FAKULTÄT MASCHINENBAU
Master of Science in Manufacturing Technology
Lehrstuhl Für Kunststofftechnologie
Prof. Dr.-Ing. Markus Stommel

Master Thesis

Material selection for a strut bearing using finite elements analysis

by

Enver Caliskan

Registration Number: 198684

Supervisors:
Prof. Dr.-Ing. Markus Stommel
Assist. Prof. Dr. Mehmet Gokhan Gokcen
M. Sc. Kevin Breuer

Submitted on August 16, 2019

TURKISH-GERMAN UNIVERSITY
INSTITUTE FOR GRADUATE STUDIES IN SCIENCE AND ENGINEERING
MASTER'S PROGRAM IN MECHANICAL ENGINEERING
(MANUFACTURING TECHNOLOGY)
THESIS PRESENTATION PROTOCOL

10.09.2019

The result of the thesis presentation of Enver ÇALIŞKAN, who is registered in the joint graduate program Manufacturing Technology between Turkish-German University and Technical University Dortmund with the registration number 1661011101, titled "Material selection for a strut bearing using finite elements analysis" held on 10.09.2019 at 16:00 is presented below.

X	Successful		Extension (3 months)		Unsuccessful

<u>Thesis Presentation Committee</u>:

Dr. Mehmet Gökhan GÖKÇEN ....
(Advisor)

Prof. Dr.-Ing. Markus STOMMEL ....
(Co-advisor)

Dr. Ali Kazım ÇAMLIBEL ....
(Member)

Dr. Duygu EKİNCİ ....
(Member)

Dr. Alpay ORAL ....
(Member)

Abstract

Material selection is a crucial aspect of any product. There are huge number of possible materials. So in order to meet the necessary requirements; selecting the optimum material for the optimum design is what makes a product safe, comfortable and profitable. Plastic materials are a huge family of materials and their usage have been rapidly increasing especially in the automotive industry where many plastic material have replaced metals. Their lower weights and increased mechanical properties of the plastic composites make them an ideal selection for many application. An example for the usage of plastics in the automotive is the plastic components used in the vehicle suspension systems.

Suspension systems play a vital role in an automobile. It is responsible for offering a safe and comfortable ride. Suspension system dampens the vibrations caused by uneven terrain surfaces and prevents transmitting those excitations to the passenger cabin thereby providing a safe and comfortable drive. It carries out these functions as a result of the harmonic work between components such as spring and shock absorber. There are various types of suspension systems depending on the type of vehicle. The most commonly used ones are the double wishbone suspension and the MacPherson strut suspension.

In the frame of this thesis work; components called upper spring seat and upper cap which are subcomponents of a component called strut bearing in the MacPherson strut suspension system were studied to select the optimum plastic materials for them. Literature research activities were conducted about the main topics of the study such as plastics, plastic injection and suspension systems. Design activities were carried out via SolidWorks to help create different designs to see which design version offers the lowest weight without altering the mechanical properties in a negative way. Then Ansys static structural analysis activities were conducted to obtain data such as stress, strain and deformation. Another tool that was used was Moldflow which was used to simulate the flow of the molten plastic. For the material selection process; various material databases were investigated to find possible materials. The mechanical properties of those materials were compared to each other.

In the end; as result of all the research, design, analysis and simulation activities; material selection and a final design selection activities were conducted. The selected new materials offer very good mechanical properties and the design modifications also lead to a better design with lower overall weight.

Keywords: Plastic, Suspension, Composites, MacPherson Strut, Material Selection, Design, Analysis, Simulation, Glass Fibre

Acknowledgements

This Master thesis work was carried out according to the collaboration between TU Dortmund, Turkish – German University and Oyak Renault. It is the final condition for my graduation from the international joint degree program called the master of science in manufacturing technologies (MMT).

It has been an incredible experience to take part in this program and fulfil my lifelong dream of doing my master abroad. I have been fortunate enough to meet with very interesting friends from all around the world and get a first class education at a high profile university.

So this master thesis is in a way a farewell to a wonderful period of my life and a welcome to the next exciting chapter. First and foremost; my deepest appreciation for everything they have done for me my entire life to my loving and supporting family of Huseyin, Zahide, Fidan and Songul Caliskan. A special thanks goes to my first ever niece Arin who will join our little family pretty soon.

I would like to thank Prof. Stommel for giving me the chance to conduct my thesis with them. Mr. Kevin Breuer who was also my supervisor from TU Dortmund has been really helpful and understanding. So I would like to thank him for his guidance.

From the Turkish – German University; Assist. Prof. Dr. Mehmet Ipekoglu who has been with me from the beginning of this master and helped me for the last 3 years. He has been very inclusive and has always given his full attention. I thank him for his constant guidance and supervision. Also to Assist. Prof. Dr. Mehmet Gokhan Gokcen; I would like to thank him for his supervision for this thesis work.

Ms. Ceren Bilgili who was my supervisor at the Oyak Renault plant has been really understanding and supportive throughout this thesis work. She has provided me with highly valuable information regarding my work and has been a huge help. I offer her my sincere gratitude for everything she has done.

To all my classmates, teachers and friends from TU Dortmund; thank you for the amazing journey from someone who always says “it is not about the destination, it’s all about the journey”.

And finally; a special thank you to a very special person - Canan Dogan - who is always there for me.

Contents

List of Figures

List of Tables

Formula Symbols and Abbreviation

Formula Symbols

Symbol	Unit	Description
F	*Newton*	*Force*
t	*Second*	*Time*
T	*Degree*	*Temperature*
d	gr/cm^3	*Density*
E	*MPa*	*Tensile Modulus*
m	*gr*	*Weight*
σ	*MPa*	*Stress*

Abbreviation

Abbreviation	Description
PA	*Polyamide*
PE	*Polyethylene*
PS	*Polystyrene*
PVC	*Polyvinylchloride*
PC	*Polycarbonate*
PET	*Polyethylene terephthalate*
PP	*Polypropylene*
PUR	*Polyurethane*
ABS	*Acrylonitrile butadiene styrene*
PEEK	*Polyether ether ketone*
PBT	*Polybutylene terephthalate*

Abbreviation	**Description**
TPU	*Thermoplastic polyurethane*
PPA	*Polyphthalamide*
PTFE	*Polytetrafluoroethylene*
PPS	*Polyphenylene sulphide*
PK	*Polyketone*
GF	*Glass fibre*

1 Introduction

In order to have economic success and a profitable business and more importantly maintain that success in today's globally challenging industry; the products have to satisfy the customer demands on so many levels and also they have to be produced in a way that the production costs are at the minimum. So the main priorities of any production process are to produce the products with high quality and low costs.

Customers have many expectations such as high quality, safety, functionality, long service life, appealing design and low cost. The products have to satisfy all these criteria along with making a profit for the producer. Because of the high expectations and the competition in the industry it is vital for the companies to constantly work on improving themselves. Therefore; the companies invest a lot of their resources into research and development activities to define the possible improvement ways with innovative ideas.

One of the most important aspect of production processes is the material selection. Choosing the right material for the right job is the key to a high quality product. In layman terms it is essential to know what you are working with in order to be successful. So knowing different material groups, their properties, their advantages and disadvantages is a must. Because of this; the material science is today's one of the most important and rapidly growing industry with new information and materials coming almost on a daily basis. Besides it is importance for the industries; the material science is also a major field for the scientific research activities.

There are different types of material and each of them have different uses. Their properties, their design, their production method and their service life vary greatly from each other. There are plenty of material characterization test methods developed to help define the material properties which are essential for material selection process. With the data obtained from these tests; the materials can be compared to each other and in doing so the optimum material can be selected for the right job. Material selection is the main focus of this thesis work. As part of the continuous improvement activities; components are constantly evaluated for improvement possibilities. This improvements can be accomplished via design changes, process changes, assembly changes or material changes. As the components that are the topic of this thesis work are not manufactured on site; changes to the production process are not possible. Changing the assembly is also not optional as these parts are assembled to various other components and any sort of change would require changing the design and assembly of every other component as well. Therefore; the only way these improvement activities can be carried out are via design and material changes. The designs of the parts were evaluated to see if it would be possible to reduce weight without altering the mechanical properties. But the extent of changes can be made were limited as this would affect the overall assembly. Hence; material selection offers the greatest possibility for improvement activities. A new material with better mechanical properties would accomplish the improvement goals without affecting the design, process or the assembly. It is possible to select a material with good mechanical properties such as strength and a low density which would also mean reduced overall weight.

So in summary; main focus was selecting new materials with better properties compared to current ones and improving the design without altering the assembly if possible. But material selection is a rather complex process as there are countless choices. Their properties vary in a great range and their microstructure also varies a lot. So optimum material selection requires comparing materials according to their properties, their molecular structure, their production processes, their operation conditions and so on. For this thesis work; plastic materials were investigated thoroughly. Plastic material types were investigated based on their properties. Especially the strength of plastic composites were studied. The filler content and the type of main compound define the final properties of the part. All these parameters combine and define whether the material in question would deform plastically under the applied loads and boundary conditions or it can withstand these conditions and offer a safe product.

This thesis focuses on material selection for a strut bearing using finite elements analysis. The thesis work is conducted at Oyak Renault plant in Turkey which is a part of Group Renault family. It comprises general research activities about suspension systems, plastic materials, plastic injection process and finally design and analysis activities for the material selection. The procedure followed for this thesis work is illustrated in Figure 1.1 below and each step is explained in detail.

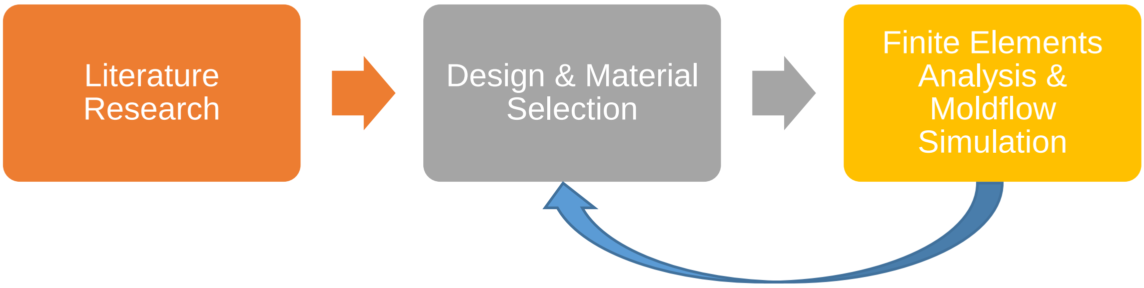


Figure 1.1: Procedure followed for the thesis work

In the frame of this thesis work; firstly literature research activities were conducted to gain the necessary fundamental information about plastics, plastic types and their properties. Also plastic injection process was studied to understand the process, the machines, the moulds etc. Then suspension systems, suspension system components and their functions were studied. Different suspension types were compared to each other. Most important part of the research activities was the material properties and comparison activities. Different material databases were studied to check the properties of different material types.

Secondly design activities were conducted using software such as SolidWorks and UniGraphics. Current design was modified in order to see if the weight can be reduced and analyse how the properties change according to the design modifications. The aim was to decrease the weight if possible without affecting the mechanical properties.

Lastly different designs were analysed with different materials using Ansys software. Materials were appointed to the designs and the effects of the loads applied were studied to select the optimum material. Moldflow simulation activities were also conducted to simulate the plastic flow.

The strut bearing is a component in the suspension system of automobiles. Automobiles have many complicated systems integrated together to work as a unit. Steering system, braking system, cooling system, suspension system etc. are some examples and each of them has their own function.

Suspension system is responsible for providing a safe and comfortable ride. It serves as a dampening mechanism by absorbing the shocks created by the road surface and not transferring those to the passenger cabin. Suspension system makes sure that the tires do not lose contact with the road surface which is vital for the safety as losing contact between the road and the tires could lead to serious accidents.

Depending on the type of vehicle; the suspension system might vary. Different suspension systems are used based on the vehicle type. Heavier vehicles such as trucks and buses do not use the same type of suspension as the passenger vehicles. There are options even with in the passenger vehicles as well. The suspension type also varies depending on whether it is used on the front or the rear of the vehicle.

There are different types of components in a suspension system. While some components are specific to certain suspension types; some components such as shock absorber, spring, dustboot, anti - roll bar etc. are common in most of the suspension system types.

As it was stated earlier; the main focus of this work is the material selection process. The components in question are made of plastics and therefore another important part of this thesis work will be plastic materials. Plastic material usage has been growing rapidly and in so many industries particularly automotive and aviation plastic materials are replacing metals due to their high advantages such as low weight, high strength, high stiffness, good corrosion resistance as well as their low costs. Weight reduction is a huge goal for any product and is one of the most popular terms in the automotive industry in the recent years. Due to their low costs and high mechanical properties plastic materials are gaining more and more attention. Furthermore there are plenty of different plastic material types which offers a wide range of selection and their properties can be improved by using different kind of reinforcements such as chalk, talc, carbon fibre and glass fibre. [1]

2 State of the Art

The aim of this chapter is to provide the fundamental data regarding the subjects of this thesis work. Firstly the basics about plastic materials, composite plastics and plastic injection process are explained. Secondly the suspension system, suspension system components, different suspension types etc. are explained to create the necessary background. Then strut bearing which is the topic of this thesis is explained.

2.1 Plastics

Usage of plastic materials has increased rapidly due to their good mechanical properties and their relatively low costs. It is today's one of the biggest industries. According to data from European Plastic; the plastic industry had a turnover of 350 billion Euros in 2017. Same data showed that 350 million tonnes of plastics were produced in 2017. There are around 60000 companies with more than 1,5 million people working in the plastic industry [2]. An example of the plastic parts used in an automobile is showed in Figure 2.1 below.

Figure 2.1: Plastic parts in a vehicle [3]

Plastics are a popular choice nowadays and they are very resource efficient materials made of polymeric materials. Polymer is a chemical compound and it is made of many small particles known as monomers. The molecular structure of a polymer is illustrated in the Figure 2.2. [4]

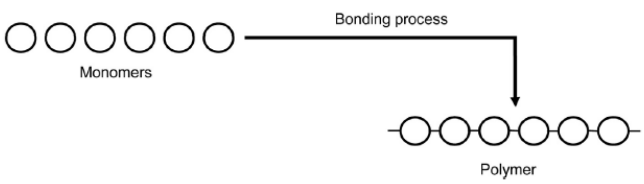


Figure 2.2: Molecular structure of a polymer made of monomers [4]

Polymeric materials offer a variety of choices and there is huge differences between different polymer types. Polymers can be derived from a number of different sources. Based on the source of origin; polymers can be categorized as organic, inorganic, natural or synthetic. Natural polymers are materials that exist in the nature or they can be extracted from various plants or animals. This type of polymeric materials are vital for our daily life because the human forms are based on them. Some examples of natural polymers are proteins, nucleic acid, cellulose, natural rubber, wool and silk. [4]

In contrast to natural polymers; synthetic polymers are man-made. They are produced in laboratories to be used in many different areas. They are usually derived from fuel based resources in controlled environments but there are also plenty of bio based plastics nowadays. With the use of some production processes the monomers are bonded together to form a molecular chain which are the synthetic polymers. The process of bonding the monomers is known as polymerisation and the number of monomers in these molecular chain is referred as the degree of polymerisation. Some examples for synthetic polymers are polyamides (nylon), polyethylene (PE), polystyrene (PS), polyvinylchloride (PVC), synthetic rubber, teflon, epoxy and so on. [5]

In Table 2.1 a comparison between natural and synthetic polymers is given.

