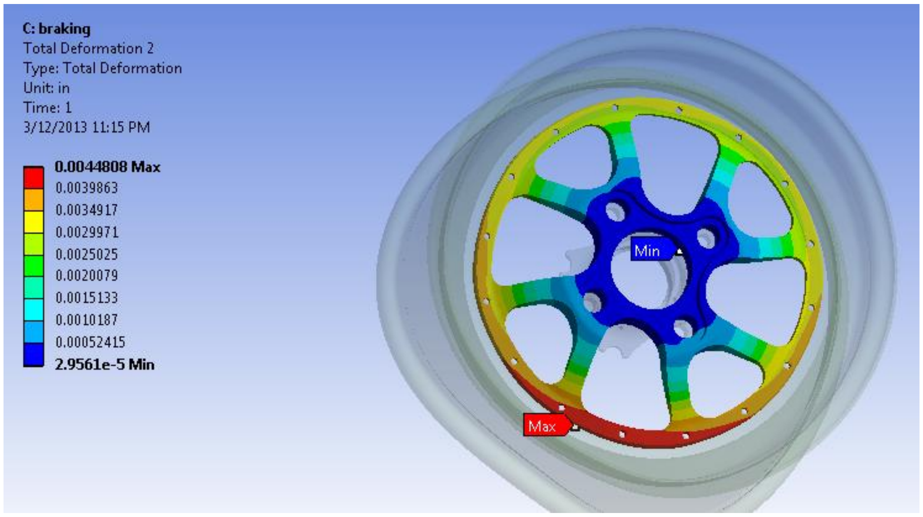

Figure 12 Deformation plot under braking load in existing wheel center

3.2.4.3 Result interpretation

The component needs to be strengthened for the lateral stiffness. Arms which connect the wheel center radially are the weakest points in the model. These areas should be strengthened. High stress points are found in the arms in both the scenarios. High stressed areas in wheel center are shown in figure 13.

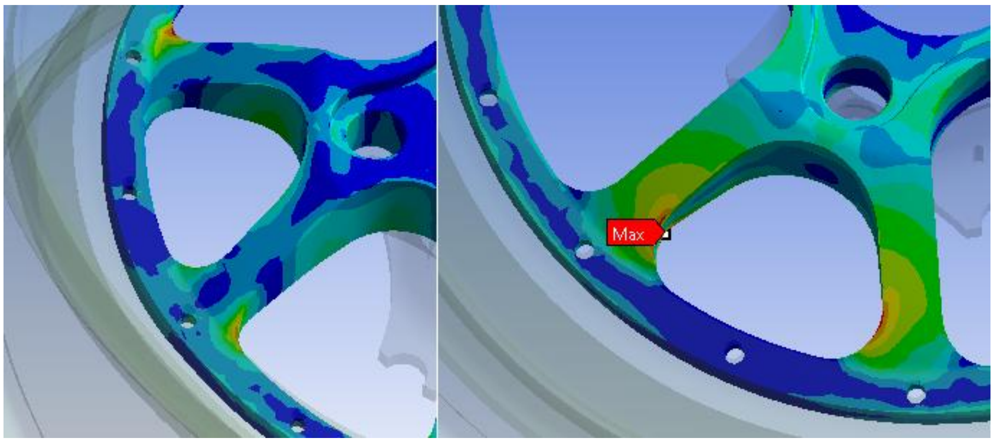

Figure 13 High stress areas in wheel center

3.3 Proposed design

The periphery of the wheel center is thin and it is connected by arms to the center. When the lateral load acts on the bottom edge of the wheel center it immediately bends because of the lack of rigidity. It is not supported by a solid section. The loading regions must be strengthened by adding material in these areas. The critical dimension for the proposed dimension is shown in figure 14.

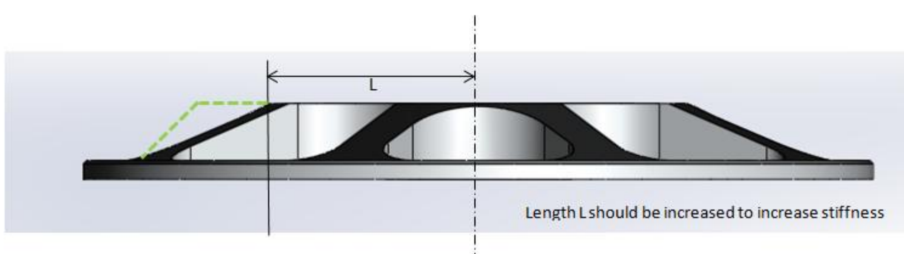

Figure 14 Stiffness increase section

Empty spaces between the patterns are not advisable. Compression molding process requires the part to have a minimum draft angle of 1.5 deg in the direction of pull. Thickness variation should be gradual. We cannot use a single charge to create the part at the present condition. We need to place multiple charges in the mold all along the arms and the center areas to process the part. The problem with using multiple charges is that the flow front of two charges will meet creating a low strength area. We have too many spaces and we are inviting too many flow front joining areas with the existing design. Instead we can use reduced thickness in these regions or create mash off regions which will be removed once the part is molded.

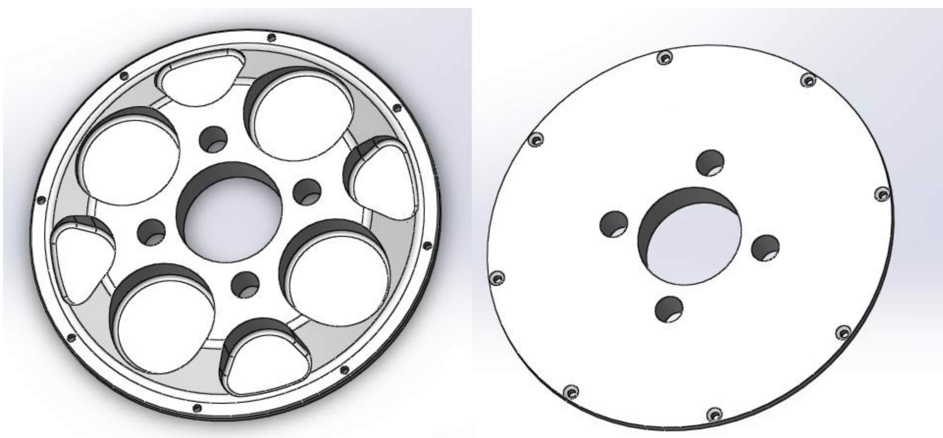

Figure 15 Proposed wheel center

Various design patterns are considered and analyzed for the stress values in the part for lateral load conditions. Above design was finalized because of the ease of simplicity in manufacturing and wider areas at the rivet intersection to provide better load transfer. Front and rear view of the proposed design is shown in figure 15.

3.4 Analysis of proposed design

Similar loading and analysis conditions are used for the proposed design analysis too. Proposed design promised over 20 % reduction in stress, deformation and weight than the current design. The results are shown in figures 16 - 19. Proposed design reduces the part weight by 24 %. It saves 1.84 lbs for the whole car. All three raw materials are analyzed for the lateral load condition and the results are tabulated in table 7. Lateral stiffness of the component is the prime deciding factor for the selection of raw material. Based on the values MS4A has got the minimum deformation in the part under the analysis. Selected MS4A raw material behaves in an isotropic fashion and hence isotropic properties are considered for analysis. Comparisons between the existing and proposed wheel center are shown in figure 20-22.

Table 7 Raw material comparison

Material	Stress (ksi)	Deformation (in)
MS1H	32.177	0.036
MS4A	30.452	0.0358
HexMC	25.112	0.045