Table 2.1: Comparison of Natural and Synthetic Polymers [4]

Natural Polymers	**Synthetic Polymers**
Develop naturally	Artificially produced
Have been around for millions of years	Have been used for approximately a century
Similar but not identical units	Identical units
Properties defined by natural reactions	Properties defined by engineering processes
Molecular chain lengths usually similar	Wide range of molecular chain length
Usually biodegradable	Some are biodegradable
Environment friendly	Harmful to the environment
Usually carbon, oxygen and nitrogen based	Mainly carbon based
Recyclability limited	Some can be recycled plenty of times

2.1.1 Plastic Material Categorization

Plastic materials are categorized into 3 categories which are thermoplastics, thermosets and elastomer. This classification is made based on the differences between them such as their molecular structure and their properties. In Table 2.2 below some examples of thermoplastic and thermoset materials are given.

Table 2.2: Thermoplastic and Thermoset Material Examples [2]

Thermoplastics	Thermosets
Polyamide (PA)	Polyurethane (PUR)
Polystyrene (PS)	Polyester
Polyvinylchloride (PVC)	Epoxy resins
Polyethylene (PE)	Vinyl ester
Polycarbonate (PC)	Silicone
Polyethylene terephthalate (PET)	Phenolic / Acrylic / Melamine resins
Polypropylene (PP), ABS, PEEK	Phenol / Urea formaldehyde

Molecular structure is a distinguishing feature of these plastic material types. Each of them are made of polymer chains comprising many monomers. However the linkage of these polymer chains differs. In Figure 2.3 below the molecular structures of these plastic material types are illustrated.

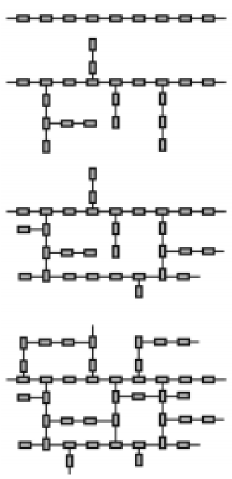


Figure 2.3: Molecular structure of plastic types [8]

2.1.1.1 Thermoplastics

Thermoplastics are a big portion of the plastic materials. They are used in almost every industry due to their advantage such as lower weight and cost. They are also easier to process. Thermoplastic materials molecular structure comprises of many polymer chains and these individual polymer chains do not cross link between themselves. There is no chemical reaction between these polymer chains. The molecular structure of thermoplastics is illustrated in Figure 2.4.

Thermoplastic materials are solid at room temperature and they liquefy at certain temperatures and solidify again once cooled. One of the biggest advantages of thermoplastic materials is their ability to be remelted and used again. They can undergo heating and cooling cycles without significant changes to their final properties. So they can be reused and recycled which is a major advantage [9]. Thermoplastic material examples are given in Figure 2.5.

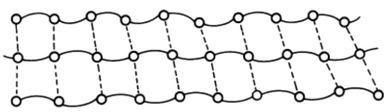


Figure 2.4: Molecular structure of thermoplastics [10]

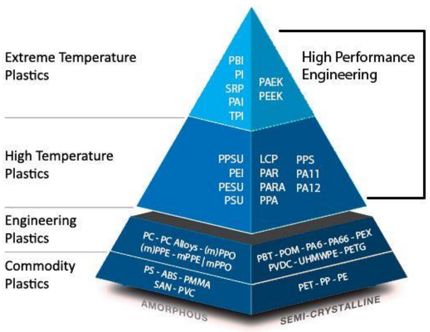


Figure 2.5: Thermoplastic materials [11]

As this figure illustrates; there are plenty of thermoplastic material types and they are all used for different applications. Depending on the environment; it might be required to have a material with better mechanical properties so the high performance engineering plastics might be the better choice whereas the use of an amorphous thermoplastic makes more sense for high temperature environments. Evaluation of all the parameters are vital for the material selection process.

2.1.1.2 Thermosets

Thermosets also known as thermosetting materials have different molecular structures and properties compared to thermoplastics. Thermosets are also used widely in many industries. Their molecular structure is more complex in contrast to thermoplastics. They also comprises many polymer chains made of monomers but these polymer chains also cross link between themselves.

Thermosetting materials gain their final properties after a process called curing. During these process; chemical reactions occur and cross linked bonds are formed between the polymer chains. The final product cannot be reused by heating and cooling again as opposed to the thermoplastics. So thermosets are unsolvable and cannot be processed more than once [9]. The molecular structure of thermosets is illustrated in Figure 2.6.

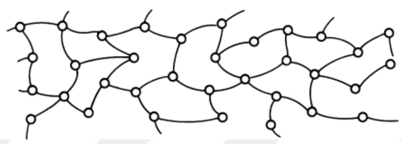


Figure 2.6: Molecular structure of thermosets [10]

2.1.1.3 Elastomer

Elastomer is another polymeric material with its own specific features and it is also known as rubber. Elastomer has very high viscosity and elasticity abilities so it is a viscoelastic polymer. Elastomer is usually known as a type of thermosetting material however there is also thermoplastic elastomer. This polymer has very low inter molecular bonds. The long chained polymers in its molecular structure allows the elastomer to have very high elasticity. Elastomer can extend and reverse it in a range of 5 – 700 % which is why it is a popular material especially for seals [12]. Figure 2.7 illustrates the molecular structure of an elastomer.

Figure 2.7: Molecular structure of an elastomer [10]

In Table 2.3; differences between thermoplastics and thermosets are listed.

Table 2.3: Properties comparison of thermoplastics, thermosets and elastomers [4]

Property	Thermoplastics	Thermosets	Elastomers
Flowability	Low	High	-
Raw material	Fully polymerized and supplied as solid pellets	Not fully polymerized and often supplied as resinous liquid or semisolid	Solid pellets for the thermoplastic elastomer (TPE) and liquid for thermosetting elastomer
Bonding between neighbouring chains	Chains held together by physical bonds such as Hydrogen and van der Waals bonds	Chains held together by chemical linkages or crosslinks	Long and entangled polymeric chains; crosslinks for thermosetting elastomer
Processing	Shapes are formed in molten state then cooled to retain shape	Shapes are formed in cold or warm state then heated to retain shape	Same process for TPE as thermoplastics; same for the thermosetting one
Processing equipment	Standard melt processing such as injection moulding and extrusion	Modified processing as introduction of heat is required after shapes are formed	Injection moulding, compression moulding, extrusion
Processing time	Short	Long due to forming of crosslinks	Short for TPE; long for thermosetting one
Recycling	Possible	Not possible	Possible for TPE
Dimensional stability	Moderate	High	Moderate to high; depends on the type

2.1.2 Morphology of Plastics

Another important feature of the plastic materials is their morphology. Morphology can be explained as the way the molecular chains are arranged in the structure of the material. Morphology of a plastic material is a key factor for defining the properties of the material.

An important term about the morphology is crystals. In the molecular structure; there are regions that have a sort of order and these regions are known as crystals. The amount of crystals a plastic material contains has a big influence on its properties such as strength, chemical resistance, density, hardness, melting point etc. A plastic material can either have a crystalline / semi crystalline structure or an amorphous structure. All polymeric materials are in the amorphous state in their melted form as the crystals form during the cooling process. [9]

Crystalline materials have a molecular structure comprising of ordered and organized regions. Whereas a material with an amorphous structure has a molecular structure of unorganized randomly scattered molecular chains. A semi crystalline structure is the mixture of these two structure type as it contains highly organized regions as well the randomly scattered crystals. Some examples for semi crystalline materials are polyamide (PA), polyethylene (PE), polypropylene (PP). Some examples for amorphous materials are polycarbonate (PC), polyvinylchloride (PVC) and polystyrene (PS) [4]. In Figure 2.8 below; the molecular structure types are illustrated.

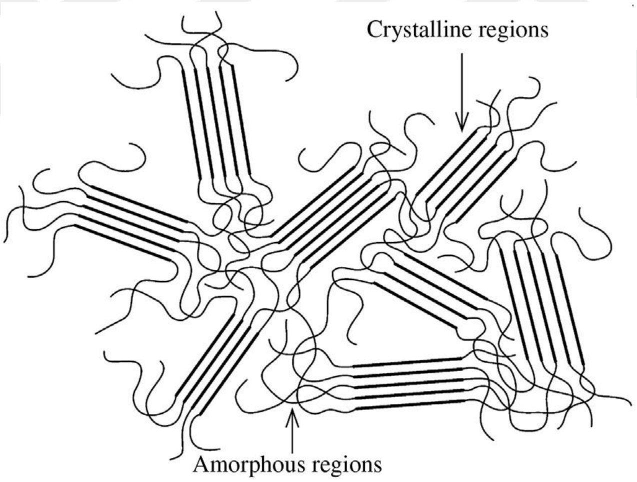


Figure 2.8: Crystalline and amorphous structure types [4]

2.1.3 Plastic Composites

Plastic materials are lighter and cost less compared to metals however they do not provide the high material properties the metals do. So in order to replace metal parts with plastics; the properties of these plastics need to be improved and this is achieved by plastic composites.

Plastic materials are used either in their natural pure form or they are used after being mixed with certain resins or additive materials. After mixing the plastic and the additive material; the composition is processed into a product. [13]

Composite material is a material comprising two or more materials with different physical and chemical properties and each material keeps its individual properties. The compositions of these materials vary and this has a huge effect on the properties of the final product. Composites have distinct phases which are the matrix phase and the reinforcement phase. The matrix is the primary phase in its continuous form and it surrounds the reinforcement phase which is also called dispersed phase. The dispersed phase is in its discontinuous form and it is embedded in to the matrix. The matrix is usually more ductile whereas the dispersed phase is stronger. [14] [15]

There are plenty of additive types for specific functions. The main additive types are listed below: [16]

- Reinforcements such as carbon fibre and glass fibre
- Fillers such as talc, chalk, mica etc.
- Functional additives such as flame retardants, plasticizers and lubricants etc.
- Colorants

2.1.3.1 Glass Fibre Reinforced Plastics

One of the most commonly used reinforcing material for plastic composites is glass fibre. They are used widely in automotive industry, construction industry, electronic products, aviation industry etc. due to their low weight, high strength and stiffness. The reinforcement phase provides the strength and stiffness whereas the matrix protects the reinforcement phase from abrasive and environmental effects. [1]

The reinforcement phase of a composite which is also called the dispersed phase is usually found in the form of a fibre or a particle. The composites that have particle shaped reinforcements have particles that are approximately dimensionally equal on all directions. The shape of these particles vary from a regular geometries such as spherical to any kind of irregular geometry. This type of composites are not as strong as fibre based composites but they cost less. [1]

Plastic composites comprising fibres instead of particles offer better mechanical properties. An important term regarding the fibres is the aspect ratio which is the ratio of its length to its diameter. The aspect ratio of fibres is usually high and can vary greatly. The fibres used in composites can either be continuous or discontinuous. Continuous fibres have high aspect ratios whereas discontinuous fibres have low aspect ratios. Another difference between continuous and discontinuous fibres is the fact that the fibres have a preferred orientation in continuous fibres whereas the discontinuous fibres are usually scattered randomly. Fibre reinforced composites offer very high strength properties and their cost is much higher. Glass fibre and carbon fibres are the most commonly used fibre based reinforcements [1]. Figure 2.9 illustrates the reinforcement types found in plastic composites.

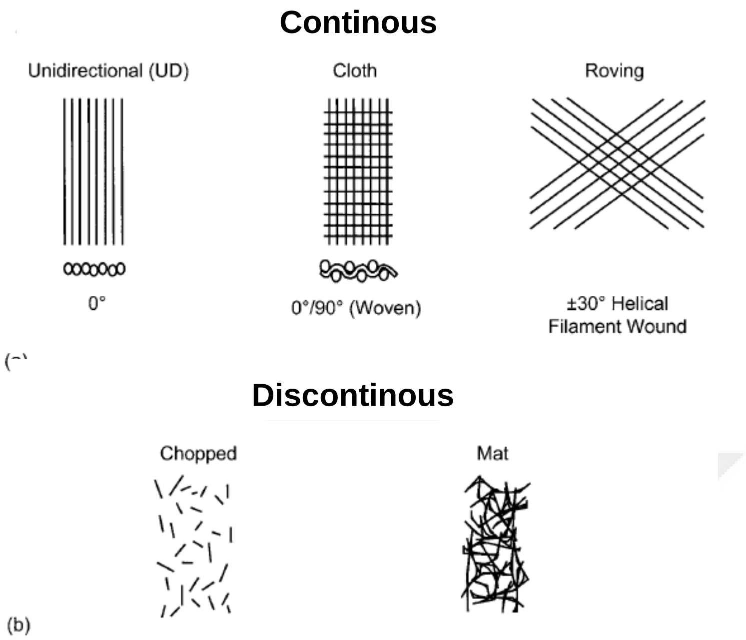


Figure 2.9: Illustration of plastic reinforcements [1]

Glass fibres are used extensively as a reinforcement for various applications. Therefore there are various glass fibre types and they are all used for different applications while their composition and properties varying from each other. Among those types; E – glass is the most commonly used type of glass fibre [13]. In Table 2.4 properties of glass fibre types are compared to each other.

Table 2.4: Properties comparison of glass fibre types [13]

Properties	**Glass Fibre Type**							
	A	**C**	**D**	**E**	**ECR**	**AR**	**R**	**S-2**
Density (gr/cm^3)	2,44	2,52	2,12	2,58	2,72	2,7	2,54	2,56
Breaking Index	1,54	1,53	1,47	1,56	1,58	1,56	1,55	1,52
Softening Temp. (℃)	705	750	771	846	882	773	952	1056
Annealing Temp. (℃)	-	588	521	627	-	-	-	816
Tensile Stress - MPa (23℃)	3310	3310	2415	3445	3445	3241	4135	4890
Tensile Modulus - GPa (23℃)	68,9	68,9	51,7	72,3	80,3	73,1	85,5	86,9
% Elongation	4,8	4,8	4,6	4,8	4,8	4,4	4,8	5,7

2.2 Plastic Injection Moulding

Plastic material production is a fast growing industry with new technologies being developed very rapidly. There are various production methods used for plastic production and these can be seen in Figure 2.10. The most popular of those methods is the plastic injection process. Plastic injection moulding is a popular production method for many plastic part with different sizes and shapes. Some advantages and disadvantages of this process is listed below: [17]

- Costs per unit are low
- High production capacity
- High quality products
- Different shapes can be moulded
- Wide material selection
- Full automation possibility
- High initial costs (machine, mould etc.)

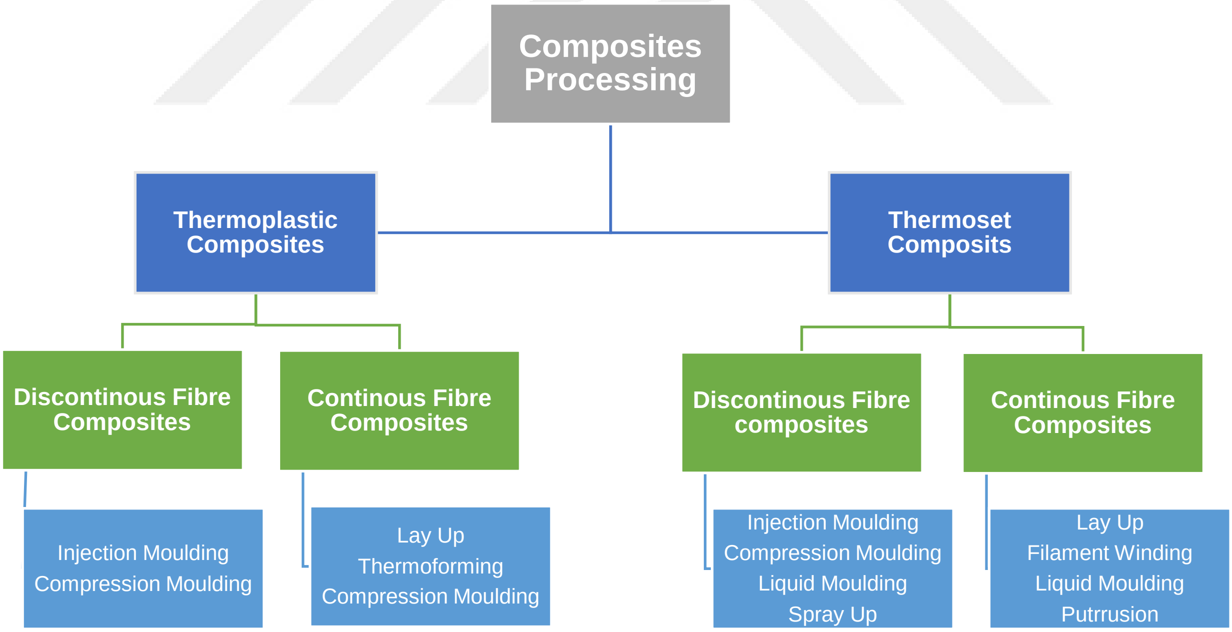


Figure 2.10: Plastic production methods [1]

Plastic injection moulding is a cyclic process where a molten plastic material is filled into a cavity under high pressure then ejected after allowing it to cool down. It requires a plastic injection machine, a mould with a cavity and the material which is either pure plastic or a composite. An example of a plastic injection moulding machine is shown in Figure 2.11.

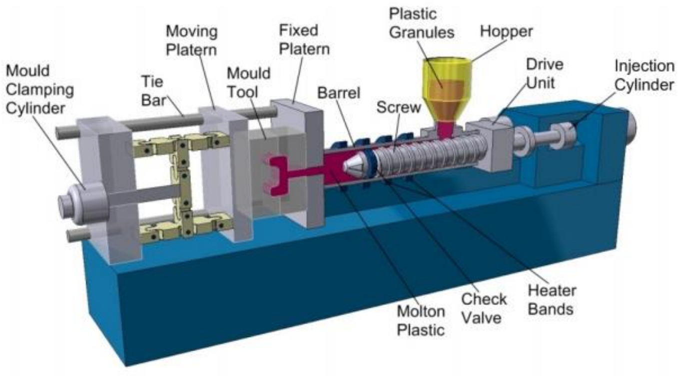


Figure 2.11: A plastic injection machine example [18]

Plastic injection process starts with the transfer of raw material into the barrel from the hopper. The barrel is heated to a degree enough to melt the particles through heater bands circled around it. The screw starts to rotate and move towards the moulds. The movement of the screw pushes the particles towards the moulds as well. As a result of the heat and the friction; particles melt completely before reaching the cavities. Then the molten material is injected into the cavity with high pressure via the channels on the mould which are known as runners. Once the cavity is filled; the melt starts to solidify as a result of the cooling. Finally the product is ejected from the cavity. An illustration of plastic injection process is given in Figure 2.12 below.

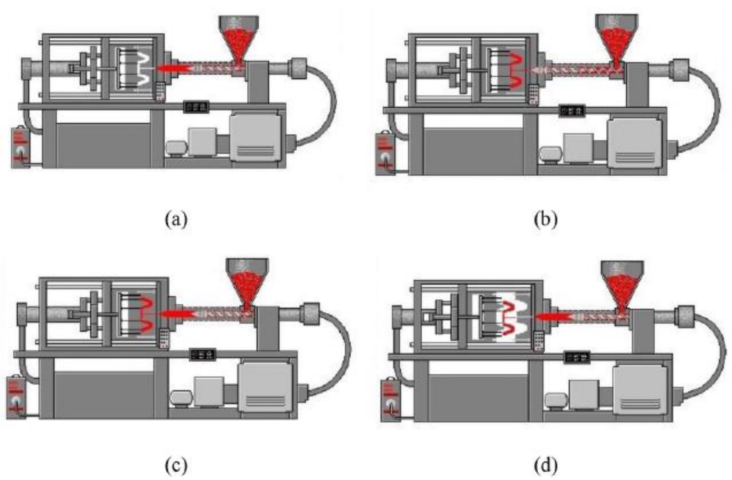


Figure 2.12: Plastic injection cycles: a) closing, b) injection, c) cooling, d) ejection [13]

Plastic injection moulding machines comprise of various components such as the injection unit, the clamping unit, temperature controller etc. Each of these units have their own function and they work together to complete the process.

In Figure 2.13; the injection unit of an injection moulding machine is illustrated.

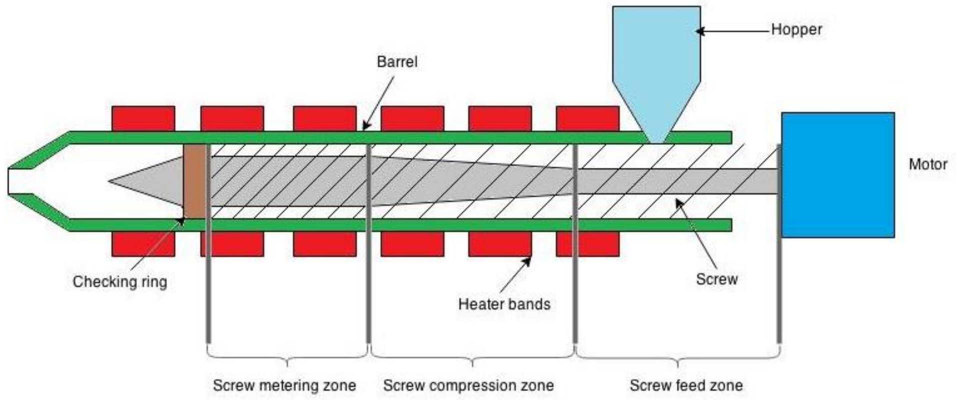


Figure 2.13: Injection unit of an injection moulding machine [19]

The injection unit comprises of components such as screw, hopper, motor, heater bands etc. The screw has different zones such as feed zone, compression zone and metering zone in order to make sure all of the particles are melted. The plastic material is placed into the hopper in the shape of powders. Then the particles are transferred into the cylindrical part called barrel which surrounds the screw. As the screw is rotated and pushed towards the mould by the motor; the plastic particles start to melt as a result of the heat and the friction. The temperature is controlled with the heater bands so that all the particles will be melted before reaching the mould. There are various screw types for the injection unit [19]. Some examples for different screw types are given in Figure 2.14.

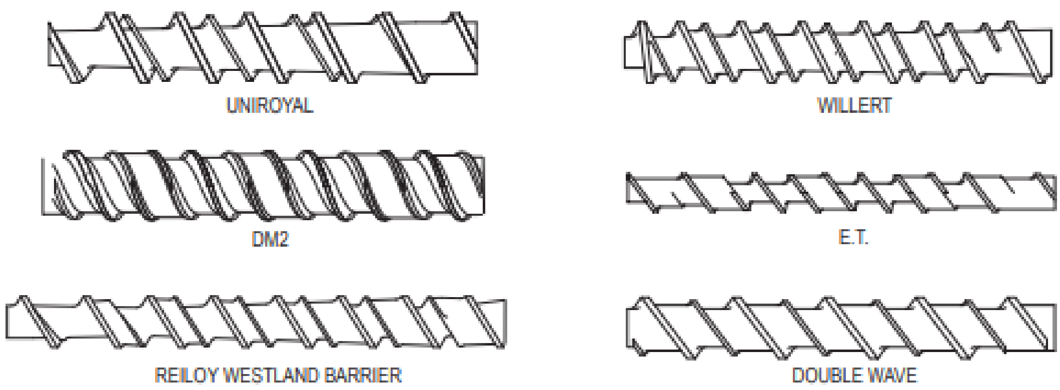


Figure 2.14: Injection unit screw types [20]

2.3 Suspension Systems

Automobiles are one of the most important inventions in the history and they are now a vital part of our daily life. They comprise of highly complex systems where each system has a specific function essential to the operation of the vehicle. Steering system, braking system, cooling system, power transmission system etc. are some of the examples to these systems. Some examples of these systems in an automobile are illustrated in Figure 2.15 below.

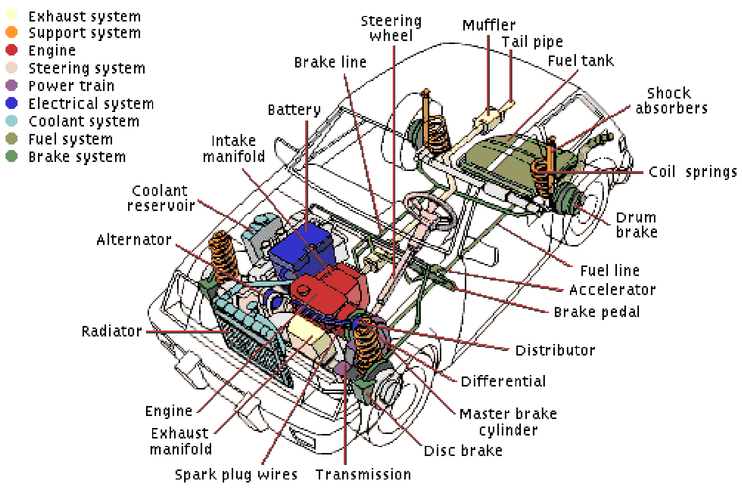


Figure 2.15: Component examples in an automobile [21]

Safety and comfort are the most essential expectations of customers from any type of automobile. Manufacturers therefore focus on providing their customer with high safety products that also offer a comfortable ride. Many components in an automobile are responsible from satisfying these requirements. Manufacturers spend a lot of their resources on research and development activities in order to be absolutely sure that their products have the necessary specifications regarding the issues of safety and comfort along with other important aspects such as cost, innovation etc. Each of these systems in an automobile are tested repeatedly before approving the product.

Suspension system is a major system in an automobile for the criteria of safety and comfort. Suspension system in an automobile comprises of various components such as springs, shock absorbers / dampers and linkages. Each of these components have different functions. These components also show differences among themselves based on the type of suspension used. These components work in harmony with each other to carry out the expected function of a suspension system. Main functions of a suspension system in an automobile are: [22]

- Ensuring driving safety
- Offering a smooth comfortable ride to the passengers
- Improving road handling features

An illustration of suspension systems location in an automobile along with its components are given in Figure 2.16 - 17 below. The type of suspension used in the following figures is known as MacPherson suspension which is a common choice and is also the type of suspension that this thesis work focuses on.

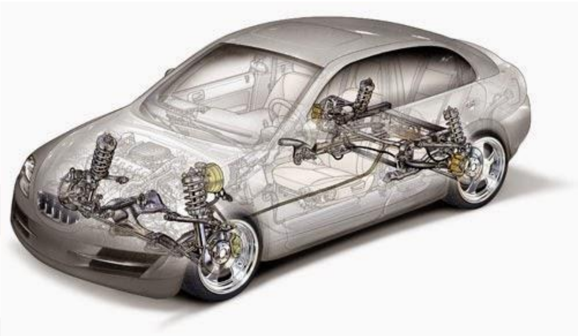


Figure 2.16: Suspension system in an automobile [23]

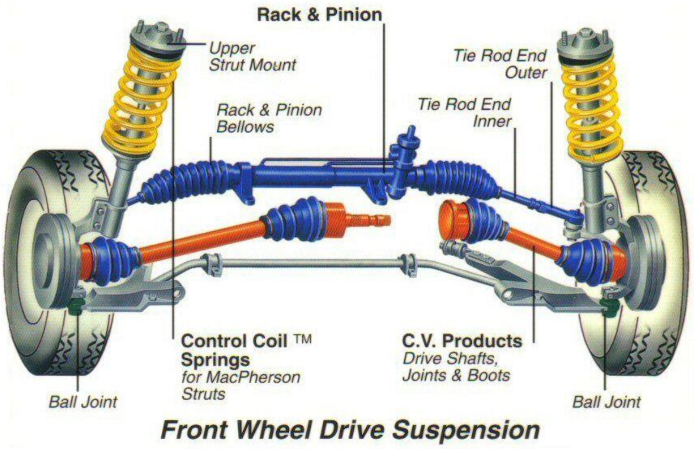


Figure 2:17: Suspension system example and its main components [24]

A suspension system absorbs the shocks originated from the road surface and in doing so offers a more comfortable ride while also offering a safer driving since the suspension system is also responsible for making sure the tyres do not lose contact with the road surface. This also offers better road handling possibilities. [25]

If the surface of the roads were perfectly flat without irregularities; it would not be necessary for a suspension system to absorb shocks originating due to road surface issues such as holes, bumps, unevenness etc. in order to isolate the passenger cabin from these excitations. But since that is not the case; every time a tire goes over a bump that tire will move upwards. Thanks to the spring and the dampener in the suspension system; the tire will be pushed down the entire time and therefor making sure constant contact between the road and the tire which is vital for a safe driving experience. [26]

2.3.1 Suspension Systems Classification

Suspension systems are mainly classified into the following two groups:

- Non – independent suspension systems
- Independent suspension systems

The difference between these 2 groups is the relationship between the tires on the opposite sides. The classification criteria is whether the movement of one tire affects the other tire or not. This difference is important for parameters regarding road handling subject.