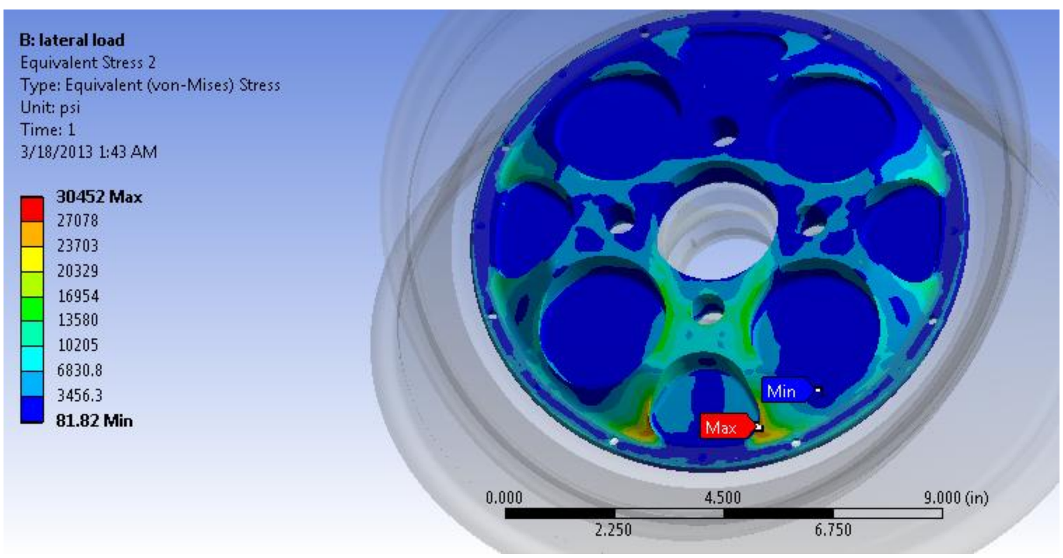

Figure 16 Stress plot for lateral load condition in proposed wheel center

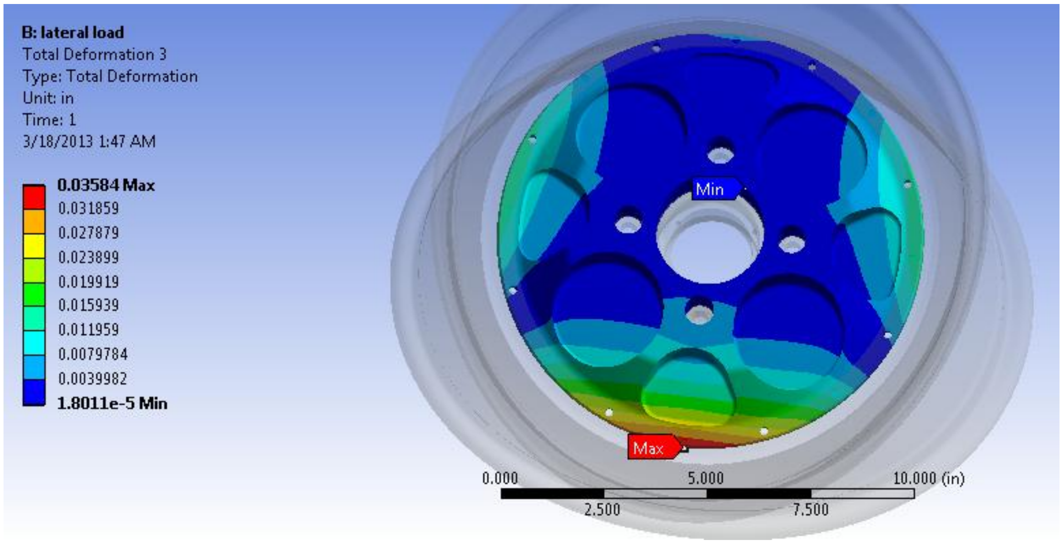

Figure 17 Deformation plot for lateral load condition in proposed wheel center

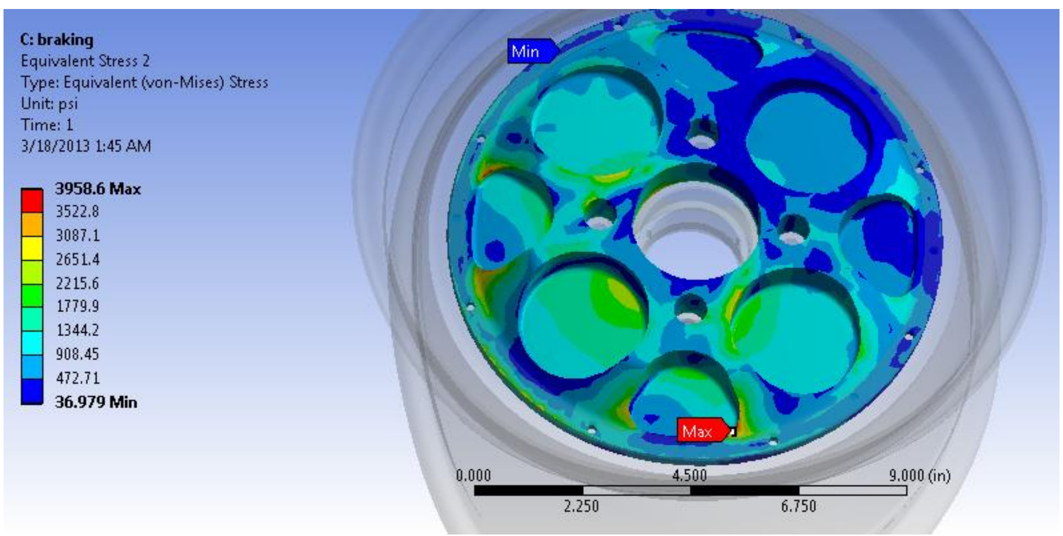

Figure 18 Stress plot for braking load in proposed wheel center

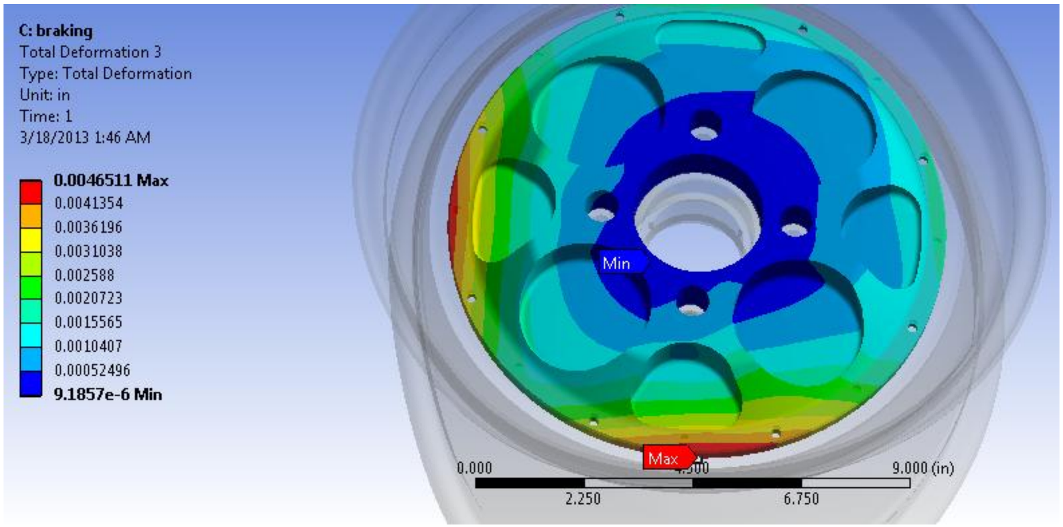

Figure 19 Deformation plot for braking load in proposed wheel center

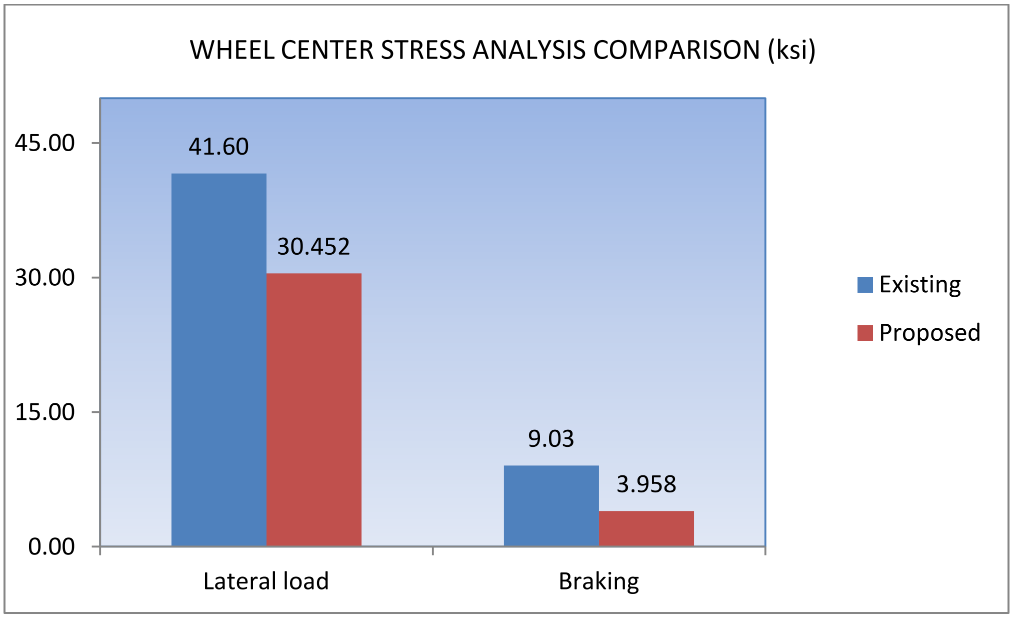

Figure 20 Wheel center stress comparison

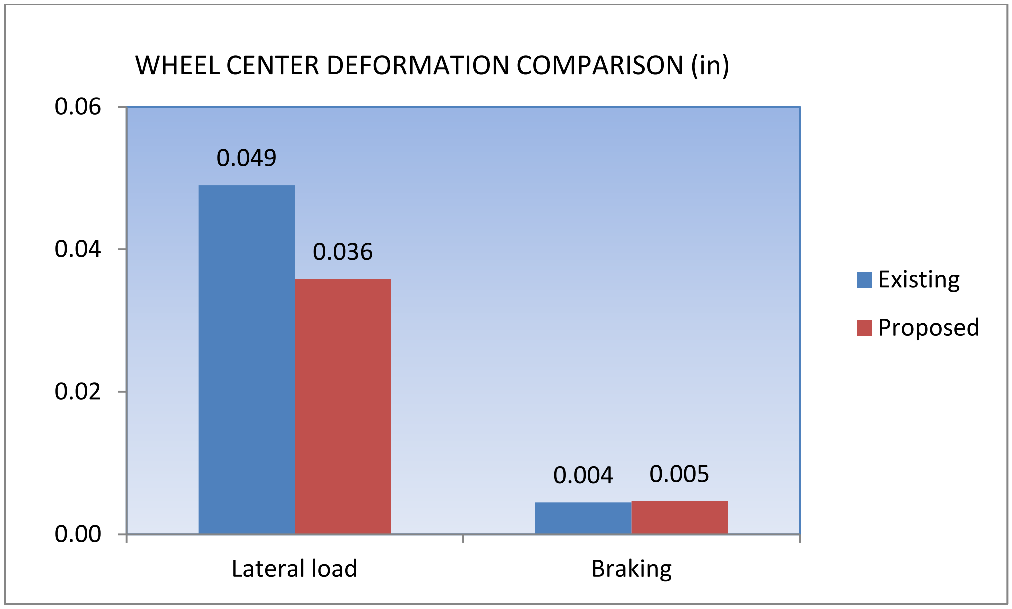

Figure 21 Wheel center deformation comparison

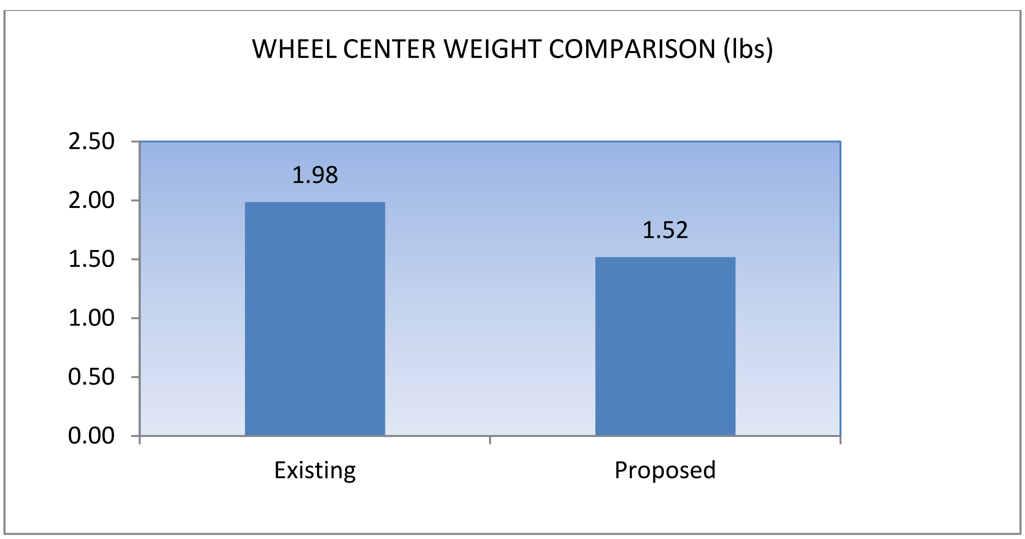

Figure 22 Wheel center weight comparison

3.5 Alternate design proposals

The mash off regions can be removed by additional machining operation. It will lead to reduce further weight at the expense of increased deformation values. Proposed design B is shown in figure 23 and the deformation plot for proposed design B in figure 24.

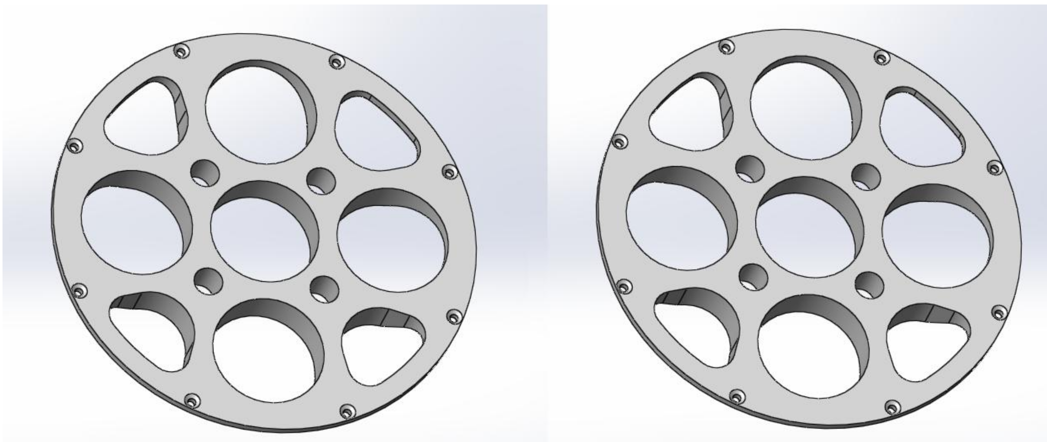

Figure 23 Proposed design B

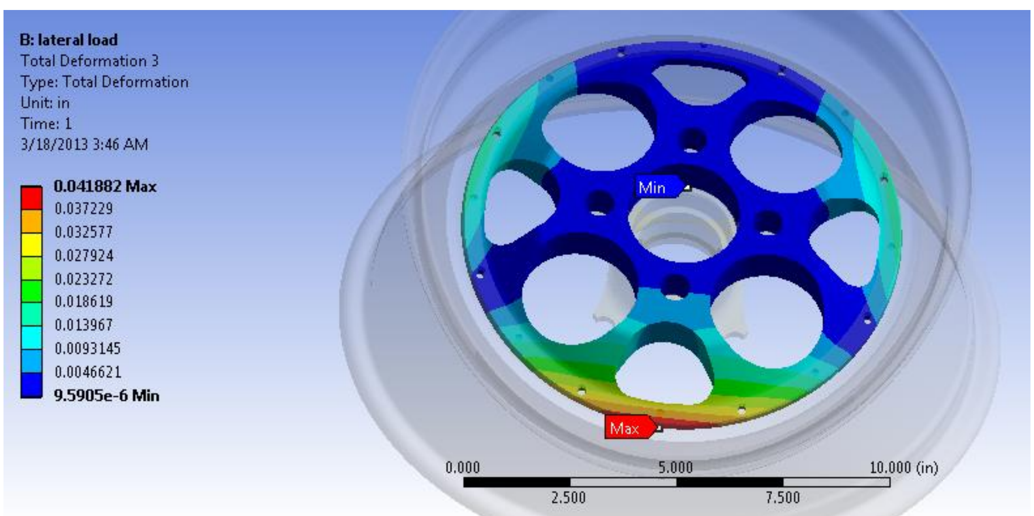

Figure 24 Deformation plot under lateral load in proposed design B

The analysis results and weight comparison of existing and the proposed designs are summarized in table 8-10. With additional weight reduction the percentage deformation reduction decreases.