When a tire moves upward or downward in an automobile with non – independent suspension system; the other tire will be affected by this movement. The reason for that is the fact that this type of suspension systems comprise a solid axle and both suspension systems on the right and left sides are connected to that axle. The effect of one wheel movement on the other will affect the camber angle which is an important parameter regarding tire geometry. An illustration of a non - independent suspension system is shown in Figure 2.18 below. Non independent suspension systems are usually preferred on the rear suspensions of many passenger cars, trucks and on the front suspensions of some passenger cars. [27]

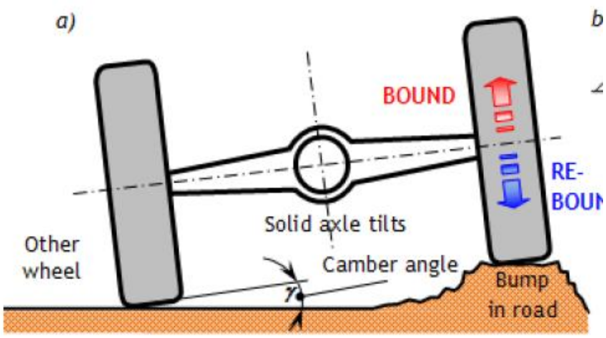


Figure 2.18: Non independent suspension system example [27]

The other suspension system type is independent suspensions. This type of suspensions comprise of suspensions not effected by the movement of the other suspension. In contrast to the non-independent suspension systems; independent suspensions move upwards and downwards individually. When one of the tires upwards or downwards; the other tire is not effected by that movement. The suspensions on right and left sides are not connected to one axle. Instead they are connected to different locations of the chassis separately. An illustration of this type of suspension systems is shown in Figure 2.19 below. As it can be seen from the figure below; since the wheels on opposite sides do not share a common connection point their movements are individual and do not affect each other. When a wheel moves up or down the other wheel does not show any vertical movements while the suspension system makes sure the wheel that goes over a bump does not lose contact with the surface. Independent suspension systems are widely used in front suspensions of many modern passenger cars. [27]

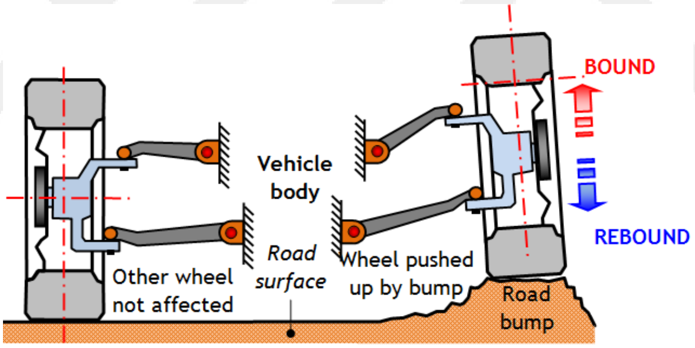


Figure 2.19: Independent suspension system illustration [27]

Independent suspension systems offer some advantages over non independent ones. The first advantage is obviously the fact that the movement of one wheel does not affect the other wheel which provides a safer and more comfortable ride. Independent suspension systems also require less space and lastly they offer lower weight which is always a benefit especially in the automotive industry. [28]

2.3.2 Suspension System Components and Types

As stated before; there are various suspension system types. They are used in different ways depending on the type of vehicle and the expectations. The suspension system used in heavier vehicles such trucks is not same as the system used in passenger cars.

The main components in various suspension systems are common. But these components also have different types. Some of the common suspension system components and different types of suspension systems are explained in the following.

2.3.2.1 Suspension System Components

Suspension systems are vital equipment for vehicles and they comprise of various sub components which allow the suspension system to function properly and provide a safe, comfortable ride to the passengers. A simple illustration of a suspension system of a vehicle is shown in Figure 2.20 below.

The main components of a suspension system are listed below:

- Spring
- Shock absorber / damper
- Anti - roll / sway bar
- Various linkage elements

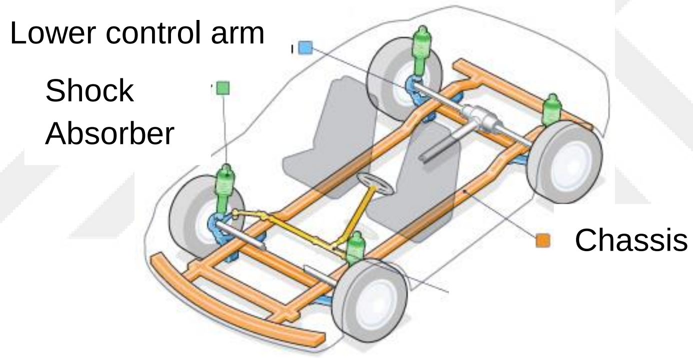


Figure 2.20: Simple illustration of a vehicle suspension system [29]

Springs: Springs are one of the most important components in a suspension system. The working principle of a suspension system is based on a spring absorbing the vibrations caused by the irregularities on the road surface and not transferring these vibrations to the passengers and therefore providing a safe and comfortable ride. [30]

When a wheel goes over a bump; the spring will compress due to the movement of the wheel. With the help of a damper which is another important component; these excitations will not be transferred to the passenger cabin. Stiffness of the spring is an important parameter here as it defines how effectively the spring can compress and dampen the excitations.

Depending on the type of suspension system used; the spring type varies as well. One of the oldest type of springs used in suspension system is leaf springs. They are not as popular as they used to be however they are still used in suspension systems for trucks and buses. Leaf springs are preferred for heavier vehicles [30]. Examples of leaf springs are shown in Figure 2.21 - 22.

Figure 2.21: Leaf springs used fur suspension in a heavy vehicle [31]

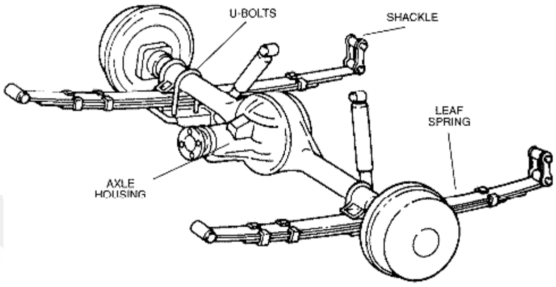


Figure 2.22: Illustration of leaf springs in suspension systems [32]

Leaf springs are in layman terms a stack of metal stripes in different lengths. Leaf springs are simpler compared to modern day suspension types. Leaf springs do not compress so much and therefore vehicles with leaf springs might lose contact between the tyres and the road.

Another spring type used in suspension system is coil springs. Coil springs which are also known as helical springs due to their shape are pretty much what comes to mind when talking about springs nowadays. They are the most commonly used spring types. Figure 2.23 below shows various types of coil springs.

Coil springs are produced from steel rods and are able to compress to a great degree depending on the specifications. Due to this ability of theirs; the coil springs absorb the shocks originated from the road surface. Compared to leaf springs; coil springs can absorb twice the amount of energy. [30]

Figure 2.23: Coil spring types [29]

Coil springs are widely used in many modern automobiles. There are various important parameters regarding the coil spring. Spring diameter, pitch and number of turns are vital for the compression and load carrying abilities of these springs. These parameters vary depending on the type of the vehicle as the important aspect here is the weight of the vehicle [29]. A suspension system with a coil spring illustration is shown in Figure 2.24 below.

Figure 2.24: A suspension system with a coil spring [33]

Further types of spring are used in various suspension system types. Torsion bar springs and rubber springs will be explained shortly.

Shock Absorber: Shock absorbers / dampers are another key component in a suspension system. Shock absorbers work in combination with springs in a suspension system. As it was explained earlier; the spring compresses as a result of the vertical movement of the wheels and the spring absorbs these vibrations. If there was no shock absorber in a suspension system; the spring would push the wheel back to the ground with a very high force because the force that compresses the spring is also quite high and the spring constantly tries to push the wheel back. So if there was no shock absorber; the spring would oscillate and push the wheel with a high force that when the wheel touched the road surface the vehicle would bounce.

A shock absorber in a suspension system converts the energy absorbed by the spring into heat. In doing so the shock absorber allows the spring to return to its uncompressed state in a much steadier way that it prevents the oscillation movement of the spring. Therefore; a shock absorber is vital for a suspension system and a shock absorber plays a big role in providing a safe and comfortable ride while also extending the service life of the suspension system [30]. An example of a shock absorber is given in Figure 2.25 below.

Figure 2.25: Shock absorber example [34]

Shock absorbers also differ among themselves. For instance; the substance inside of the tube which helps in preventing the spring from oscillating can be hydraulic or gas. Figure 2.26 shows the schematic of a shock absorber.

Anti – Roll Bar: Anti - roll bar which is also known as anti - sway bar is another important component in suspension systems. This component acts as a stabilizer. They are necessary in a suspension system to prevent the vehicle to roll during a sharp turn. Whilst turning a corner or making a sharp turn the vehicle body will intend to roll which will put more pressure on one of the suspensions on the right and left. The anti - roll bar will transfer some of this energy to the less pressurized suspension in order to keep the car from rolling over [35]. In Figure 2.27; an example for anti – roll bar / anti - sway bar is given.

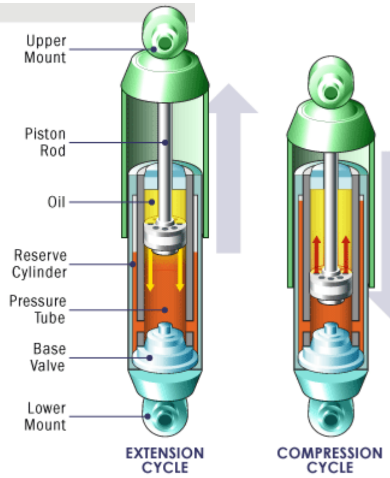


Figure 2.26: The schematic of a shock absorber [36]

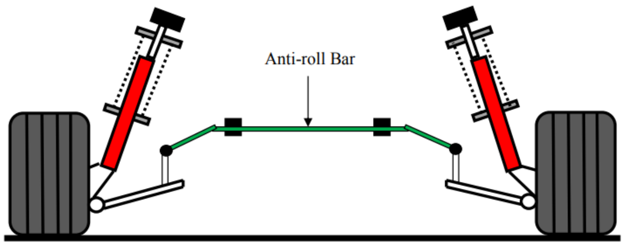


Figure 2.27: An example of an anti - roll bar in a suspension system [37]

In addition to these components; suspension systems comprise further linkage elements such as bushings, ball joints etc.

2.3.2.2 Suspension System types

Suspension system type chosen for a vehicle has a big effect on the ride comfort and safety. The selection of the suspension system is based on parameters such as safety, weight, cost, design etc. Although the function of a suspension system is same for all different types; some suspension types offer more advantageous than others.

2.3.2.2.1 Solid Axle Beam Suspension

Solid axle beam suspension is actually a non-independent suspension system which was explained earlier. It is one of the oldest examples of a suspension system. Nowadays it is usually preferred as the suspension system for rear side of the vehicles. They are also used in situations where heavy loads are carried.

This type of suspension system is in layman terms a rigid axle with wheels on both sides. And on these beam; a combination of shock absorbers and springs are used. Solid axle beam suspension system may comprise leaf springs or coil springs which are more advantageous. Leaf springs are not as efficient as coil springs in regards to their dampening abilities. So a solid axle suspension with coil springs would be able to absorb the vibrations more efficiently. Examples for a solid axle beam suspension with leaf and coil springs are given in Figure 2.28 – 29 below.

Since this type of suspension systems share a rigid beam and therefore are non – independent from each other; the movement of one wheel would affect the other one as well. Due to that; this suspension type offers less ride quality. However they offer good load carrying capabilities and they are relatively cheaper and simpler. [38]

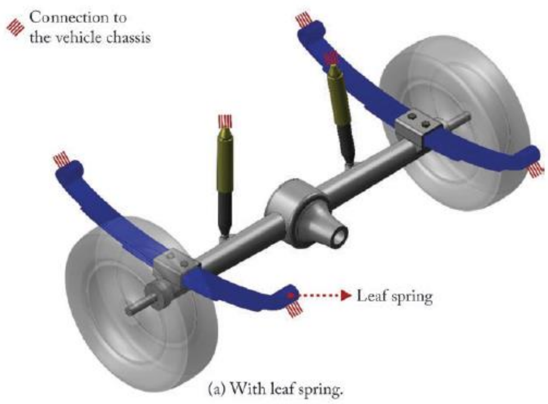


Figure 2.28: Solid axle beam suspension with leaf springs [38]

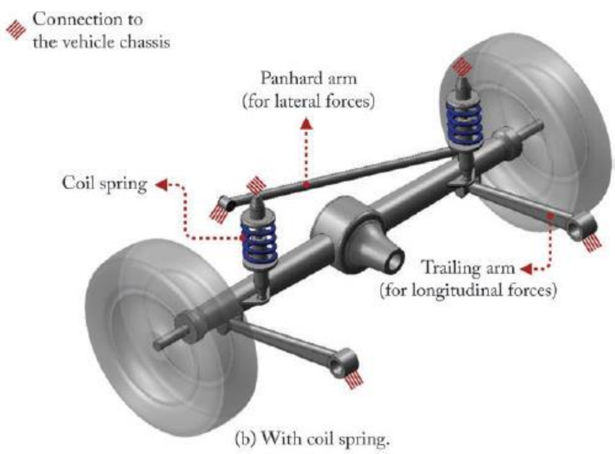


Figure 2.29: Solid axle beam suspension with coil springs [38]

2.3.2.2.2 Torsion Bar Suspension

Another type of suspension system used is the torsion bar suspension system. Torsion bar is basically a metal rod. These metal rod acts as a spring in order to absorb the vibrations. The torsion bar is fixed at one end and it is attached to the vehicle at that end while the other end of the bar is connected to the suspension system. Suspension systems that uses torsion bars are used in some light vehicles while some defence vehicles are also equipped with torsion bar suspensions. Torsion bar suspension systems are relatively simpler and they require less space which makes it possible to have more space for major components such as engine and so on.

The working principle of the torsion bar suspension system is based on the twisting movement of the torsion bar at the end that is connected to the suspension. When a wheel moves vertically due to uneven terrain; the torsion bar will be twisted. Since the other end is fixed and cannot move in anyway; the bar tries to resist this torque motion and return to its untwisted state by pushing the wheel downwards. [39]

Torsion bars must be able to resist high amount torques in order to function properly as a suspension system. Therefore torsion bars must be made of materials that possess high torsional yield properties. There are certain important parameters which defines the properties of the torsion bar. These parameters include selected material, bar length, area of the cross section [40]. Torsion bar suspension system example is given in Figure 2.30.

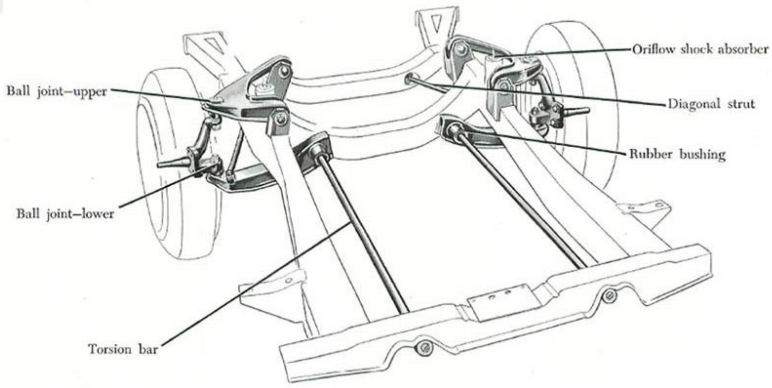


Figure 2.30: A torsion bar suspension system example [41]

2.3.2.2.3 Air Spring Suspension

Springs along with shock absorbers are the most of vital components in suspension systems as stated before. In addition to the previous spring types that were explained such as leaf and coil springs; another spring type which also is the name of another suspension system is air springs and as the name suggests they are filled with compressed air. Whenever there is a vertical movement of the wheels; the air gets more compressed and in doing so absorbs the incoming vibrations. This suspension system was and is still widely used by buses which are heavy vehicles [42]. An example is shown in Figure 2.31.