Table 8 Stress comparison

Stress (ksi)	Lateral load	Braking	% reduction Lateral load	FOS Lateral load
Existing	41.598	9.034	-	0.96
Proposed 1	30.452	3.958	27%	1.48
Proposed 2	27.709	7.627	33%	1.62

Table 9 Deformation comparison

Deformation (in)	Lateral load	Braking	% reduction Lateral load
Existing	0.049	0.00448	
Proposed 1	0.0345	0.00447	30%
Proposed 2	0.0418	0.00603	15%

Table 10 Weight comparison

	Weight (lb)	% reduction
Existing	1.98	
Proposed 1	1.52	24%
Proposed 2	1.28	36%

CHAPTER 4

MOLD DESIGN AND PROCESS PARAMETERS IDENTIFICATION

Deriving process conditions for a defect free part is a skill which comes out by experience. Process conditions will be fine tuned each and every day until the desired quality is achieved. Compression molding process depends on various process conditions which need to be understood to get a desired part out of the process. Various influencing parameters are studied and configurations are finalized in accordance to our wheel center development.

4.1 Mold type

Molds designed for this process generally have a shear edge design. Two halves when closed will leave a small gap of the order of 0.5mm to 1mm between them closely moving together but never make contact. This will allow the air to escape and also provide the material to fill completely. Example of a shear edge design is shown in figure 25.

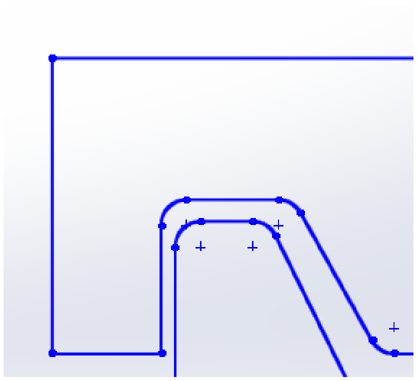

Figure 25 Mold shear edge design

4.2 Mold material

Compression molding process usually involves steel dies because of the large press pressures involved. Molds are internally heated by heating sources. Steel conducts heat at a lower rate. Nowadays aluminum molds are used for the process. The advantages of using aluminum are reduction in machining time of the mold, superior surface finish, less maintenance of the mold, free from corrosion and better heat transfer. Commonly used mold materials are P20 steel, S7 steel, Al QC7 aluminum and Al7075 aerospace grade aluminum. Comparison of the properties in terms of machining capabilities and thermal properties are tabulated in table 11.

Table 11 Mold materials properties comparison [15]

Mold materials	P20	Al QC 7	S7	Al 7075 T6
Features	Common mold steel with good fatigue abrasion and impact resistance	Developed for molds with higher strength, hardness and conductivity	Excellent toughness and high strength but lower wear resistance	High strength and corrosion resistance aircraft grade
Ultimate strength (ksi)	130	75	210	81.95
Modulus (msi)	29.73	10.5	30.02	10.5
Hardness Brinell	300	167	369	150
Cutting speed (ft/sec)	3.463	21.50	3.55	21.50
Volume machine rate (ft^3/h)	0.035	0.321	0.035	0.321
Thermal conductivity BTU ft/hr/ft^2/deg F	20	91	21	75.1
Specific heat (BTU/ lb deg F)	0.119	0.206	0.110	0.229
Density (lb/in^3)	0.283	0.101	0.282	0.102

Wheel center measures 10.5” in diameter. The mold size should be 15” in length and 14” in breadth and 2.5” thick. Aluminum is the preferred choice of the mold. Aluminum 6061 T6 grade alloy can be used for making the mold as the team gets the alloy through its sponsors.

Aluminum 6061 T6 is a heat treated aluminum alloy which stands next to Al 7075 in terms of strength.

4.3 Press pressure, Process temperature

Fiber content determines the mold closing force. Higher the fiber content, larger the force. Increase in fiber size also increases the mold closing force. The material should be squeezed and forced to flow inside the cavity. Large pressures are involved for doing this. During squeezing the entrapped air is forced out and leads to less void content in the part. Raw material selected for our process is MS 4A which is manufactured by Tencate YLA. They had fixed recommended curing pressure and temperature for this material to be followed to get a desired quality part. Recommended pressure for curing a MS 4A part is 2000 psi at 302 deg F [13].

4.4 Mold temperature

The mold is heated by a heating source which maintains a uniform temperature distribution in the mold. The charge absorbs heat from the mold and starts curing (resin starts flowing in the mold as the viscosity drops). Any variation in the temperature within the cavity will affect the part curing levels within the part. Certain areas will be fully cured and the other areas will be partially cured. Maintaining the temperature uniformly depends on heating system and temperature controllers. Thermocouples will be placed in the mold at desired areas where the temperature profile is highly important. The feedback signals from the thermocouples are fed back to the temperature controller and the controller adjusts the heater sources accordingly by switching it on and off based on the set point temperature.

4.4.1 Heating system

Heating system is embedded in the mold or sometimes in the platen which is attached to the press. Mold can be heated by a variety of sources. Oil, electric, water heating systems are available. Oil heating system and water heating system produces uniform temperature distribution in the mold but the capital investment is high and the maintenance is also high. On the other hand electric heating systems are low cost, less maintenance and easy to manage; the temperature distribution is not so uniform like oil heating system. But with the individual temperature controllers available today the heaters are controlled in zones splitted in the mold so that the change in temperature is kept less than 5 deg C (41deg F). Electric heaters will be the most feasible and economic option in terms of cost, maintenance etc. A study was made on the available electric heaters and their configuration availability in the market. For the detailed study refer Appendix F. Cartridge heaters was selected for the purpose among the various heaters available in the market. Cartridge heaters are cylindrical rod like heaters. Cartridge heaters are available under various lengths and watt densities. They are easy to place in the mold and heats up quickly.

Figure 26 Cartridge heaters [16]

It can be easily replaced in case of failure. It will provide uniform heating throughout the body. For deciding the wattage required per heater for heating the mold we need to calculate the heat required for the mold and charge to reach the processing temperature.

4.4.1.1 Wattage calculation

Mold is made of Al 6061 T6 alloy. Specific heat capacity and density are listed in the table. Heat capacity required for heating the mold is calculated and found to be 2.82 KW in 30 minutes without losses. Wattage required for charge material to be heated was found to be 0.09 KW without losses. Wattage calculations are tabulated in tables 12-14.

Table 12 Heat capacity required for heating the mold without losses

MOLD		
Mold material		Al 6061 T6
Material density	lb/in^3	0.098
Specific heat	BTU/lb ˚ f	0.214
No of halves		2
Mold length	in	15
Mold breadth	in	14
Mold thickness	in	2.5
Volume	in^3	525
Volume of the cavity (part profile)	in^3	28
Net volume	in^3	497.00
Mass /half	lb	48.46
Total mass	lb	96.92
Operating temperature	˚ f	302
Ambient temperature	˚ f	70
time required to heat up	hr	0.5
Wattage required for heat up	KW	2.82

Table 13 Heat capacity required for heating the charge

CHARGE MATERIAL		
Type		MS 4A
Mass	lb	1.51
Operating temperature	˚ f	302
Ambient temperature	˚ f	70
time required to heat up	hr	0.32
Wattage required for heatup	KW	0.09
Total wattage without heat losses		
Total wattage (A+C)	KW	2.91
Compensation factor	10%	0.29
Total wattage required	KW	3.20

Heat loss graphs are referred from a manufacturer's website [16]. Refer Appendix F for the graph. Heat loss from the side walls of the mold and from the top surface is included. Wattage lost due to convection heat loss is found to be 0.41 KW.

Table 14 Net heat capacity required after losses

Heat loss Mold		
Vertical surface area (four sides)	in^2	290
Heat loss from vertical surface at 150 deg c	W/ft^2	75
Heat loss from mold vertical surface	KW	0.15
Horizontal surface area top and bottom	in^2	420
Heat loss from horizontal surface surface at 150 deg c	W/ft^2	75
Heat loss from platen horizontal surface	KW	0.22
Total	KW	0.37
Compensation	10%	0.04
Total wattage losses	KW	0.41
Total wattage required after heat losses	KW	3.61
	W	3600

A total of 3600 W is required for heating up the mold along with the charge. Cartridge heaters of 12” in length and 0.5” in diameter will be used. Maximum of 8 heaters or 4 per mold can be used with the available mold space. Wattage required per heater is 450W. Watt density per heater is 23.88 W/in^2. Commercial available heaters come in variety of sizes and watt densities. Heater fittings can be screw mounted, NPT, L bend etc. The leads coming out of the heater has a number of options. Thermocouple can be embedded in the heater too. For our process 8 cartridge heaters of 450 W heat capacity and measuring 12” length 0.5” diameter with screw mounting and normal lead is selected.

4.4.1.2 Thermal simulation for heating system

Temperature distribution in the mold is an important consideration for curing of the part. Heaters are assembled in the mold which is designed from the proposed wheel center and analyzed for the temperature distribution in the cavity. SS 304 material is used for heaters and Al 6061 T6 for mold and each heater capacity used is 450W.

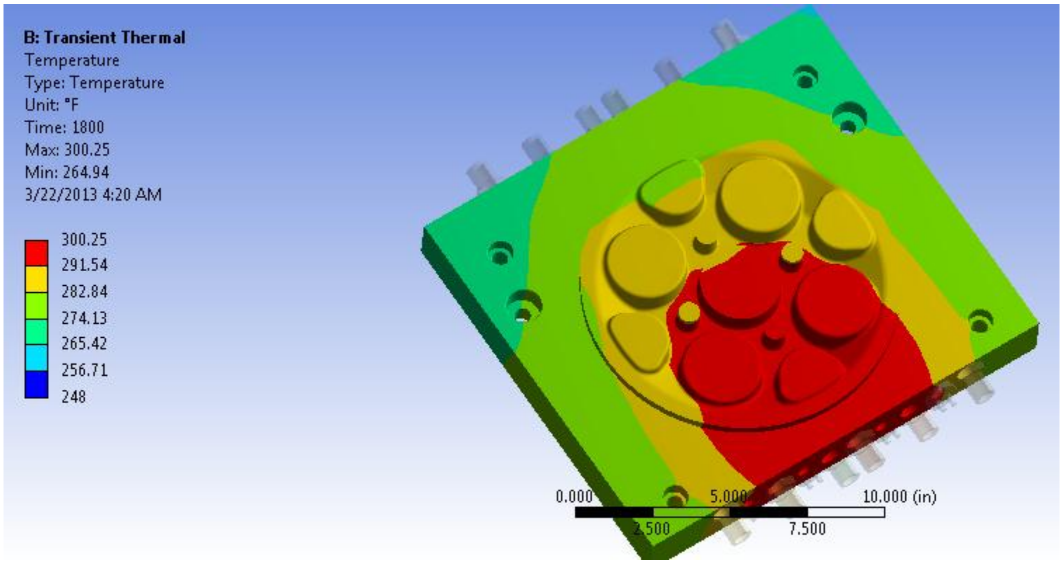

Figure 27 Top mold thermal distribution

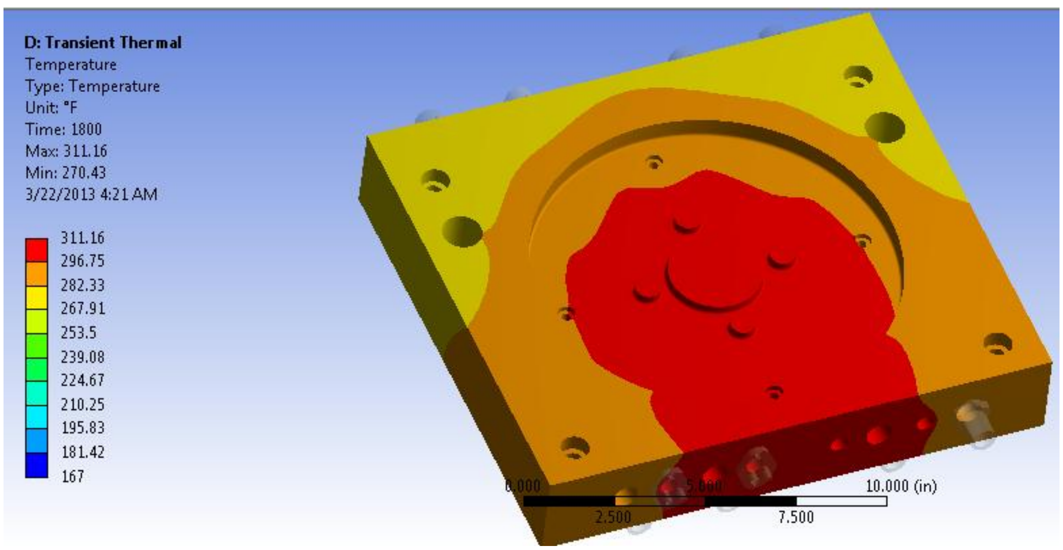

Figure 28 Bottom mold thermal distribution

Convection load is applied to the top and two sides in which the heaters are mounted. Static thermal analysis was done in Ansys. Maximum temperature variation of up to 10 deg C was found in the mold after 30 min. Thermal profiles for top and bottom molds are shown in figures

27-28. Initial charge covers up to 80% of the mold. They absorb the initial heat. Temperature uniformity in the mold coverage area is important rather than maintaining it for the entire cavity.

4.4.2 Cooling system

Charge curing involves two phases namely absorption of heat and liberation of heat during cross linking. Heating system provides the heat for absorption in order to reduce viscosity and start flowing. The heat liberated during the curing process is absorbed by the cooling channels which run in the mold which is placed in alternate fashion to the heaters. Unusual cooling will result in component warpage. Warpage is a critical issue in compression molding. Non- uniform temperature profiles will result in warping. Cooling system can be water cooled, oil cooled or by heat pipes. Oil heating system and water heating system can be reversed to cool the mold thus providing both the functions but requires machinery investment. Our process will include water cooled system. It will be circulated by water pressure which is connected to the normal water line. The outlet water will be fed to the drains. Cooling channels are made in the mold which circulates just like radiator design and the outlet water comes from the other side of the mold extracting heat from the mold. Cooling channels positions are analyzed to visualize the time required for the mold to cool from 150 deg C which is the curing temperature stated by the manufacturer. Molds are analyzed for various flow rates ranging from 0.5m/s to 3 m/s with increments of 0.5. It was observed that the time required varies between the top and bottom mold for a constant flow rate.

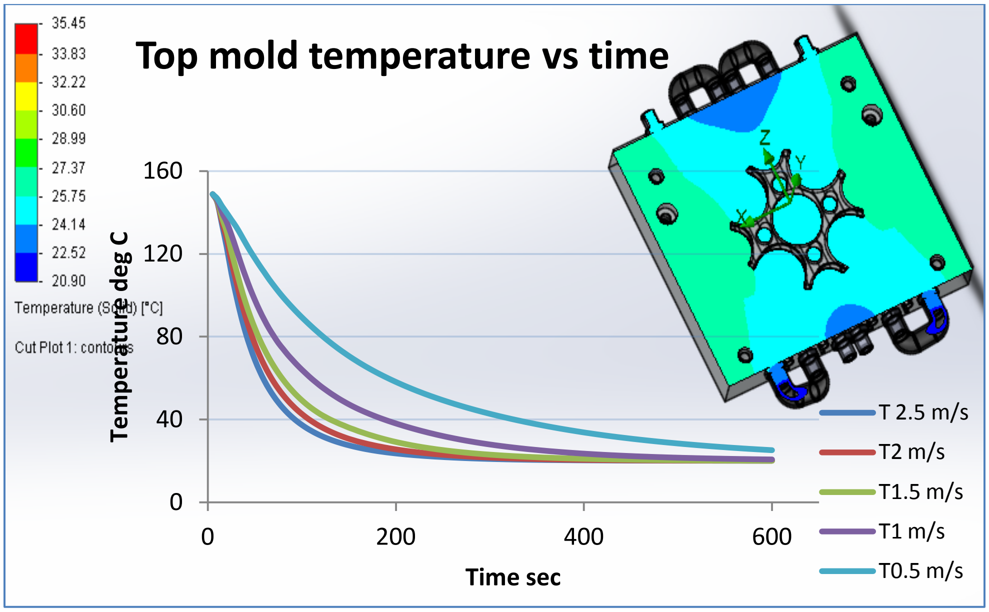

Figure 29 Top mold temperature variation with flow rate

In order to find a similar cooling curve for both the molds various flow rates are analyzed separately and the curves are plotted in figures 29-31. The closest curve between the top and bottom mold will yield an identical cooling between the top and bottom halves.

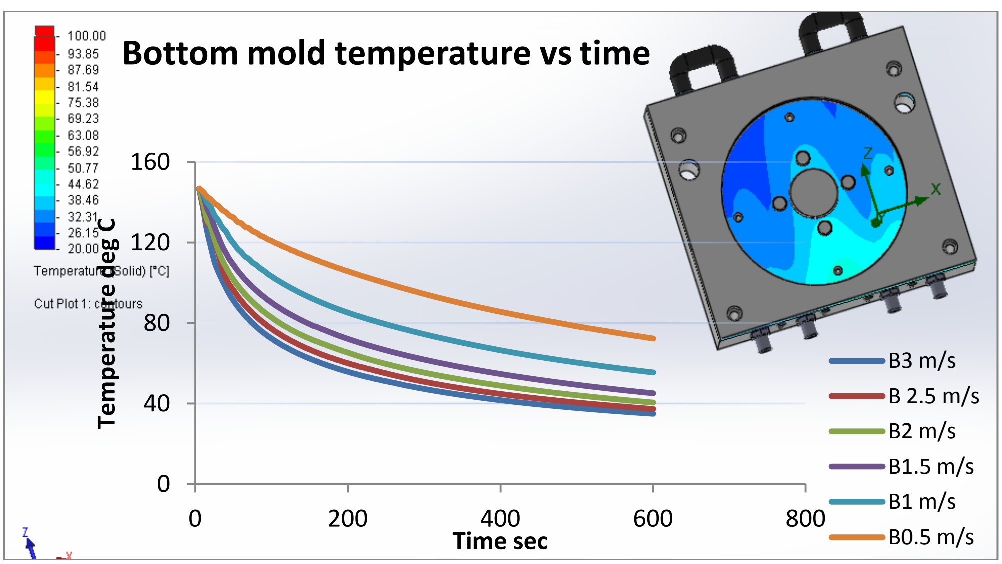

Figure 30 Bottom mold temperature variation with flow rate

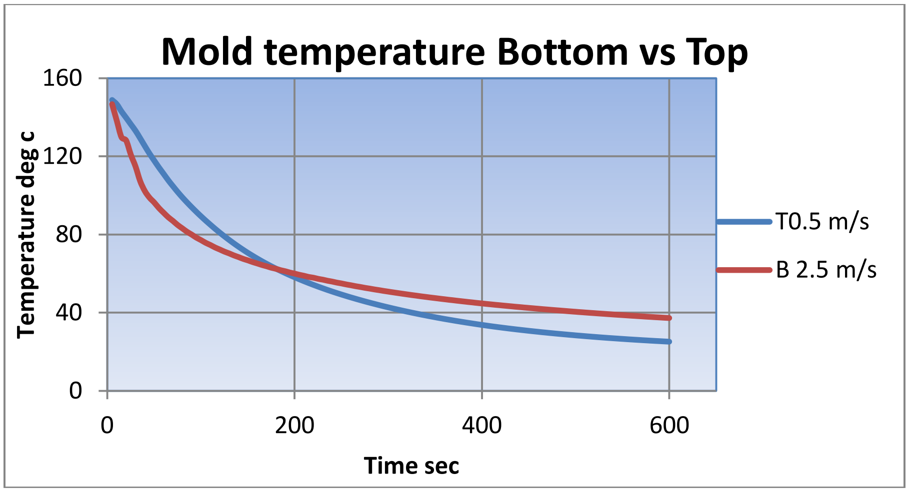

Figure 31 Mold temperature top and bottom

4.5 Mold Construction

The heating and cooling system in both the molds are analyzed for their position to produce effective heating and cooling uniformly in the mold. Guide pillars are assmebled in the top mold before clamping it in the press.The mold is clamped to the base plate or platen in the press through T slots and screws. The threaded couplings are fitted to the mold and then the heaters are placed. Bore size of the heaters is an important parameters to be achieved in machining of the mold. Gap between the heater and the bore determines the heat transfer. Close gaps of the order of 0.02 mm to be manintained. The top mold slides through the guide pillar and mates with the bottom mold ensuring a closed cavity. Parallelism of the molds is very important in ensuring uniform pressure application over the cavity and also the flash formation.

Part ejection is done by the ejector pin arrangement provided in the bottom mold. Ejector pins are placed in four locations. They can be activated by a pneumatic system.

Tonnage required for the process was found to be 85T with the proejcted area of 85 in^2 and press pressure of 2000psi. Recommended press parallelism is 0.001”/ft. Mold assmebly and exploded view of the top and bottom molds are shown in figures 32-35.