Air spring suspensions do not comprise of metal springs in contrast to other suspension system types. It comprise airbags which are filled with compressed air. Instead of metal springs; there are 4 airbags which are made rubber and the compressed air is used to absorb the vibrations. The amount of air inside the airbags can be adjusted with the help of a compressor built in to the vehicle. This ability to change the air amount allows the driver to adjust the suspension system to optimum conditions. Due to this adjustability; air springs may offer a more comfortable ride as the suspension can be tuned instantly whenever the driving conditions were changed. However this type of suspension is more complex, more prone to failures and it would also be more costly as the instalment costs are higher. [43]

Figure 2.31: Air suspension system example [44]

2.3.2.2.3 Double Wishbone Suspension

As mentioned several times; there are different suspension system types and all of them have their uses along with their advantages and disadvantages. The next suspension system type is double wishbone suspension and it is one of the most popularly used front suspension system for many passenger vehicles along with the MacPherson suspension.

Double wishbone suspension is a popular front suspension and it is also known as short long arm suspension or double A arm suspension. The reason for this is the fact that a double wishbone suspension has two control arms and their sizes are different from each other [45]. An illustration of a double wishbone suspension system is given in Figure 2.32 below.

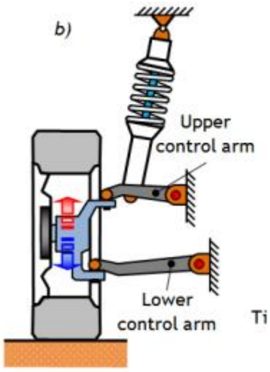


Figure 2.32: Illustration of a double wishbone suspension [46]

A double wishbone suspension comprises a coil spring placed around a shock absorber. Furthermore there are two control arms which are upper control arm and lower control arm. These control arms are called wishbones due to their shapes and they are attached to the wheel hub at one end and to the chassis on the other end. The lower control arm is larger than the upper control arm and this difference is the reason behind a major advantage of double wishbone suspensions. Double wishbone suspension systems are the better choice compared to the other popular suspension type MacPherson suspension regarding the parameters such camber, kingpin inclination, scrub radius etc. which are important factors about steering. The size difference between the control arms allow double wishbone suspensions to offer better control of these parameters. [47]

Figure 2.33 below illustrates the size differences of the control arms. The vertical movement of the wheels are much smoother as a result of having two control arms and the size difference of the control arms.

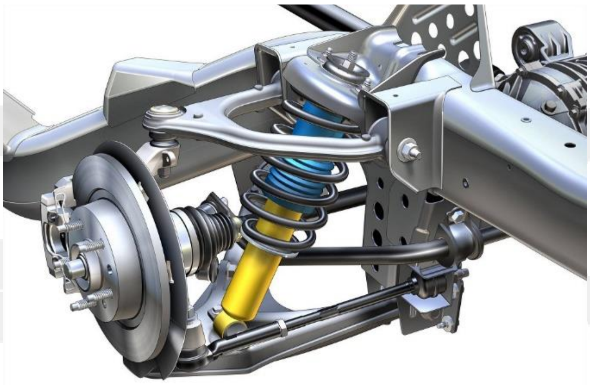


Figure 2.33: Double wishbone suspension system illustration [48]

When a car with a double wishbone suspension system goes over a bump; the corresponding wheel move vertically. Since the control arms are attached to the wheel; they would move accordingly and help controlling the vehicle position. As a result of this movement; the coil spring would compress and absorb the vibrations occurring because of the irregularities on the road surface. The compression of the spring would lead to the movement of the piston which is placed in the shock absorber. Hence the hydraulic fluid or gas inside the shock absorber would resist against the piston; the movement of the piston would be quite slow as the fluid or gas can only pass through small channels on the valve which is placed at the bottom of the piston. Therefore; the movement of the piston would transform the energy that is absorbed by the spring into heat and transfer it to the fluid or gas. These actions would result in a passenger cabin which is secluded and not affected by the vibrations.

As stated before; double wishbone suspension system is widely used in passenger cars. It is especially common for high segment vehicles and SUVs due to its good features [48]. In Figure 2.34 a photo of an Audi R8 vehicle with a double wishbone suspension is given. In this image; other components such as steering axis, brake disc etc. can be seen as well.

Figure 2.34: Audi R8 with a double wishbone suspension system [49]

2.3.2.2.4 MacPherson Strut Suspension

MacPherson strut suspension system is a front suspension system used widely in many modern passenger cars today. It is the most popular suspension system used along with double wishbone suspension system.

MacPherson strut suspension was developed by the American automotive engineer Earle S. MacPherson in the 1940s. It was during his time at Ford Motor Company where he developed the suspension system that is known by his name. MacPherson strut suspension was used for the first in Ford Vedette in 1949 [50]. Since then it gained a lot of popularity and an example of it is shown in Figure 2.35.

MacPherson strut suspension system and double wishbone suspension system are similar to each other. The main difference is the number of control arms used. MacPherson strut suspension system comprises only one control arm which is located at the bottom whereas double wishbone suspension has two control arms respectively upper control arm and a lower control arm. Other than a control arm; MacPherson strut suspension comprises a shock absorber, a coil spring, spring seats and some linkage elements such as ball joints. The lower control arm is attached to the wheel hub at one end and to the vehicle frame on the other end similar to double wishbone suspension. It was stated that having two control arms offer more control over certain parameters such as camber angle. Since MacPherson has only one; double wishbone suspension offers better control over these parameters. [51]

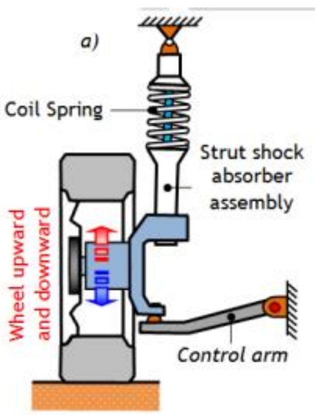


Figure 2.35: MacPherson strut suspension system illustration [46]

MacPherson's suspension system is known as MacPherson strut which is actually a name of one of the components. MacPherson strut is basically the combination of a shock absorber and a coil spring. MacPherson strut is a metal rod that acts like a second control arm and is attached to the vehicle from the top while the bottom is attached to the wheel hub. MacPherson strut is also a structural component that helps carrying load. This component has a piston and a hydraulic fluid inside of it which is used to prevent the oscillation of the spring. The strut also has spring seats where the coil spring is placed. So a MacPherson strut can be defined as a component comprising a strut housing which carries the coil spring which is used to absorb the excitations and surrounds the damping unit to transfer the energy absorbed by the spring [45]. An example of a strut is shown in Figure 2.36 below.

Figure 2.36: A strut example [52]

As the MacPherson strut is attached to wheel hub; when a wheel moves upwards the MacPherson strut moves upwards as well. The movement of the strut housing would lead to the compression of the spring and in the meantime the piston inside the strut housing which is attached to the vehicle body from the top would come in contact with the fluid or the gas inside the strut housing. The piston itself is a metal rod with a valve with channels and it attached to the vehicle frame from the top so it does not move. However the strut hosing moves upwards and downwards in accordance with the wheels and this leads to the fluid inside to pass through the valve and in doing so slow down the movement of the spring in order to prevent from oscillation and bouncing. Figure 2.37 below shows a Audi TTRS with a MacPherson strut suspension.

Figure 2.37: Audi TTRS with MacPherson strut type suspension [49]

MacPherson strut suspension's biggest advantage is its simplicity. The fact that the major components which are the shock absorber and the coil spring are brought together into one component is one of the main reasons for the popularity of this suspension system. All other components such as dustboot, upper mount and strut bearing which is the combination of the upper spring seat, the metal bearing and the upper cap are all assembled together. A MacPherson strut suspension could easily be assembled separately and then installed to the vehicle with everything ready. Attaching the bottom of the strut housing to the wheel hub and attaching the top side to the vehicle frame is all that is needed. A comparison between the most popular suspension systems which are double wishbone suspension and MacPherson strut suspension system is given shortly [23]. Another illustration of the MacPherson strut suspension is shown is Figure 2.38 and all major components are named.

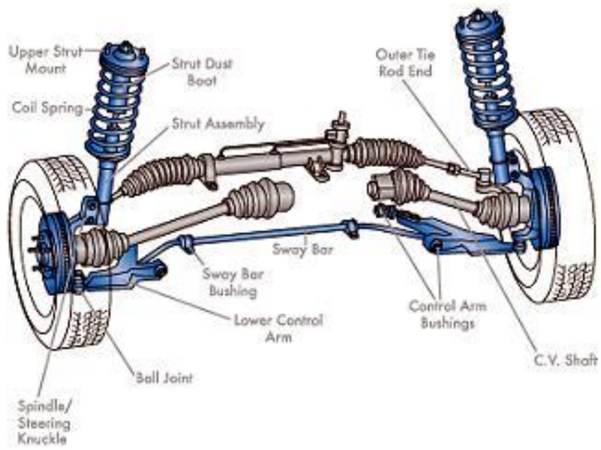


Figure 2.38: Illustration of a MacPherson strut suspension and its components [53]

3 Design and Analysis Activities

In this chapter; design and analysis activities that were conducted are explained. The suspension system component which is the topic of this thesis is called strut bearing. Strut bearing is an important component in the MacPherson strut suspension system and it comprises subcomponents. These subcomponents are called as the upper spring seat, upper cap and a bearing. The upper spring seat and the upper cap are made of plastic and they are the focus of this thesis work whereas the bearing is made of metal and is excluded from this study. Steps followed for the design and analysis activities are shown below in Figure 3.1.

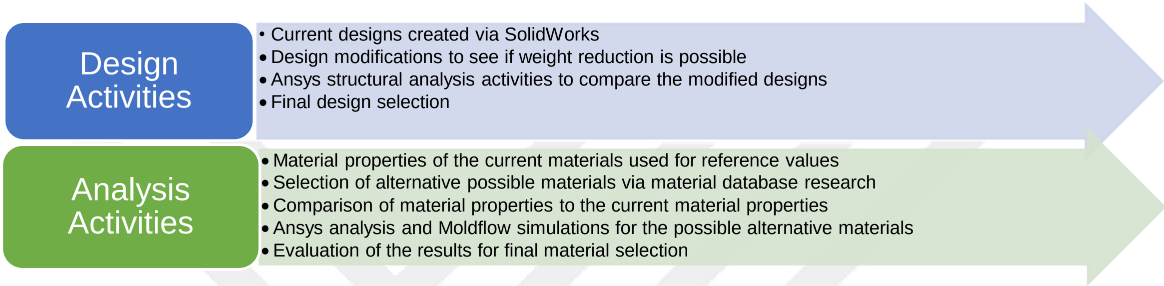
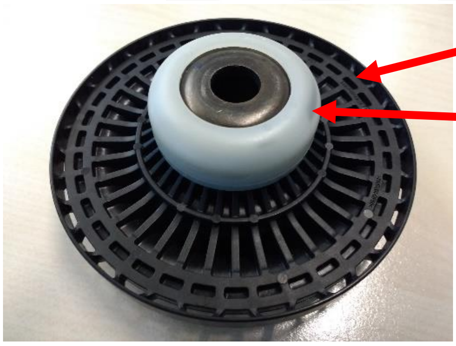


Figure 3.1: Design and analysis activities procedure

In Figure 3.2 below; the strut bearing used by Renault is shown and the sub components are defined. The function of these components are explained as well.



- **Upper Spring Seat:** Coil spring presses against it from the bottom side
- **Upper cap:** Covers the metal bearing from environmental effects
- Strut bearing enables the rotation of the suspension system in acc. to the tire movements (Suspension system is attached to the wheel hub from the bottom)

Figure 3.2: Strut bearing used by Renault and the function of the components

The strut bearing is a vital component in the suspension system. The upper spring seat is under constant load from the spring from the bottom side whereas the upper cap covers the metal bearing from environmental effects. Another important function of the strut bearing is to enable the rotation of the suspension system in accordance to wheel movements as the suspension system is attached to the wheel hub from the bottom side. Due to its importance; design and material selection activities for the strut bearing were conducted under the following criteria:

- Design improvement without affecting the overall assembly
- Overall weight
- Not restricted materials by Renault
- No performance loss

3.1 Upper Spring Seat

Upper spring seat is the part of the strut bearing in a MacPherson strut suspension system where the coil spring presses against. The coil spring is placed on the lower spring seat on the strut housing from the bottom and it presses against the upper spring seat. When a wheel moves vertically due to road irregularities; the strut housing moves upwards as well and since the upper spring seat is fixed and therefore cannot move; the coil spring compresses and in doing so prevents the transfer of road shocks to the passenger cabin.

An example of a MacPherson strut suspension system assembly is shown in Figure 3.3 below. From this figure; the location of the upper spring seat can be seen and also how the suspension system is connected to the wheel hub is shown.

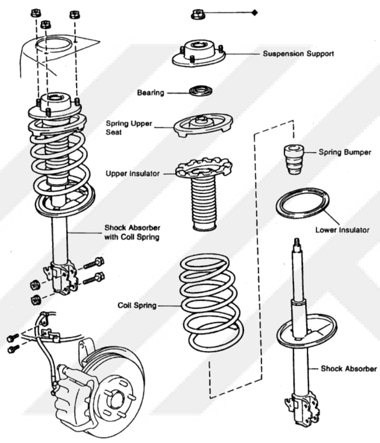


Figure 3.3: MacPherson strut suspension assembly and components [55]

3.1.1 Design Activities

While the function of the upper spring seat is same for all customers; the design of the part varies from manufacturer to manufacturer. Therefore in the frame of this thesis work; the design of the upper spring seat was modified to see if the design can be improved via weight decrease without affecting the properties of the part. The main objective of this study was to find the optimum material and improve the design if possible.

SolidWorks software was mainly used for the design activities of the upper spring seat. The current part was designed and analysed geometrically. Then modifications were conducted to see if material removal is possible. Modified design were analysed to see the effect of these modifications on the mechanical properties of the final product. The main parameter was the strength values as the upper spring seat carries the loads coming from the coil spring compression. In Figures 3.4 – 3.5; a simple design of a MacPherson strut suspension system is shown in order to highlight the function and location of the upper spring seat. Components such as upper strut mount, filtering unit etc. which are located above the upper spring seat are excluded from the design.