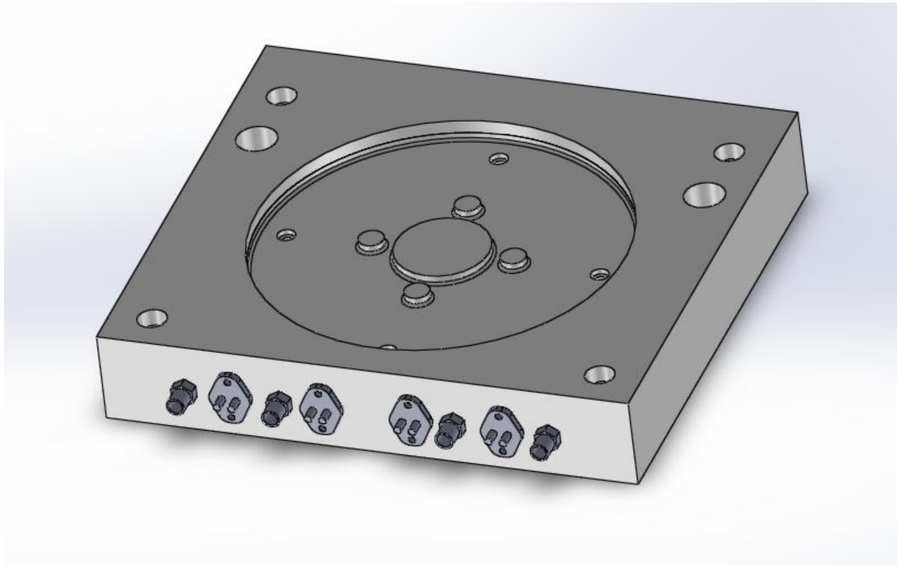

Figure 32 Top mold

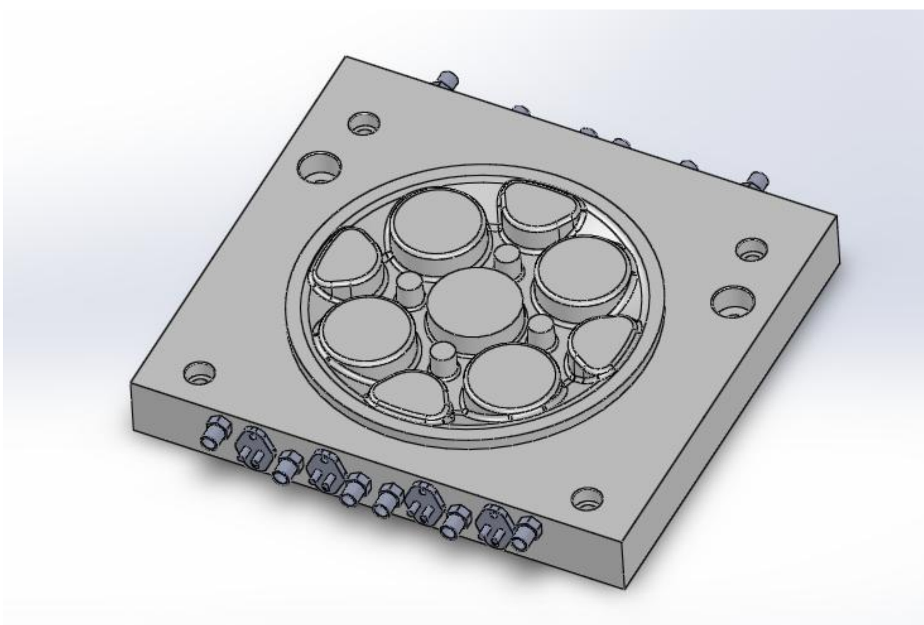

Figure 33 Bottom mold

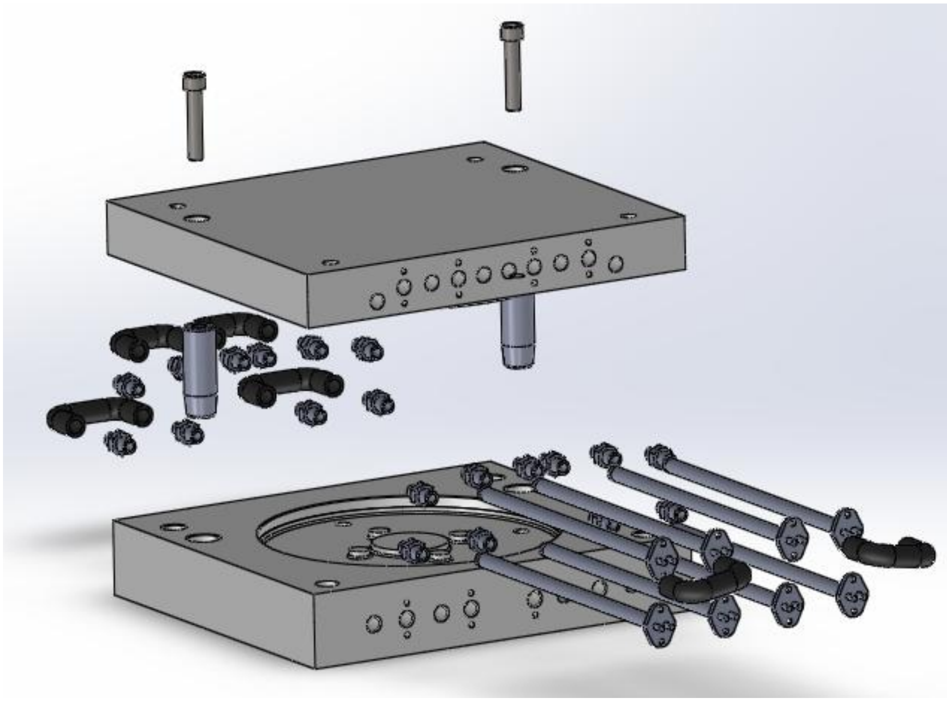

Figure 34 Mold exploded view

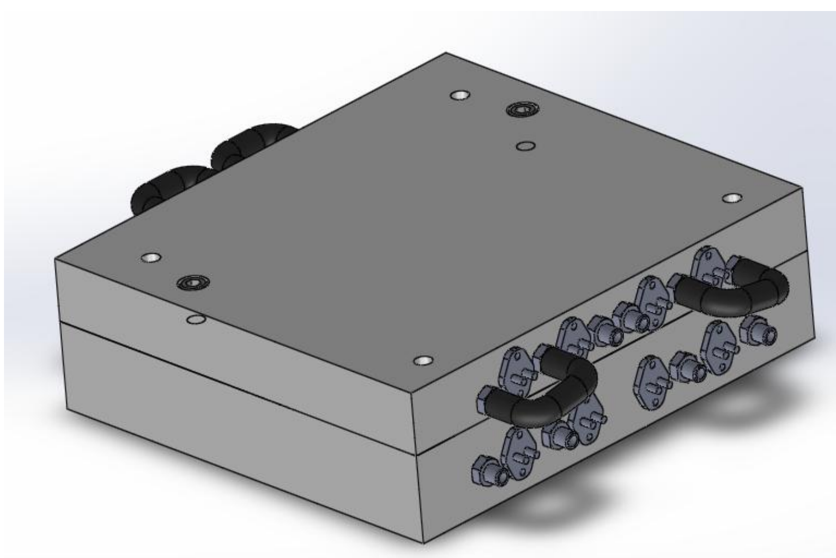

Figure 35 Mold assembled view

4.6 Press closing speed

Closing speed of the mold will affect the flow of the material. When the material gets heated up it softens (i.e., viscosity drops) and starts flowing in the cavity. At this point of time the mold should be closed as soon as possible. Flashes in the mold are controlled by the mold closing speed. Closing speed can be finalized by using trial and error method during process trials or using simulation.

4.7 Charge pattern

Charge pattern plays an important role in determining the properties in each section of the part. Sheet molding compounds also called as charge is placed in the mold. A single sheet cannot facilitate for the entire mold. Sheets should be cut and strategically placed in order to avoid knit lines (place where flow of two sheets meet) when they are cured. This will lead to less strength in that area. The knit lines should be predicted based on the charge pattern and should be offset to non critical areas as they cannot be avoided completely. Charge usually covers around 80% of the mold.

4.8 Process simulation study

Process simulation will help us understand the compression molding process better which will lead to better part design, mold design and process design. The cost incurred for preparing the mold is high because of the heating and cooling system requirements in the mold. Hence a process simulation will help us reduce costs greatly in mold design. Temperature distribution in the mold can be simulated and with respect to the temperature the curing of the charge varies in the mold. The flow characteristics of the charge depend on the part design, mold design, temperature distribution. The fibers will tend to flow during the cure along with the resin and it will be cured once it fills the cavity. The fiber orientation will be a critical parameter to be tested and that is done effortlessly by the process simulation. Fiber orientation model was developed by Folgar-Tucker [12]. Based on the fiber intensity the strength can be calculated and the structural analysis can be done based on the fiber orientations. Charge placement is another important aspect that requires a lot of trials to be decided when we manufacture the part. The trials can be done to simulate the effective filling and the optimum charge placement can be found. These are some of the advantages of the software process simulation.

4.9 Software

Compression molding process simulation is relatively new to industry. There are not too many players in the simulation industry market. Few software's are developed for the consulting purpose or for private use.

Cadpress (Madison group) [17]

Express (M Base) [18]

Passage (Technalysis) – Commercial version available [19]

Moldflow (Autodesk) [20]

Moldex3d – Commercial version launched in Mar 2013 [21]

CHAPTER 5

CONCLUSIONS AND FUTURE WORK

Three key areas influencing the compression molding process are studied and the systems are designed and process conditions are predicted through the wheel center part development. With the mold design and the associated systems in place manufacturing of the part can take place. The next step in the development is manufacturing and testing of the part. Some of defects which might be encountered during manufacturing are blisters, chipped edges, drag marks, fiber pull, flow lines etc. These defects can be avoided by close control in the process parameters. Troubleshooting of compression molding process for various defects which are found during the process was explained in detail by Davis [12].

In future the process simulation will play a key role in designing the part and mold. In future part developments by compression molding process, process simulation in addition to structural analysis can be done to evaluate the process variables.

APPENDIX A

LITERATURE REVIEW

Importance of composite parts and development of a carbon/epoxy structural part for a high performance vehicle was studied by Feraboli [22]. Fiber architecture, Failure modes, factors affecting strength are discussed in this paper. A fiber reinforced thermoset part development (engine valve cover) which is used in Daimler Chrysler 4.7L V8 engine was studied by Steve Crawford [23]. The development process and the importance of FEM simulation in the analysis of the part and process are explained. Flow simulation was done to simulate the mold filling to optimize the process.

Modulus measurement for prepreg based discontinuous fibers was studied by Paolo Feraboli [24]. Notched behavior for a discontinuous carbon fiber/epoxy system was done by Paolo Feraboli [25]. The elastic behavior and the failure response are studied. Comparison is made between a notched specimen and an unnotched specimen. Short fibers are notch insensitive is the key finding in this research study. Failure initiation in HexMC molded panels and the effect of defects was studied by Bruno Boursier [26]. The differences in failure initiation in both discontinuous and continuous fiber composites were discussed. Characteristics and influence of strength with respect to various attributes are studied by Paolo Feraboli [27]. The relationship between aspect ratio and tensile, compressive and flexural moduli and strengths are observed. Failure in these materials is mainly dominated by matrix rather than fibers were a key finding in this study.

A method of finding modulus value in discontinuous fiber molded panels was proposed by Paolo Feraboli [28]. Large modulus variations are observed in short fibers molded panels due to the heterogeneous nature of the material. In order to evaluate the modulus value of these types of panels a randomization process called Random Representative Volume Element (RRVE) algorithm was developed.

Forged composite technology which was demonstrated in Lamborghini and Callaway was discussed by Paolo Feraboli [29]. Development of control arms with discontinuous fibers was discussed. Design methodology, FEM analysis comparison, Material selection was discussed and compared with the current manufacturing process by Aluminum. Characterization and the mechanical properties of Callaway forged carbon fiber reinforced sheet molding compound was studied by Bradley Jones [30]. Panels were prepared and tensile strength, flexure strength values are measured and the variations are recorded for the test panel.

Molding parameters such as mold closing speed and mold temperature are studied for their effect in tensile and flexural properties by Ki-Taek Kim [31]. Surface roughness, tensile and three point bending tests were conducted on the molded parts. Fiber orientation and distribution in the molded parts were also investigated in this study.

Analysis and certification of discontinuous carbon fiber reinforced composite is difficult because it does not behave like unidirectional composites or isotropic materials. Panels made of HexMC are molded and the effects of material flow and material behavior are studied by Mark Tuttle [32]. The panels are tested for tensile strength and the results were discussed.

Manufacturing a part by various processes and by various available materials that is available for composites processing and the costs involved are compared by Michael G Bader [33]. Importance of computer aided engineering CAE in compression molding process simulation was demonstrated by Antoine Rios [34]. The effect of flow pattern, temperature and curing will affect the properties of the part. Warpage simulation, residual stress analysis is done in order to optimize the design at the development stage. The mechanism by which the sink marks occur in the compression molded parts are studied by Tsuneo Hirai [35] and methods to minimize the sink mark formation is developed.

Reasons for poor surface quality in compression molded parts was studied and the parameters was found and parameterized compression molding process was performed with Design of Experiments approach to find the influence of the parameters in the surface quality of the parts by N E Jimmy Olsson [36].

Dodge viper demonstrated the usage of carbon fiber SMC in large volume for the first time. Carbon fiber SMC is used in right and left fender systems and for stiffening in windshield support along with fiber glass SMC. Development process of the carbon composite molded parts was studied by Mark Bruderick [37].

Numerical simulation of the compression molding process was compared with a simulation of a thermoset sample by Sejin Han [38]. Comparison results include flow pattern, fiber orientation, fiber length distribution and curing of the resin. Comparison yields reasonable agreement between the experiment and simulation.

Importance of chopped prepregs was studied by jack D Fudge [39]. Characteristics, advantages of chopped prepregs in comparison with normal unidirectional prepreg and aluminum is included and validated for the cost impact between them. Effect of reinforcement type and length in the properties of the part was studied by Sarah Boylan [41]. Comparison include usage of various sizes of glass fibers and carbon fibers and the effect on properties and surface quality of the molded part.

The essential guidelines for a high volume compression molded carbon epoxy part was studied by Donald M. Lasell [42].

APPENDIX B

THERMOSET MANUFACTURING PROCESSES REVIEW

Thermoset composites are more rigid and suitable for high strength applications than thermoplastic composites. Thermoset composites occupy a major portion of the composite market. They comprise around 75% of the total composite market. Processes used for thermoset composites are more established and it's used in variety of industries. Thermoset composites are used in aerospace, automotive, sporting and commercial applications. We are limiting our study on the various manufacturing methods available for thermoset composites.