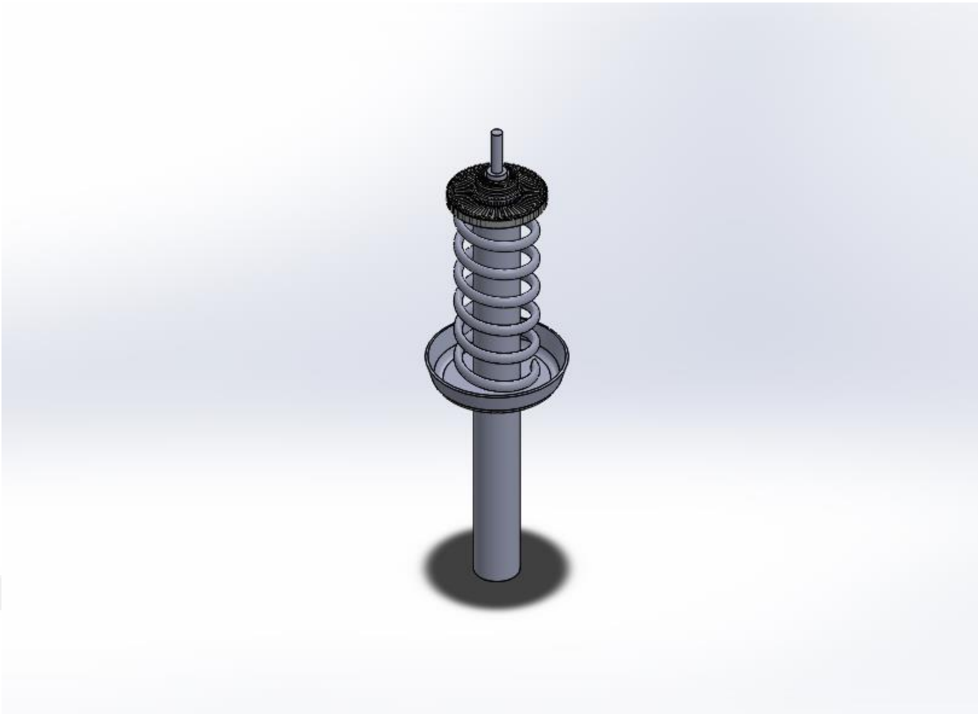


Figure 3.4: Isometric view of the MacPherson strut suspension system design

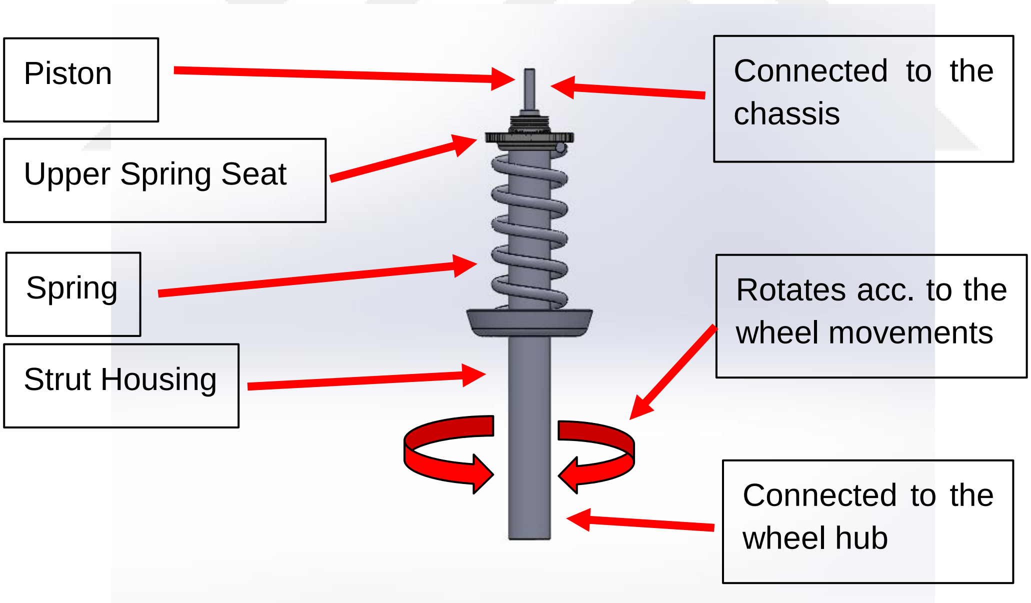


Figure 3.5: Front view of the MacPherson strut suspension design

It can be seen from these figures that the upper spring seat is in contact with the coil spring and also the piston inside the strut housing passes through the upper spring seat. The metal bearing in the strut bearing component mentioned earlier is used to enable the rotation of the upper spring seat around the piston when the wheels turn right or left.

In Figure 3.6 below; current upper spring seat design is shown. The highlighted part on the bottom right figure is the contact point with the coil spring. Since the bottom part has to withstand the load from the spring; the design modifications were focused on the top surface so the strength would not be affected. Another design criteria was the overall assembly as mentioned before. Since the upper spring seat is in contact with various components such as piston, spring, dustboot, filtering unit etc. the modifications should not affect the overall assembly.

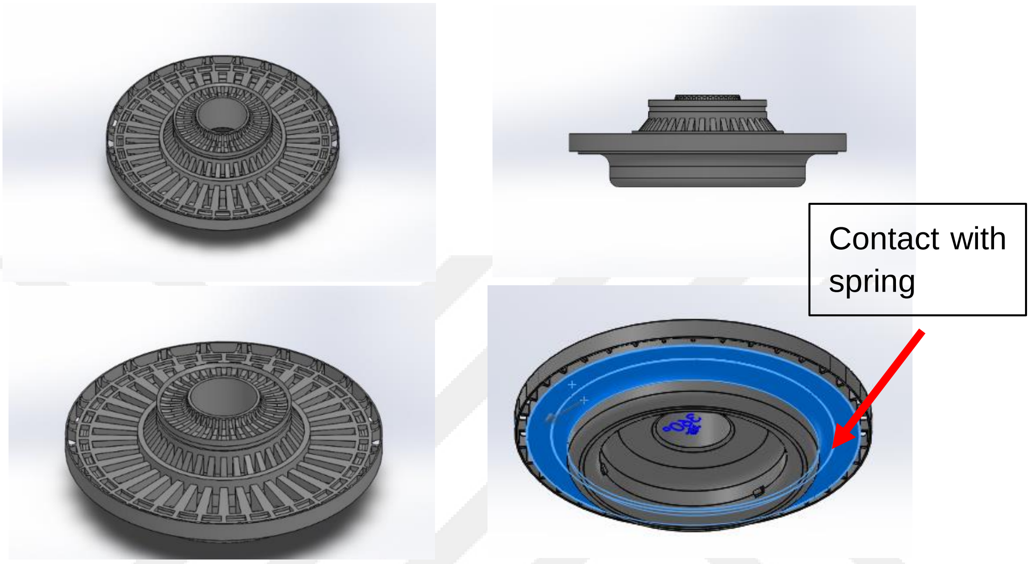


Figure 3.6: Current upper spring seat design

As it can be seen from Figure 3.6; the upper spring seat has a complicated geometry. The geometry of the upper spring seat along with the chosen material is vitally important regarding the final properties of the part. The bottom side is where the spring seat and the spring has contact. The upper side has plenty of channels to have a lighter part and it also comprises channels for the bearing. The channels on the upper level in the figures is where spherical metal balls are used to allow the rotation of the upper spring seat around the piston inside the strut housing.

The design modifications were focused on the upper side of the geometry. The channels geometry, number etc. were modified in order to evaluate the effects of those parameters. Figure 3.7 – 8 shows modified upper spring seat designs. As it can be seen from these images; the number of channels and the dimensions of the channels were the main parameters. Since the bottom part of the upper spring seat is in contact with the coil spring; activities regarding the possibility of weight decrease via design modifications were focused on the top side of the upper spring seat. Another difference in these designs is the outer most circle. This part exist due to its necessity during some tests conducted such as seal test. The connection points between this circle and the main assembly is another variable in these designs. In summary there are three main design versions. The difference between the first and second design version is the connection points between the most outer circle and the main part. Third design version consist a design group first two groups with the addition of a circular wall.

Figure 3.7: Modified upper spring seat designs – Design Version 1

The number of channels varies between 8 and 36 whereas the degree between the channels is between 5 and 36 degrees. These changes applied regarding the number of channels and the degree between them were carried out based on trial – error as the aim was to see if weight removal would be possible without affecting the properties in a negative way.

Figure 3.8: Modified upper spring seat designs – Design Version 2

In addition to the changes to the channels on the top surface; further modifications were conducted to analyse the effect. Figure 3.9 shows that in contrast to other designs; another circular wall was added to the top surface. This secondary wall was added to evaluate if the addition of another wall would compensate the reduced number of channels.

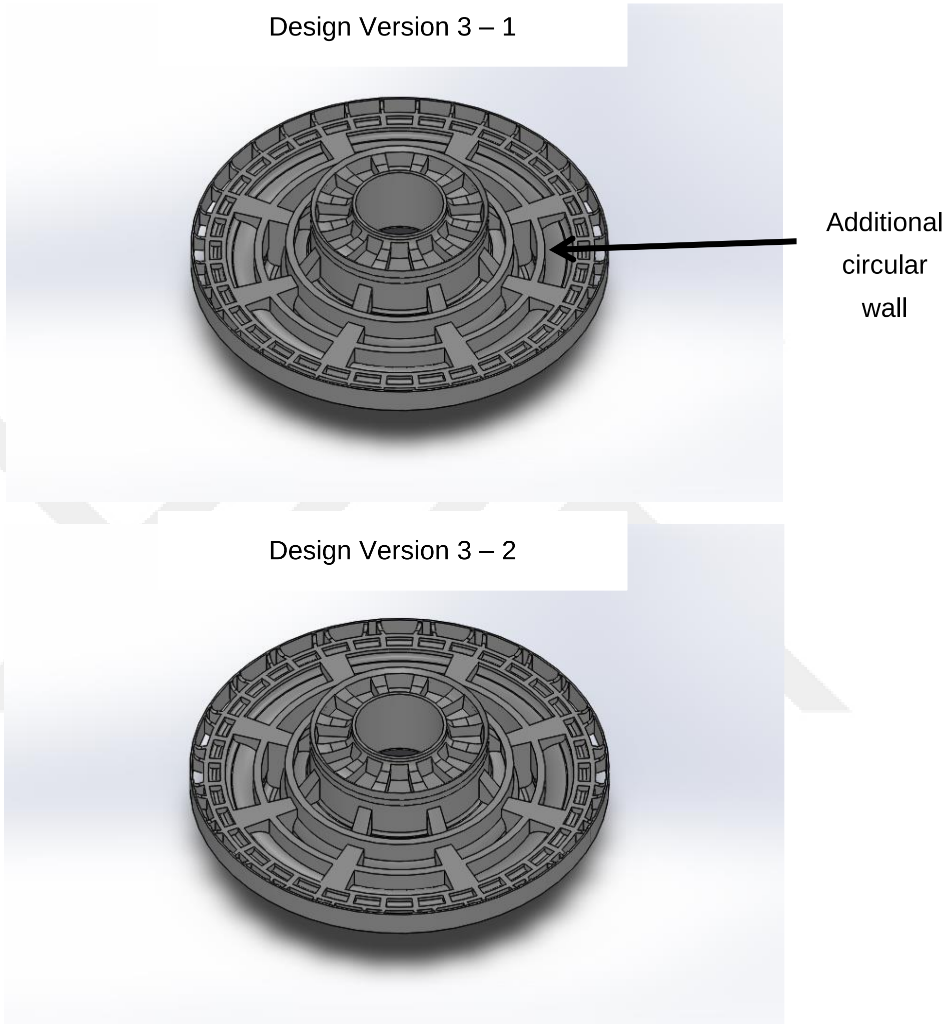


Figure 3.9: Modified upper spring seat designs – Design Version 3

3.1.2 Analysis Activities

After working on different design modifications for the upper spring seat; these designs were analysed to evaluate the effects of these changes on the mechanical properties of the final product. Ansys software was used for analysing the stress values of these designs under certain amount of loads and boundary conditions. First step after importing the geometry was to apply the mesh. Table 3.1 shows data regarding mesh type and statistics along with data regarding applied force values and boundary conditions.

Table 3.1: Ansys Static Structural Analysis Details

<table>
<tr><th rowspan="2">Design Identification</th><th rowspan="2">Mesh Method</th><th colspan="2">Mesh Statistics</th><th rowspan="2">Forces Applied (Newton)</th><th rowspan="2">Boundary Condition Type</th></tr>
<tr><th>Number of Nodes</th><th>Number of Elements</th></tr>
<tr><td>Design Version 1 – 1</td><td rowspan="7">Body Sizing</td><td>319034</td><td>188233</td><td rowspan="7">F_1: 4000N in -y direction
F_2: 15600 N in y direction</td><td rowspan="7">- Cylindrical Support
- Radial: Fixed
- Axial: Fixed
-Tangential: Free</td></tr>
<tr><td>Design Version 1 – 2</td><td>302910</td><td>178414</td></tr>
<tr><td>Design Version 1 – 3</td><td>286694</td><td>168940</td></tr>
<tr><td>Design Version 1 – 4</td><td>288788</td><td>169841</td></tr>
<tr><td>Design Version 1 – 5</td><td>280248</td><td>164393</td></tr>
<tr><td>Design Version 1 – 6</td><td>275317</td><td>160769</td></tr>
<tr><td>Design Version 1 – 7</td><td>259317</td><td>151326</td></tr>
</table>

The data in the table above are given only for one design group as the parameters such as applied forces, boundary conditions and mesh method were same for all the design versions. The forces applied to the upper spring seat are shown in Figure 3.10 and the details about those forces are shown in Figure 3.11.

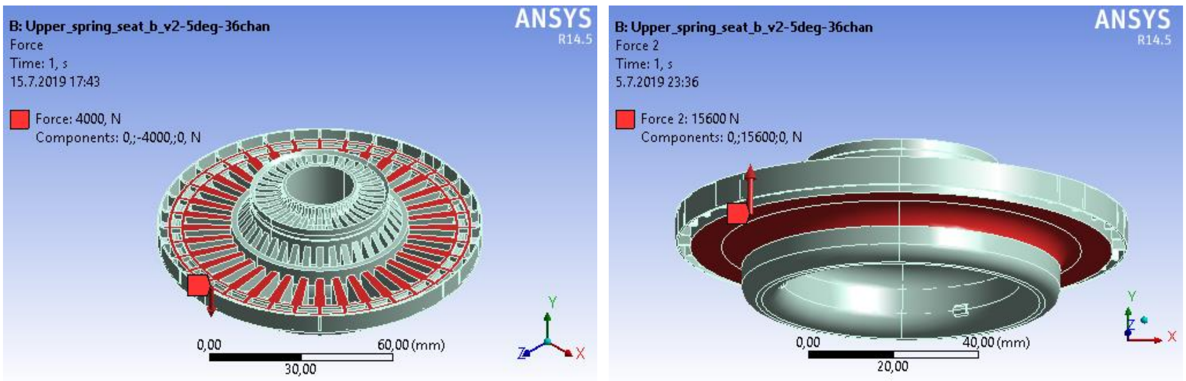


Figure 3.10: Forces applied to the upper spring seat for Ansys analysis

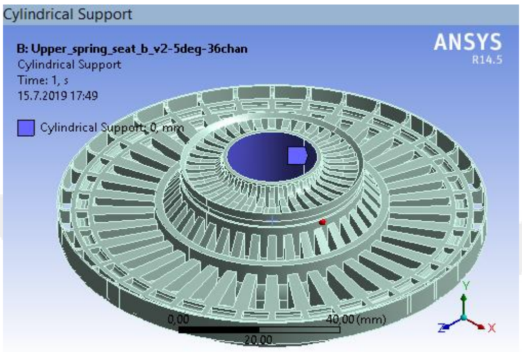
Details of "Force"

Scope	
Scoping Method	Geometry Selection
Geometry	1 Face
Definition	
Type	Force
Define By	Components
Coordinate System	Global Coordinate System
X Component	0, N (ramped)
Y Component	-4000, N (ramped)
Z Component	0, N (ramped)
Suppressed	No

Details of "Force 2"

Scope	
Scoping Method	Geometry Selection
Geometry	3 Faces
Definition	
Type	Force
Define By	Components
Coordinate System	Global Coordinate System
X Component	0, N (ramped)
Y Component	15600 N (ramped)
Z Component	0, N (ramped)
Suppressed	No

Figure 3.11: Details of the applied forces



Details of "Cylindrical Support"

Scope	
Scoping Method	Geometry Selection
Geometry	2 Faces
Definition	
Type	Cylindrical Support
Radial	Fixed
Axial	Fixed
Tangential	Free
Suppressed	No

Figure 3.12: Boundary condition of the upper spring seat and its details

Cylindrical support boundary condition was selected due to part's geometry and since the upper spring seat can rotate around the piston; tangential direction was chosen as free to move whereas radial and axial directions were chosen as fixed.

Before explaining the activities conducted via Ansys software; further details about the analysis settings such as analysis type, solver target etc. are shown in Figure 3.13 below. The analysis type was static structural as the aim was to get values such as stress, strain etc.

Details of "Static Structural (B5)"

Definition	
Physics Type	Structural
Analysis Type	Static Structural
Solver Target	Mechanical APDL
Options	
Environment Temperature	22, °C
Generate Input Only	No

Details of "Analysis Settings"

Step Controls	
Number Of Steps	1,
Current Step Number	1,
Step End Time	1, s
Auto Time Stepping	Program Cont...
Solver Controls	
Solver Type	Program Cont...
Weak Springs	Program Cont...
Large Deflection	Off
Inertia Relief	Off

Details of "Analysis Settings"

Restart Controls	
Generate Restart Points	Program Cont...
Retain Files After Full Solve	No
Nonlinear Controls	
Force Convergence	Program Cont...
Moment Convergence	Program Cont...
Displacement Convergence	Program Cont...
Rotation Convergence	Program Cont...
Line Search	Program Cont...
Stabilization	Off

Details of "Analysis Settings"

Output Controls	
Stress	Yes
Strain	Yes
Nodal Forces	No
Contact Miscellaneous	No
General Miscellaneous	No
Store Results At	All Time Points
Max Number of Result Sets	Program Cont...

Details of "Analysis Settings"

Analysis Data Management	
Solver Files Directory	C:\Users\SAM...
Future Analysis	None
Scratch Solver Files Directory	
Save MAPDL db	No
Delete Unneeded Files	Yes
Nonlinear Solution	No
Solver Units	Active System
Solver Unit System	nmm

Details of "Analysis Settings"

Visibility	
[A] Force (X)	Display
[B] Force (Y)	Display
[C] Force (Z)	Display
[D] Force 2 (X)	Display
[E] Force 2 (Y)	Display
[F] Force 2 (Z)	Display

Figure 3.13: Ansys static structural analysis settings and parameters

In Figure 3.14; an example of the analysis activities can be seen.

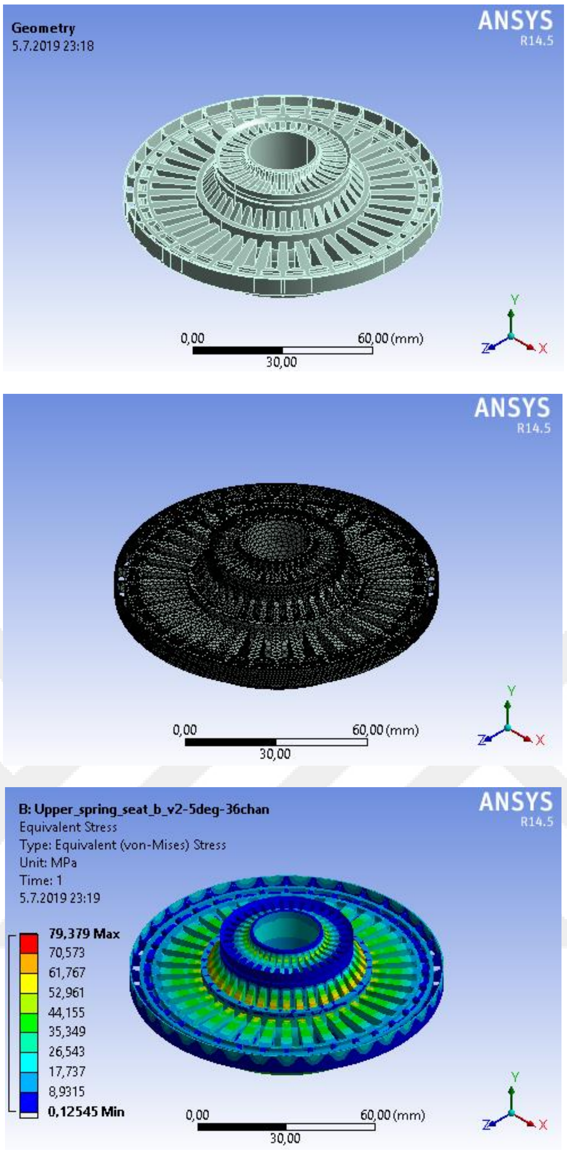


Figure 3.14: An example from Ansys analysis activities

A cut through of the examples shown above are shown in Figure 3.15 to illustrate the inner stress distribution.

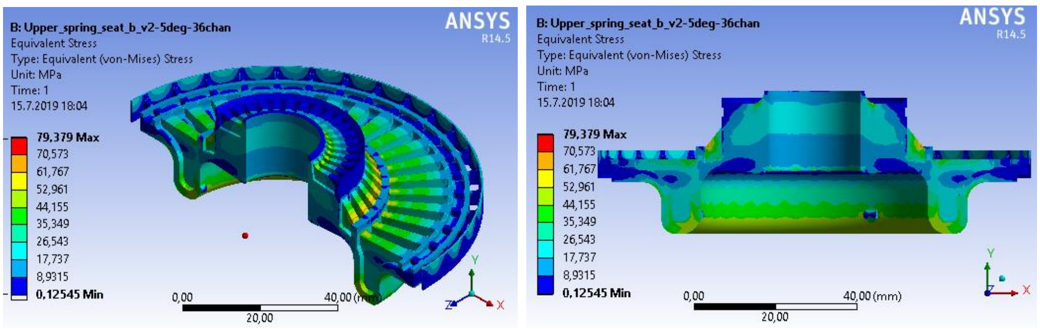
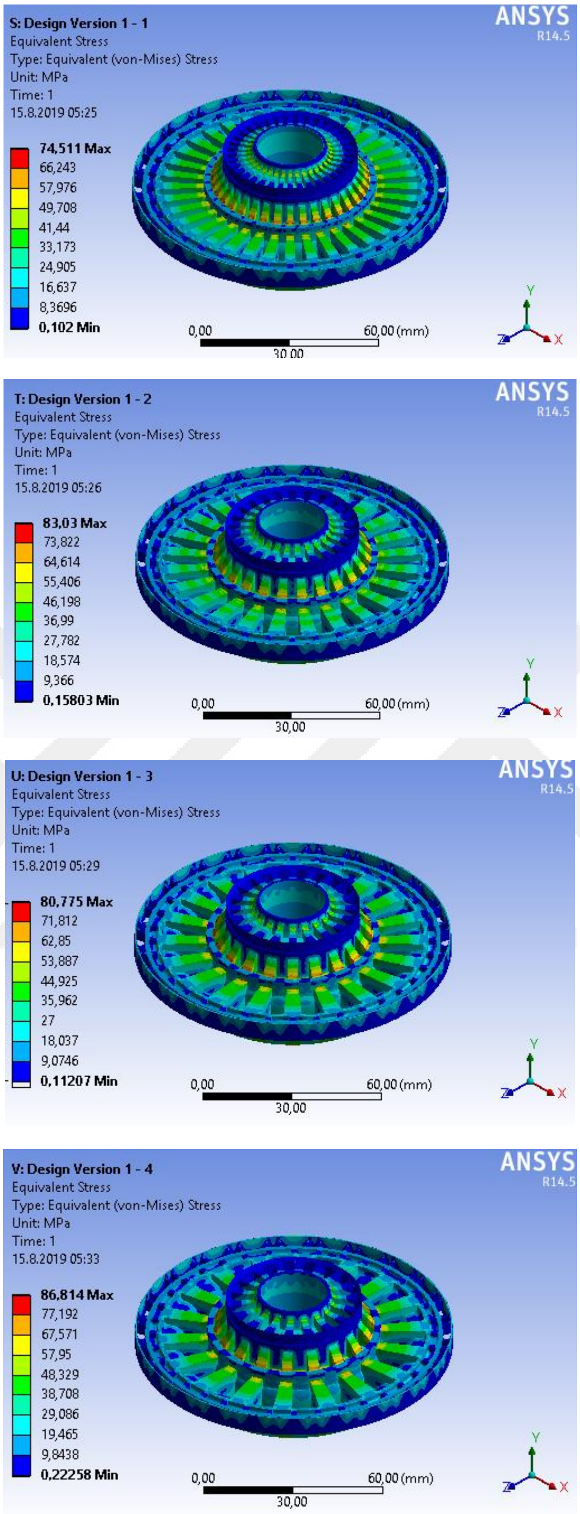


Figure 3.15: Inner stress distribution of the upper spring seat

Figure 3.16 – 20 shows the results of the analysis of upper spring seat designs.



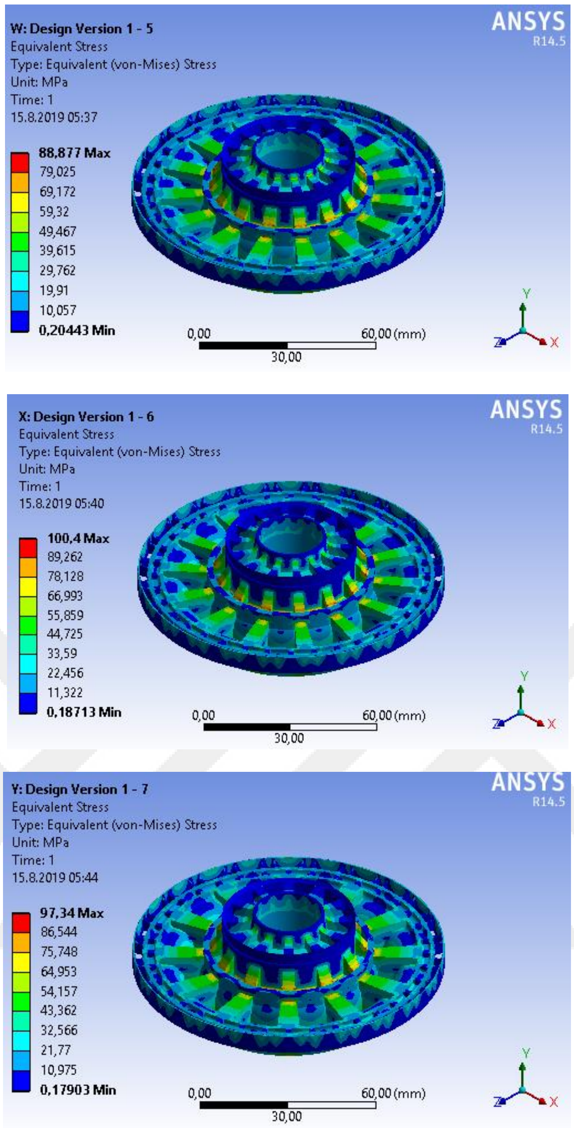
Design Version 1 – 1

Design Version 1 – 2

Design Version 1 – 3

Design Version 1 – 4

Figure 3.16: Ansys analysis results of design version 1



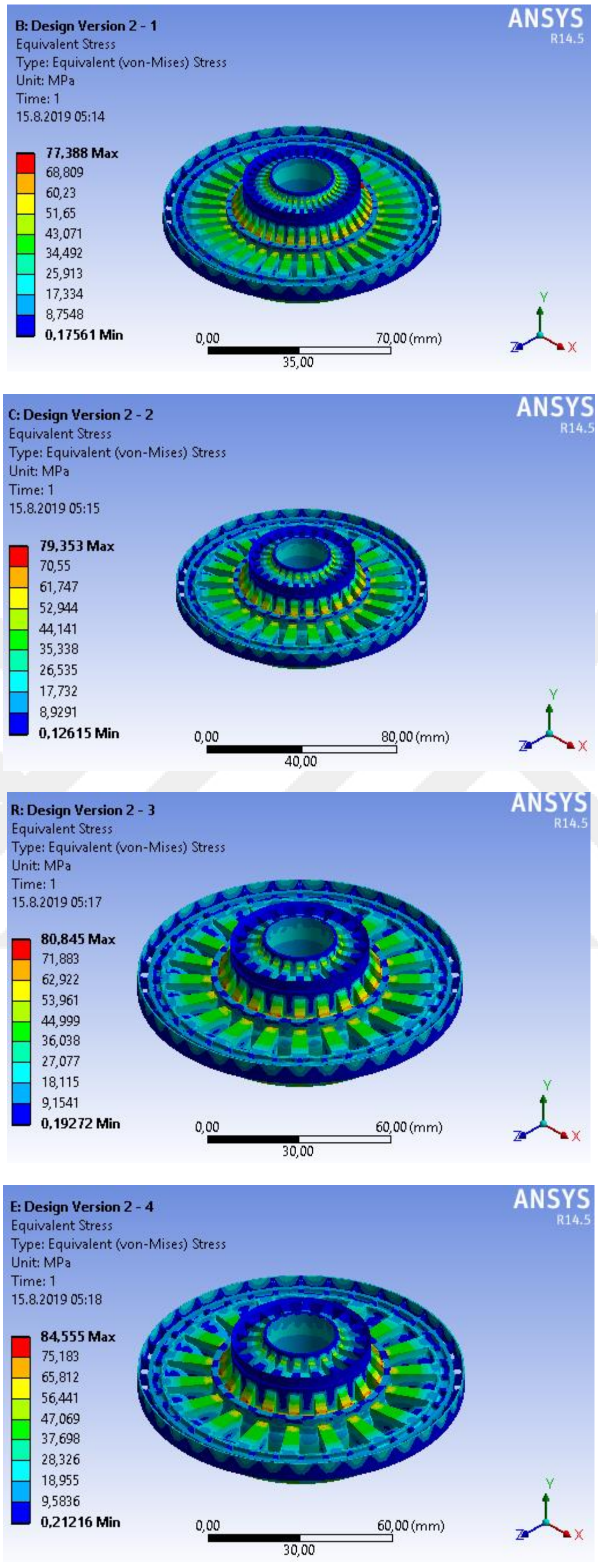
Design Version 1 – 5

Design Version 1 – 6

Design Version 1 – 7

Figure 3.17: Further Ansys analysis results of design version 1

Analysis results shown in Figure 3.16 and 3.17 are from the design version 1 group. The difference between these designs is the number of channels and the degree between the channels. Figure 3.18 – 19 shows analysis results for designs from design version 2 group. The difference between design version 1 shown in Figure 3.16 – 17 and design version 2 shown in Figure 3.18 – 19 is the connection between the most outer circle and the rest of the assembly. The designs in the same design version group varies from each other by the number of channels and the degree between the channels.