Prepreg layup process

Process description: Prepreg layup is a type of hand layup process. Prepreg sheets are nothing but resin impregnated sheets. Process sequence include placing the prepreg sheets in the mold in desired pattern to achieve desired fiber orientation, vacuum bag the entire mold setup, place the setup in the autoclave under monitored pressure and temperature.

Process parameter: Labor skill

Advantages: High fiber volume fraction can be achieved, minimum tooling requirement and suitable for low volume industries.

Applications: Big parts used for aircraft structures are primarily manufactured by prepreg layup because of the high fiber volume fraction requirement which is related to the strength. Applications include large aircraft structures, yachts and sporting goods.

Challenge: achieving desired orientation, maintaining low void content.

Disadvantages: high lead time, labor intensive process.

Wet layup process

Process description: It is a hand layup process. Curing is done under normal room temperature. Resin is applied to the mold and then the reinforcements are added over to the mold and compacted by a roller until it is impregnated by a resin. This process is repeated until the desired thickness is achieved.

Process parameters: Operator skill

Advantages: simplicity and less expensive.

Applications: manufacture of boats, yachts in the marine industry.

Challenges: achieving part consistency, fiber volume fraction control

Disadvantages: High labor skill dependency, low productivity, High styrene emission

Spray layup process

Process description: Spray layup process differs from wet layup process in the method of application of fibers and resin over the mold. An air gun is used which is fed with continuous roving's of fibers and the fibers are chopped and immersed in the resin and sprayed over the mold. Chopping and impregnation with resin is done in the spray gun. Compaction to remove air bubbles is done by rollers.

Process parameters: Operator skill and spray pattern.

Advantages: less expensive, relatively simple process, suitable for low volume and large non structural items.

Applications: Bathtubs, storage tanks, swimming pools

Challenges: Achieving uniform density of fiber is difficult.

Disadvantages: Suitable for low volume and non structural applications.

Filament winding process

Process description: Filament winding process is suitable for producing tubular structures. Continuous roving's of fibers are wound over rotating mandrel after immersing the fiber over resin. By adjusting the motion of tail stock and rotational speed of mandrel the desired fiber orientation angle is achieved. Curing can be done at room temperature and also under heated ovens. Filament winding process is the only available process for making pressure vessels. Tooling cost is less and the mandrels used are relatively inexpensive.

Process parameters: Motion of tailstock, speed of mandrel and fiber tension

Advantages: Use of cheap raw material such as fiber roving's, high volume production, desires fiber angle can be achieved by CAM control, independent of operator skill

Applications: Tubes, fishing rods, golf equipments, pressure vessel

Challenges: Achieving small fiber angles, controlling the fiber volume fraction.

Disadvantages: Limited to only tubular structures, Investment in the form of machinery and automated software for controlling the fiber orientations are required

<u>Pultrusion Process</u>

Process description: Pultrusion process is mainly suitable to produce constant cross section parts. Roving's of fibers are immersed in a resin bath and pulled through a steel die with the impression of the final part shape. Curing is almost done when the part comes out of the die as the dies are heated.

Process parameters: Resin impregnation, Steel dies heating, Part shape

Advantages: High volume production, can be automated, utilization of cheap raw material such as fiber rovings

Applications: constant cross section parts such as channels, bars etc

Challenges: Achieving fiber angle.

Disadvantages: Suitable for only constant cross section, High tolerances cannot be achieved, surface texture is not smooth, thin walled parts cannot be processed

<u>Resin Transfer Molding</u>

Process description: Resin transfer molding is suitable for manufacturing high strength parts at moderate volumes. Process includes layup of a preform in the mold and then the mold is closed and the resin is forced into mold under pressure to wet out the fabric. The resin impregnates the fabric and starts curing. After certain period of time depending on the part geometry the mold is opened to take out the part. Preform can be conformal mats, or fabric. Tooling is inexpensive when compared to injection and compression molding.

Process parameters: Resin infusion

Advantages: High strength parts can be made, suitable for moderate volumes, less expensive tooling as the processing pressure is low, better surface finish as the mold is closed and High tolerances can be achieved

Applications: bicycle frames, windmill blades, sports car bodies, automotive panels

Challenges: achieving uniform resin infusion, avoiding dry areas

Disadvantages: Good knowledge about resin transfer is required which includes simulation model of the resin infusion, tooling expensive than hand layup process

<u>Structural reaction Injection molding</u>

Process description: This process is derived from RTM. The main difference is the method of application of resin. In this method the two resins are forced to mix at high velocity and pressure on a separate chamber and the mixed resins are forced into the mold at low pressure. A preform is already placed in the mold which is made of short fibers. The resin impregnates the preform and the curing starts. The cross linking is quick in this process as the resin is allowed to mix at high pressures.

Process parameters: resin mixing and injection into the mold

Advantages: High volume production, high strength parts can be made, automated process for better results

Applications: Used in automotive industry where high volume and low cycle time are required.

Challenges: Fibers wash away while resin is injected

Disadvantages: Requires large investment in the form of tools, high fiber volume fraction cannot be achieved.

Compression molding

Process description: Sheet molding compounds are cut to defined shapes and placed in a heated mold. The mold is closed and the material is allowed to flow in the cavity, because of the viscosity drop by the absorption of heat from the mold. Once the curing is done the mold is unclamped and the part is removed. Steel tools are used because of the high pressures involved in the process.

Process parameters: Mold filling, mold temperature, mold closing speed, pressure, charge placement

Advantages: High volume production, less labor dependency, high intricate shapes can be produced, good dimensional tolerance

Applications: panels, spoilers, doors hoods

Challenges: mold filling

Disadvantages: High initial investment in the form of tooling, high strength parts cannot be made, reinforcements required.

Roll wrapping

Process description: It is similar to prepreg layup but the prepreg mats are rolled over by mandrels and a shrink wrap is made and it is allowed to cure. Once the curing is completed the mandrel can be withdrawn and the part is taken out. It is suitable for producing cylindrical tubes. Tooling is inexpensive.

Process parameters: Operator skill in rolling the mandrel with uniform pressure and squeezing the entrapped air

Advantages: high volume production, less expensive tooling, high fiber volume fraction, highly suitable for thin and tapered cross sections

Applications: golf shafts, fishing rods

Challenges: reducing voids, surface quality

Disadvantages: Limited to tubular structures and thick composite parts cannot be made

Injection Molding

Process description: Injection molding is one of the most commonly used process in the industry because of its advantages and productivity. Bulk molding compound is used as raw material which is available in the form of pellets. Pellets are loaded in a hopper and it is propelled through a chamber by a rotating screw. The injection chamber is heated so that the mixture viscosity is reduced before injecting it into mold. Then it is injected to the mold at high speed by a plunger. Because of the high processing pressures high strength tools are required

Process parameters: plunger speed, temperature of the feed chamber, Mold closing pressure

Advantages: high volume production, good dimensional stability,

Applications: small appliances, motor housings, electrical fuses

Challenges: mold flow design

Disadvantages: High investment in tooling, fiber breakage during injection

Manufacturing Process Selection Criteria

Process	Production Speed	Cost	Strength	Size	Shape	Raw Material
Filament winding	Slow to fast	Low to high	High	Small to large	Cylindrical and axisymmetric	Continuous fibers with epoxy and polyester resins
Pultrusion	Fast	Low to medium	High (along longitudinal direction)	No restriction on length; small to medium size cross-section	Constant cross-section	Continuous fibers, usually with polyester and vinylester resins
Hand lay-up	Slow	High	High	Small to large	Simple to complex	Prepreg and fabric with epoxy resin
Wet lay-up	Slow	Medium	Medium to high	Medium to large	Simple to complex	Fabric/mat with polyester and epoxy resins
Spray-up	Medium to fast	Low	Low	Small to medium	Simple to complex	Short fiber with catalyzed resin
RTM	Medium	Low to medium	Medium	Small to medium	Simple to complex	Preform and fabric with vinylester and epoxy
SRIM	Fast	Low	Medium	Small to medium	Simple to complex	Fabric or preform with polyisocyanurate resin
Compression molding	Fast	Low	Medium	Small to medium	Simple to complex	Molded compound (e.g., SMC, BMC)
Stamping	Fast	Medium	Medium	Medium	Simple to contoured	Fabric impregnated with thermoplastic (tape)
Injection molding	Fast	Low	Low to medium	Small	Complex	Pallets (short fiber with thermoplastic)
Roll wrapping	Medium to fast	Low to medium	High	Small to medium	Tubular	Prepregs

Figure 36 Manufacturing process selection criteria [1]

APPENDIX C

SHEET MOLDING COMPOUND

Table 15 SMC study comparison [6,7]

Manufacturer	Hexcel	Quantum Composites							
Properties/Material name	HexMC® / C / 2000 / M77	AMC8590 HT	AMC 8590	AMC8592	AMC8593	AMC8593 HT	Lytex 4149	Lytex 4181	Lytex 4197
Type	carbon epoxy	carbon vinyl ester	carbon vinyl ester	carbon vinyl ester	carbon vinyl ester	carbon vinyl ester	carbon epoxy	carbon epoxy	carbon epoxy
Material Density lb/in^3	0.056	0.053	0.053	0.053	0.053	0.052	0.053	0.053	0.053
Fiber Length in	2	1	1	2	1	1	1	1	2
fiber width in	0.31	NA	NA	NA	NA	NA	NA	NA	NA
Fiber Volume %	Up to 57	53	53	53	50	50	55	55	55
Cure temp °F	302	259-309	259-309	259-309	259-309	259-309	280-329	280-329	280-329
Cure time min	3	5 to 10	5 to 10	5 to 10	5 to 10	5 to 10	5 to 10	5 to 10	5 to 10
Tensile strength ksi	44	40	40	55	61	40	42	25	42
Tensile modulus msi	38	10	9	10	9.5	10	8	7.8	11
Compression strength ksi	42	NA	NA	NA	NA	NA	40	0	0
Compressive modulus msi	38	NA	NA	NA	NA	NA	4.6	NA	NA
Flexural strength Ksi	73	82	90	92	115	82	89	70	107
Flexural modulus msi	30	5.9	5.2	4.7	6.5	6.2	5	5.5	7.2
Shelf life at room temp weeks	6	8	8	8	8	8	NA	NA	NA
Shelf life at 0 °F	18 months	NA	NA	NA	NA	NA	6 months	6 months	6 months
Press pressure psi	725-2175	NA	NA	NA	NA	NA	NA	NA	NA
NA - Data not available									

Table 16 SMC study [8]

Manufacturer	Tencate						
Properties/Material name	MS 1A	MS 1D	MS 1H	MS 2D	MS 4A	MS 4H	MS 4F
Type	carbon epoxy	carbon epoxy	carbon epoxy	carbon epoxy	carbon epoxy	carbon epoxy	carbon cyanate ester
Material Density lb/in^3	0.056	0.062	0.055	0.061	0.054	0.055	0.054
Fiber Length in	1	25	1	25	1	1	1
fiber width in	0.13	NA	0.13	0.13	0.13	0.13	0.13
Fiber Volume %	52	52	52	52	52	52	52
Cure temp °F	280-309	138 -154	280-309	138 -154	280-309	280-309	325-365
Cure time min	30	30	30	30	30	30	50
Tensile strength ksi	42	28	37	28	45	44	45
Tensile modulus msi	19	19	10	19	9	6.2	7
Compression strength ksi	41	26	33	19	52	48	42
Compressive modulus msi	16	19	9	20	8	7.3	7
Flexural strength Ksi	67	50	64	64	93	109	90
Flexural modulus msi	13	13	10	10	7	9.3	7
Shelf life at room temp	NA	NA	NA	NA	NA	NA	NA
Shelf life at 0 °F	6 months	6 months	6 months	6 months	6 months	6 months	6 months
Press pressure psi	2000	2000	2000	2000 psi	2000	2000	2000
NA - Data not available							

APPENDIX D

ANALYSIS SETTINGS AND DESIGN PATTERN

Material conditions

Table 17 Material properties table

Properties	Units	Al 6061 T6	Al alloy	Carbon epoxy
Density	lb / in^3	0.097	0.0975	0.054
Young's modulus	msi	10	10.297	8.357
Poisson ratio		0.33	0.33	0.3
Parts		Wheel hub, existing wheel center	Wheel rim	Proposed wheel center

Loading conditions

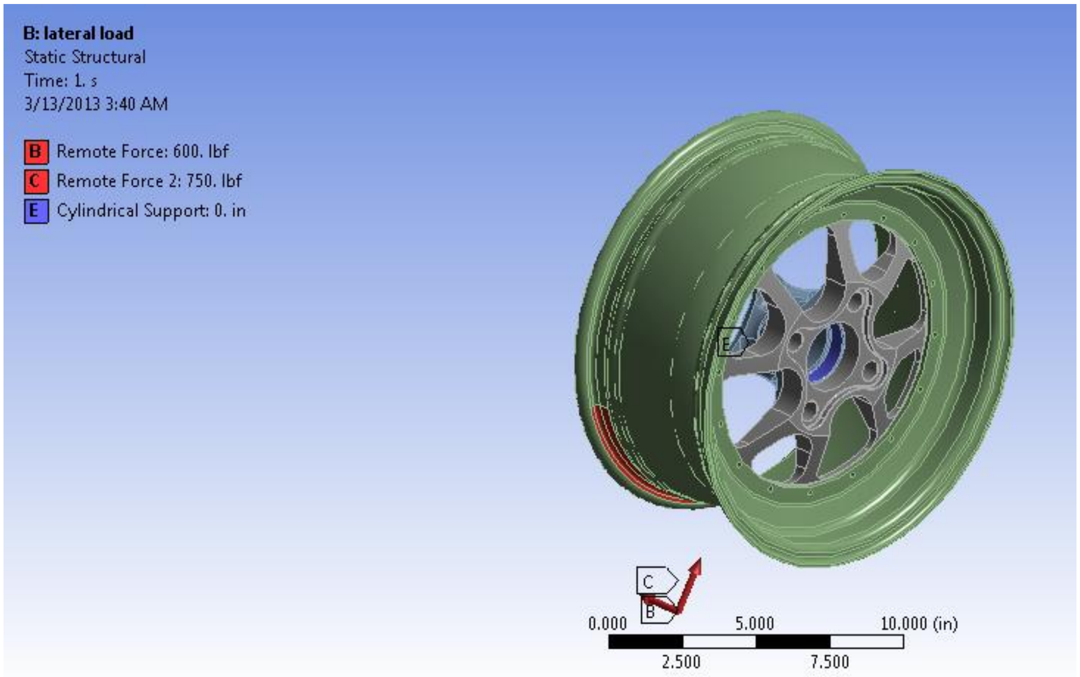

Figure 37 Analysis settings for lateral load conditions

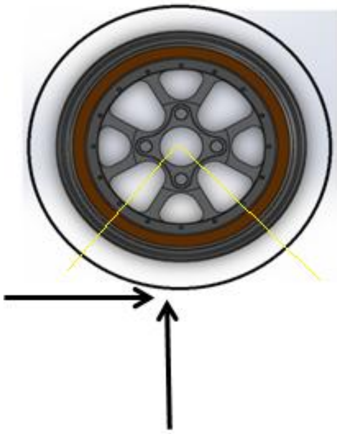

Figure 38 Loading section

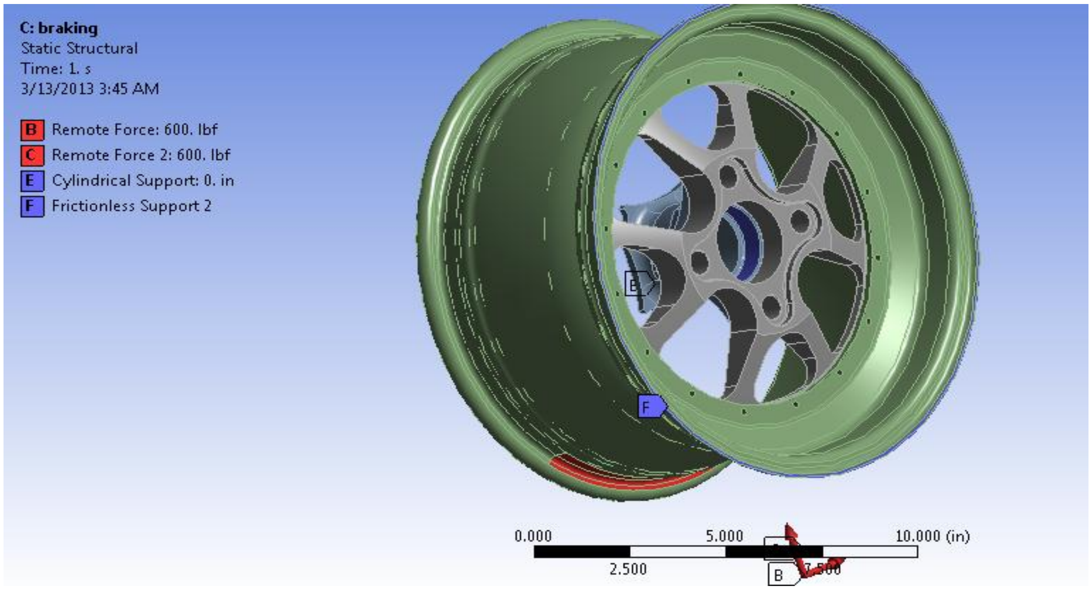

Figure 39 Analysis settings for braking load condition

Table 18 Mesh settings

Global mesh controls	
Relevance	Medium
Smoothing	Medium
Transition	Fast
Span angle center	Medium

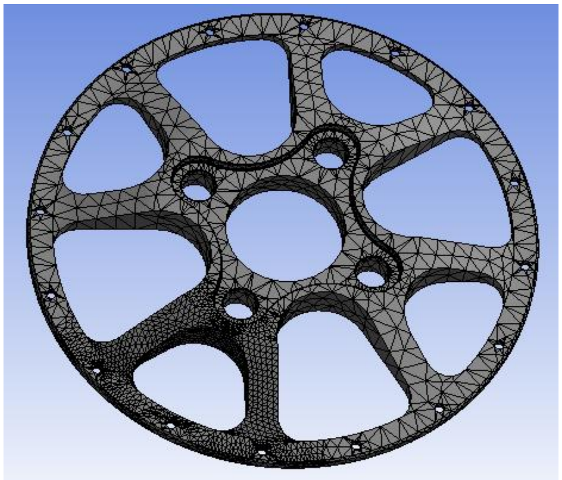

Figure 40 Mesh model

Table 19 Solution convergence

Elements	Equiv Stress (ksi)	Change %
51831	36.424	
60157	38.935	6.894%
70013	41.098	5.555%
93733	41.598	1.217%

Table 20 Lateral load stress values comparison

Stress (ksi)	Lateral load		Braking	
	Normal	45 deg	Normal	45 deg
Existing	41.598	39.417	9.034	8.835
Proposed 1	30.452	28.604	3.958	6.049
Proposed 2	28.472	21.492	7.792	5.863

Table 21 Lateral load deformation values comparison all cases

Deformation (in)	Lateral load		Braking	
	Normal	45 deg	Normal	45 deg
Existing	0.049	0.0504	0.00448	0.00441
Proposed 1	0.0358	0.0338	0.0047	0.0055
Proposed 2	0.0402	0.03912	0.00579	0.00568

Figure 41 Design patterns

APPENDIX E

ENGINEERING DRAWING

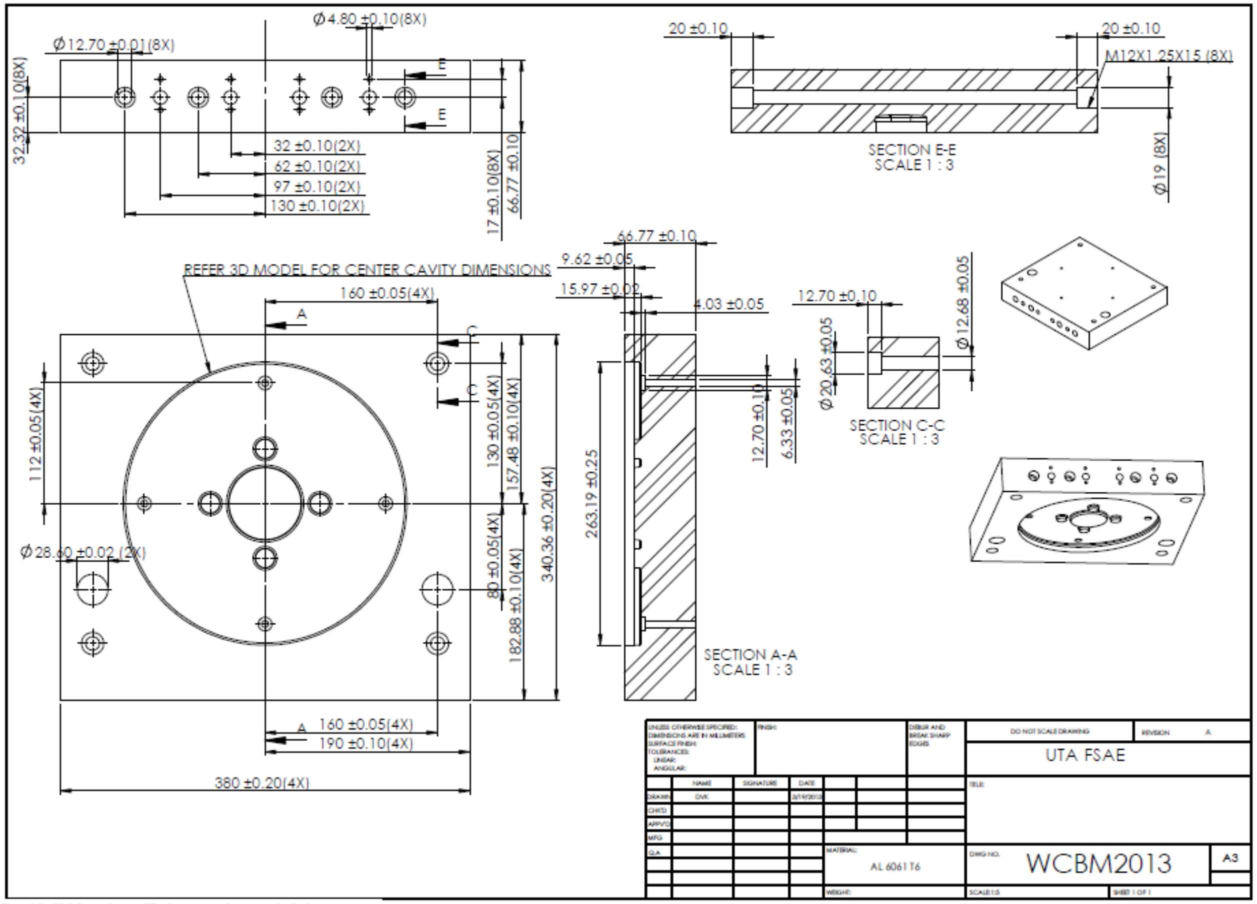

Figure 42 Bottom mold drawing

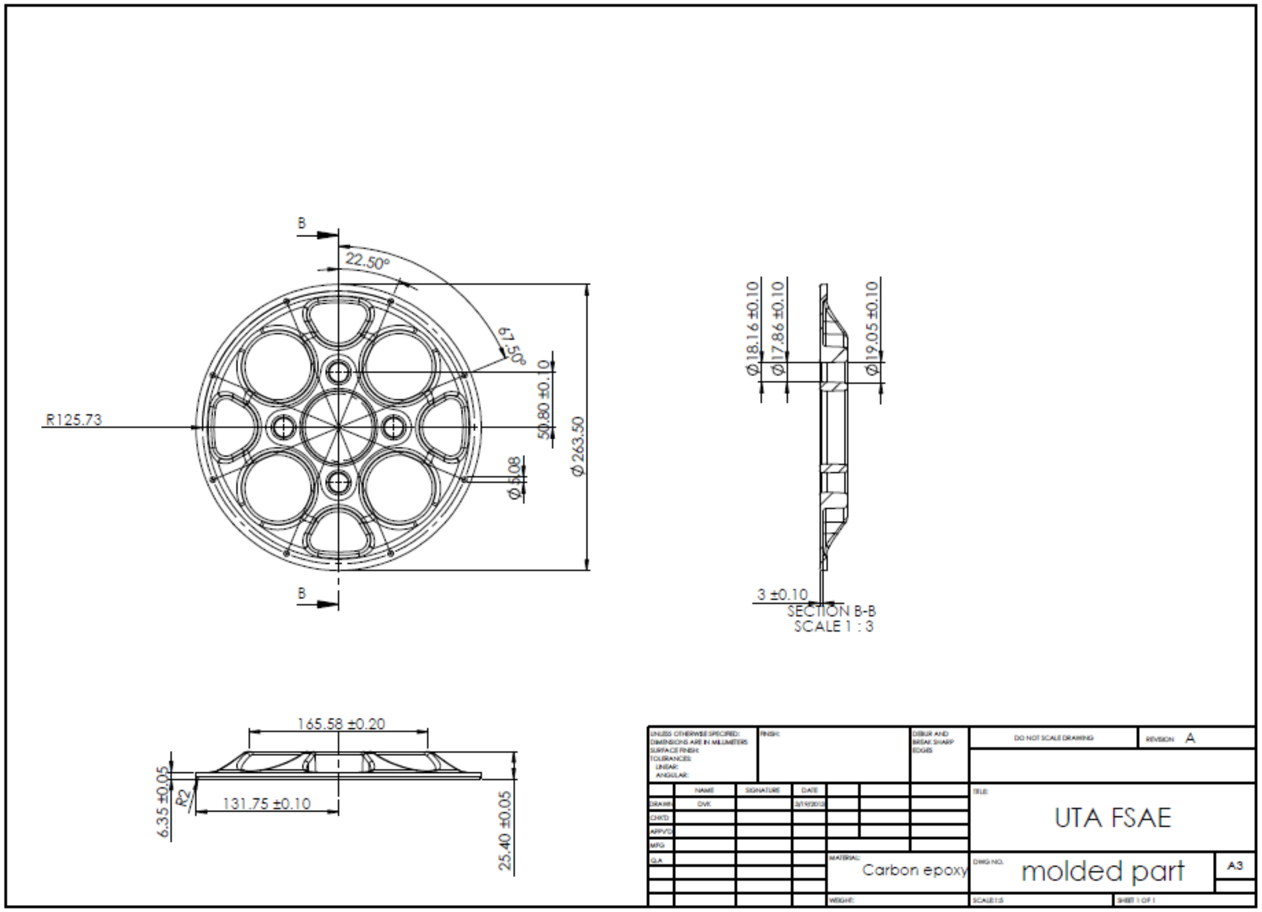

Figure 43 Molded wheel center

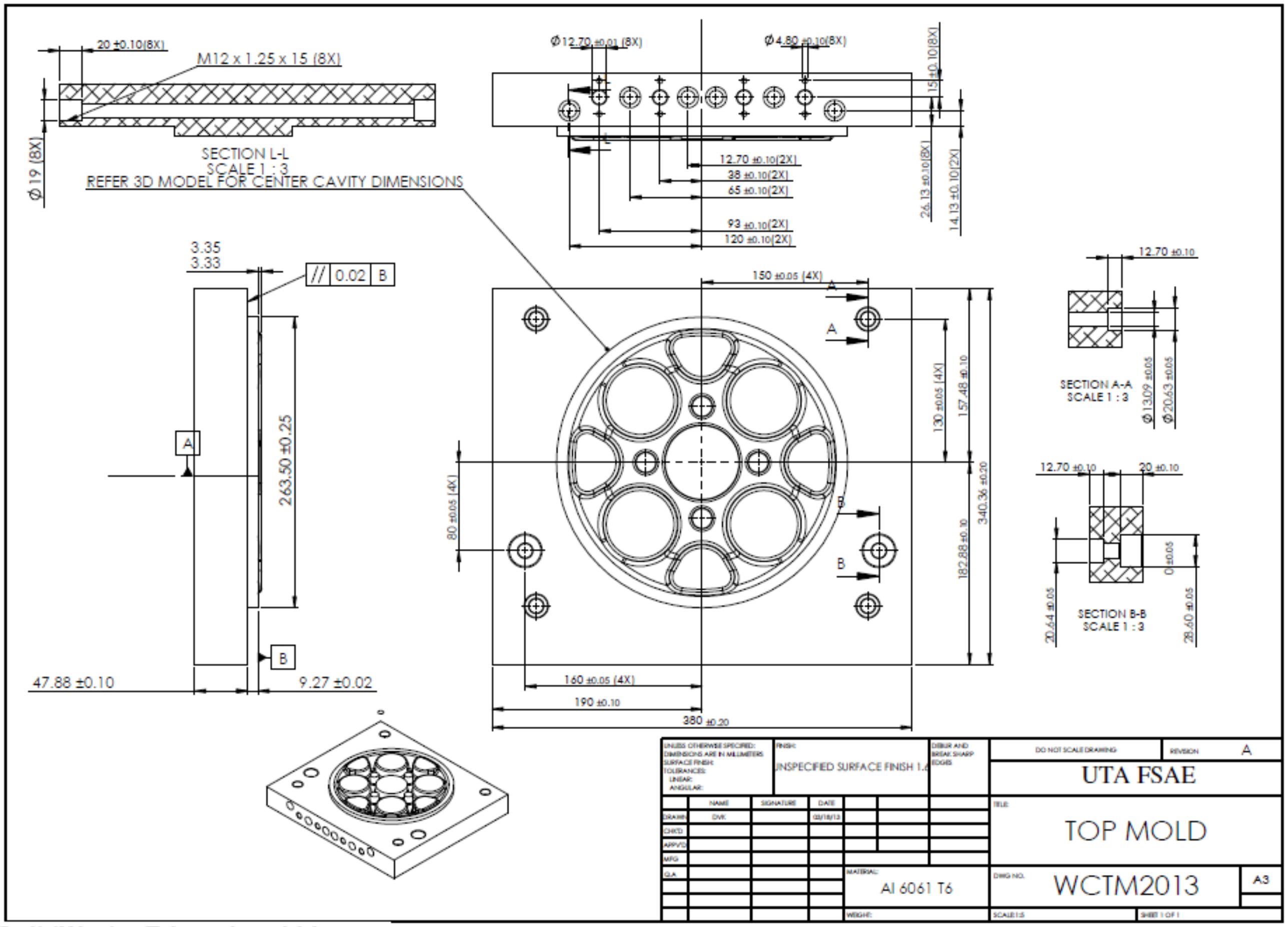

Figure 44 Top mold drawing

APPENDIX F

ELECTRIC HEATERS

Heater selection

Electric heaters are the preferred heaters for our development because of the easy installation and cost. It is available based on customer requirements in various watt densities. Uniform temperature distribution produced by oil or water heating system cannot be matched by electric heating systems. That is being addressed by modern temperature controllers available in the market which splits the mold into zones and a thermocouple is placed in each zone and heaters placed in the zone are controlled separately and thereby reducing the temperature gradient between zones in the mold.

Available forms of electric heaters are

1. Cartridge heaters
2. Strip heaters
3. Coil heaters

Cartridge heaters

It consists of hollow tube made of steel 300 series or incoloy material called as sheath. Inside that a coil is wounded over ceramic cores and a insulation is present between the coils and sheath to avoid shorting. It comes in a variety of sizes, lengths, watt densities etc. Incoloy sheath is usually recommended for high temperature applications. Steel series sheath is used for low temperature applications.

Performance of the cartridge heater depends on the clearance zone between the heater and the bore size. This plays a direct effect in the heat transfer of the part. Small clearances lead to efficient heat transfer. Thermocouples are embedded within the heaters to monitor the temperature in the heaters. Thermocouples will be fixed just below the cavity and above the heaters so that the actual temperature in the mold will be less than the heater temperature. To avoid overheating and failure separate thermocouples to monitor coil temperature are fixed in the heater itself. There are various types available for mounting the heaters. Different types of cartridge heaters are shown in figure 43.

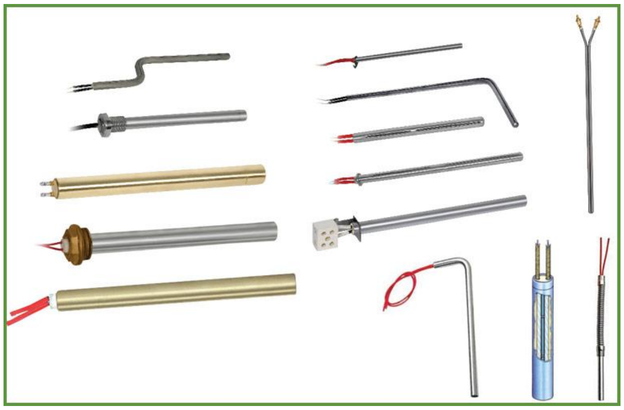

Figure 45 Cartridge heaters

Terminations are available in a variety of forms. The electrical terminations can be plain leads, Teflon leads, braided leads, SS armor leads, and flexible tubing leads.

Strip heaters

These heaters appear in a small strip and it can be placed anywhere. It can be fixed by an adhesive. Flexible forms of strip heaters are called band heaters and they are mounted over cylindrical vessels for heating purpose. Strip heaters are suitable when the part to be heated has a flat surface and it couldn’t be used in molds. Because undercuts to be machined to place the heaters with the mold. A simple strip heater is shown in figure 44.

Figure 46 Strip heaters

Coil heaters

These are thin coils and can be formed to custom shapes and fitted for certain applications. As it is a custom requirement the cost is expensive but the temperature profile will be uniform as what we expect. Figure 45 is a simple coil heater available in the market.

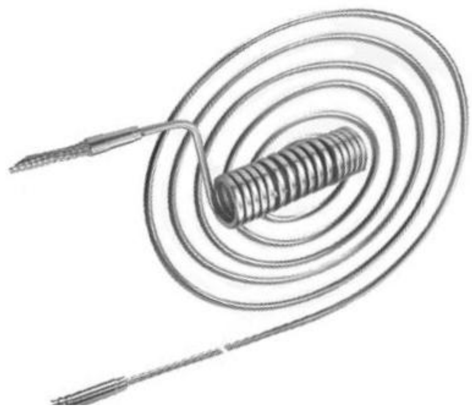

Figure 47 Coil heaters

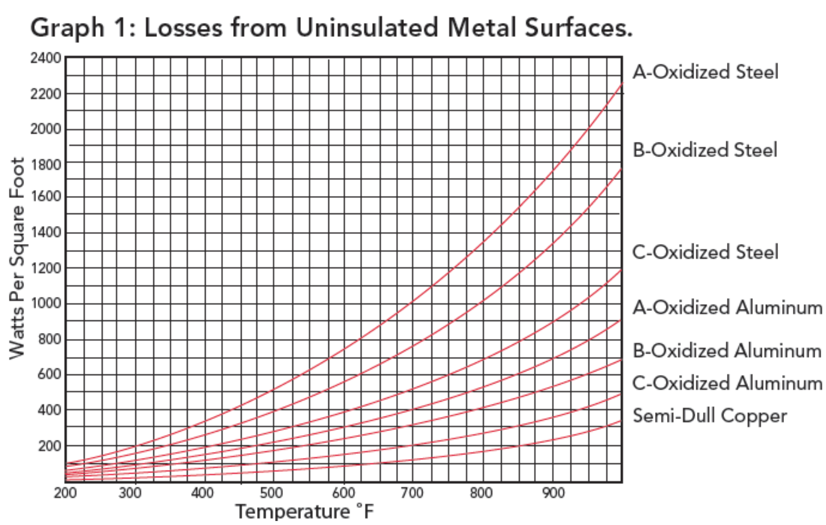

Figure 48 Heat loss graph

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BIOGRAPHICAL INFORMATION

Vinoth Kumar Dhananjayan received his Bachelor of Engineering in Mechanical Engineering from Anna University, Chennai, India. He has worked as a new product development quality assurance engineer in India for Royal Enfield (motorcycle manufacturer with engine displacements above 350cc) from Sept 2008 to July 2011. He joined UT Arlington in fall 2011 and started working under Dr. Robert L Woods in spring 2012. His research interests include composite manufacturing methods, aluminum casting technologies and compression molding. He received his Master of Science degree in Mechanical Engineering from the University of Texas at Arlington in May 2013.