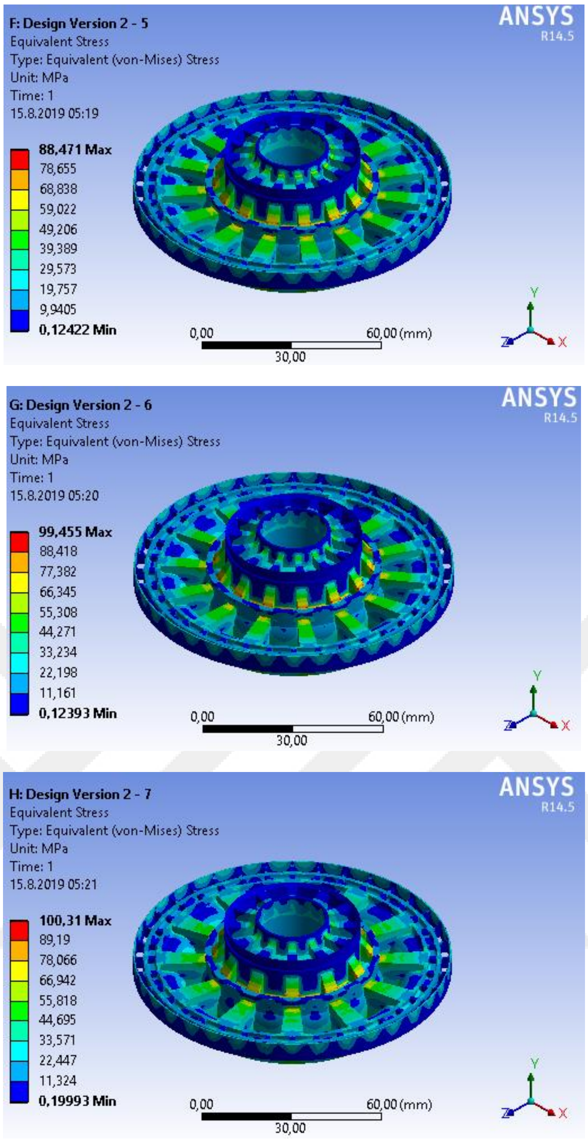
Design Version 2 – 1

Design Version 2 – 2

Design Version 2 – 3

Design Version 2 – 4

Figure 3.18: Ansys analysis results of design version 2



Design Version 2 – 5

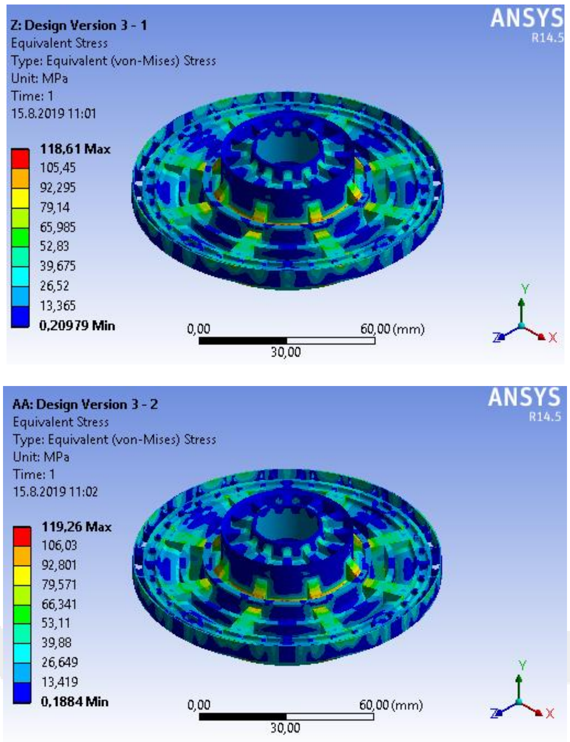
Design Version 2 – 6

Design Version 2 – 7

Figure 3.19: Further Ansys analysis results of design version 2

As it can be seen from these analysis results; the number of channels along with the degree between channels have an effect on the properties of the upper spring seat. Changing these parameters affects the strength of the part as it is shown in these analysis results by different stress values.

Besides these two design group; there is another design modification that was applied. One design from both of these two design version were modified in a different way. Another circle was added to the top surface and it was extruded towards down in order have more support. The effect of this addition was analysed in Ansys as well and the results are shown in Figure 3.20.



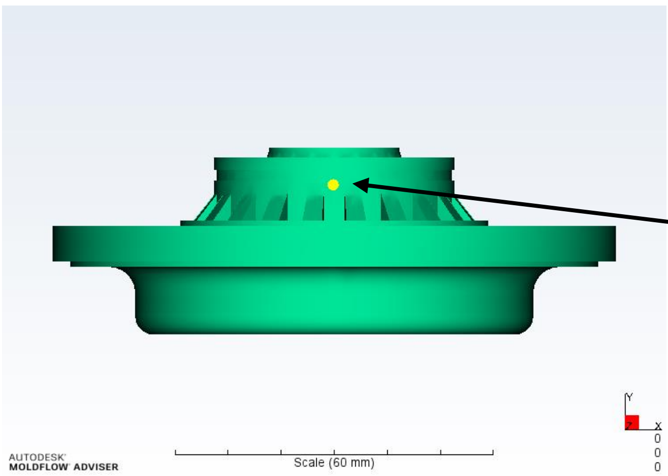
Design Version 3 – 1

Design Version 3 – 2

Figure 3.20: Ansys analysis results of design version 3

3.1.3 Moldflow Simulations

Another tool used for this thesis work was the Moldflow software. This software allows the user to simulate the flow of the plastic melt during a plastic injection process. Upper spring seat was analysed using Moldflow software. Parameters such as fill time, injection pressure, temperature drop etc. are evaluated based on the simulation results. Before conducting the simulations; certain parameters were selected. The simulation conditions were same for all the designs. These conditions are shown in Figure 3.22. A solid model example and the location of the gate which was also same for all the designs are shown in Figure 3.21 below.



Location of the gate

Figure 3.21: Solid model of the part and the location of the gate

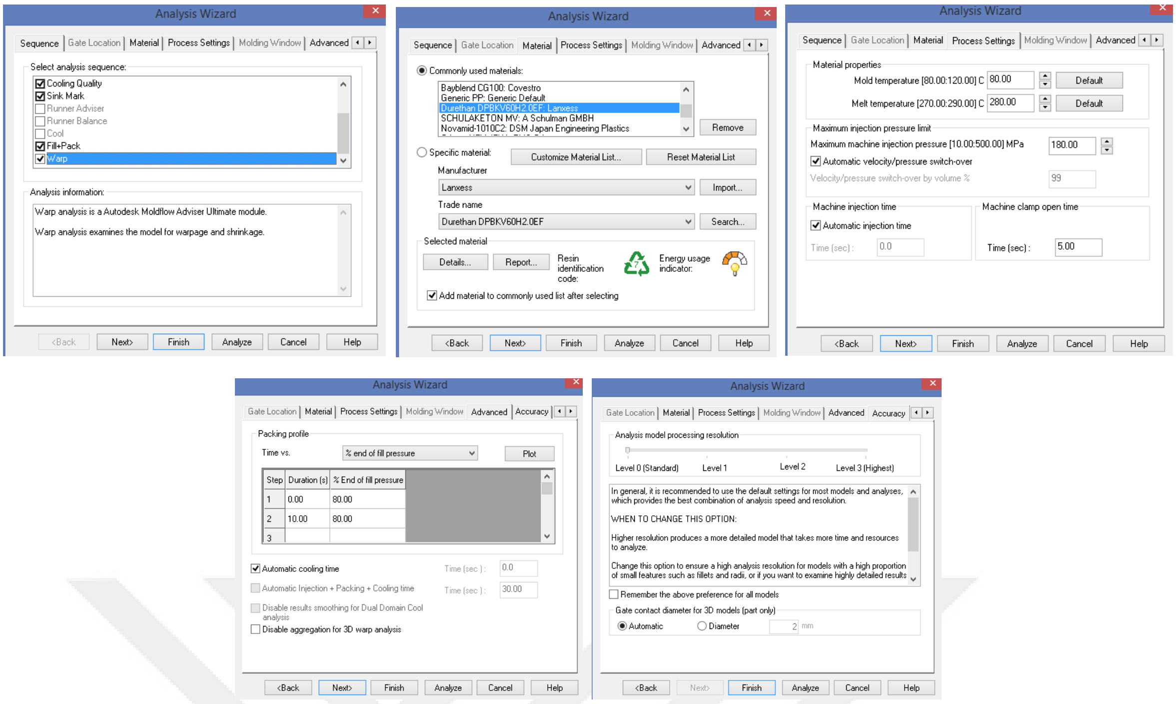


Figure 3.22: Moldflow simulation settings used for simulations

In Figure 3.23; the results obtained from the selected settings are shown.

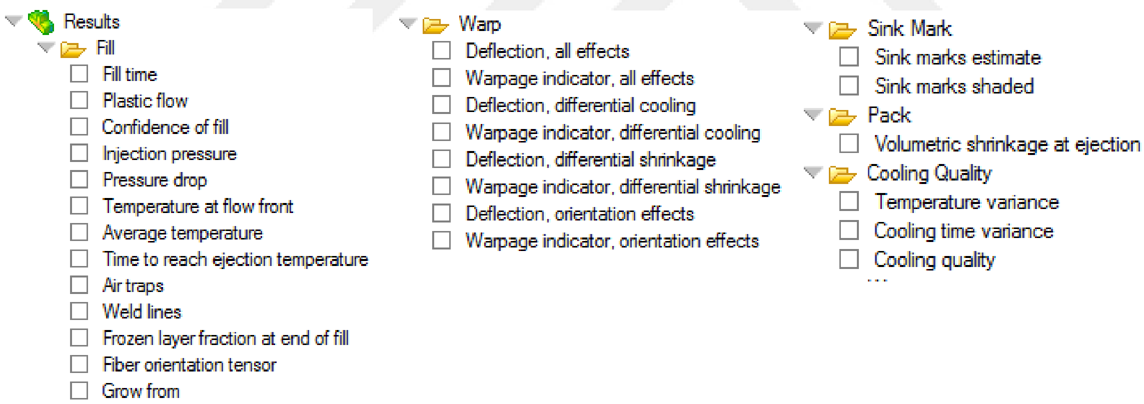


Figure 3.23: List of results obtained from the applied settings via Moldflow

After defining the settings; the simulation activities were conducted. Simulations for the upper spring seat were used for two different reasons. First reason was to evaluate the effect of the design changes on the properties such as fill time, ejection time etc. whereas the second reason was to compare different materials for the new material selection after the final design was selected. Selection criteria regarding the Moldflow simulations were the results obtained such as fill time, time to reach ejection temperature, quality prediction, confidence of fill. As shorter fill time or ejection times would mean shorter cycle times and this would lead to producing the same number of parts in a shorter time. Therefore; cost could be reduced via reducing machine costs and labour costs as a result of shorter working time for the machine and people. An example of the Moldflow simulation activities is shown in Figure 3.24.

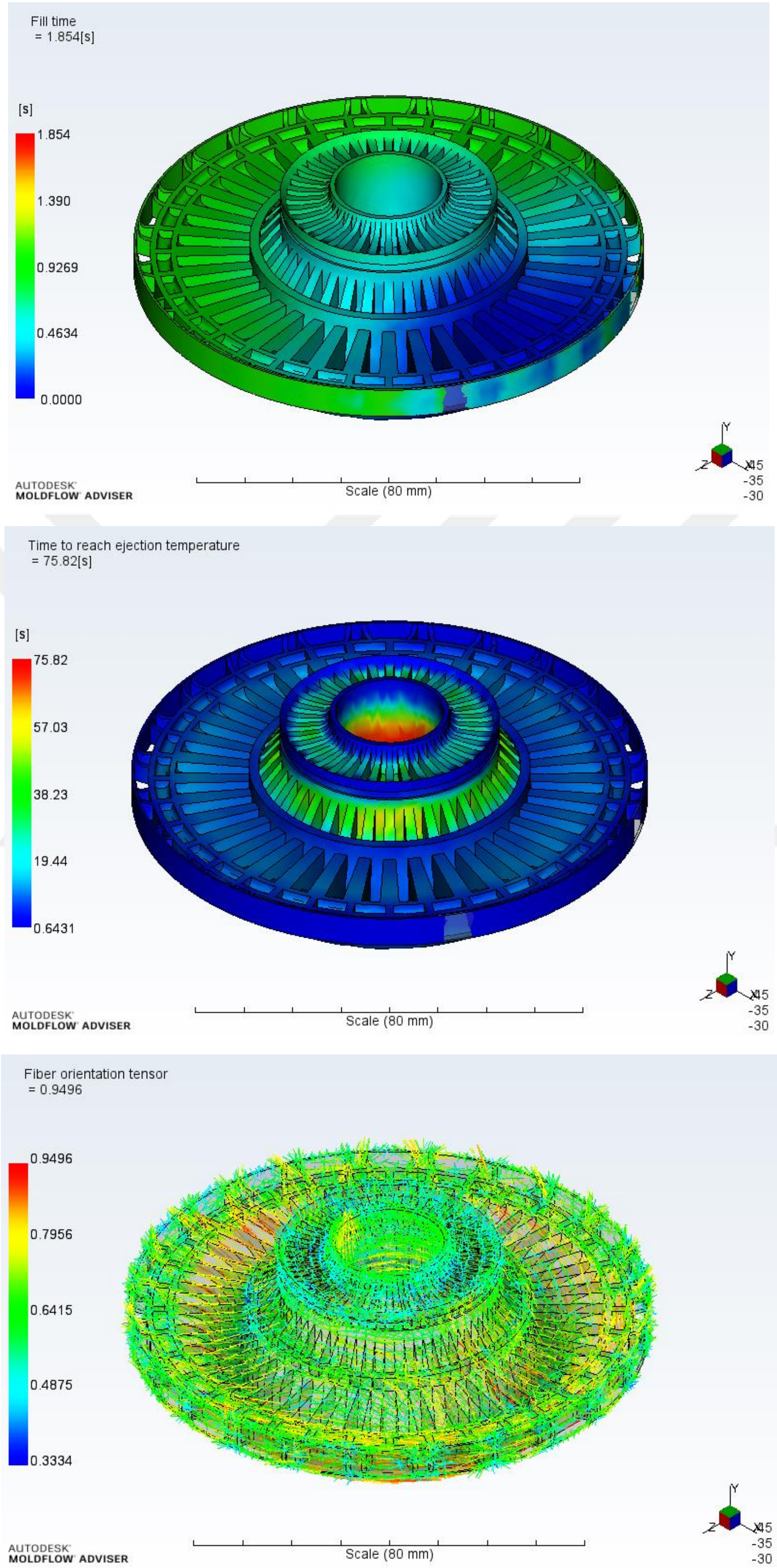


Figure 3.24: Moldflow simulations of the upper spring seat

3.2 Upper Cap

Second component of this thesis work is called the upper cap. It was mentioned earlier that a strut bearing comprises subcomponents respectively upper spring seat, upper cap and metal bearing. It was also stated earlier that the focus of this thesis work is on selecting the optimum material for the upper spring seat and the upper cap which are made of plastics.

3.2.1 Design Activities

Upper cap is a small component used in the MacPherson strut suspension system. It is placed onto the upper spring seat. In the design of the upper spring seat there were channels on two different levels. The channels on the higher levels are where the spherical balls of the bearing are placed and the upper cap is used to provide cover for the bearing. In Figure 3.25 below; design of the upper cap is shown.

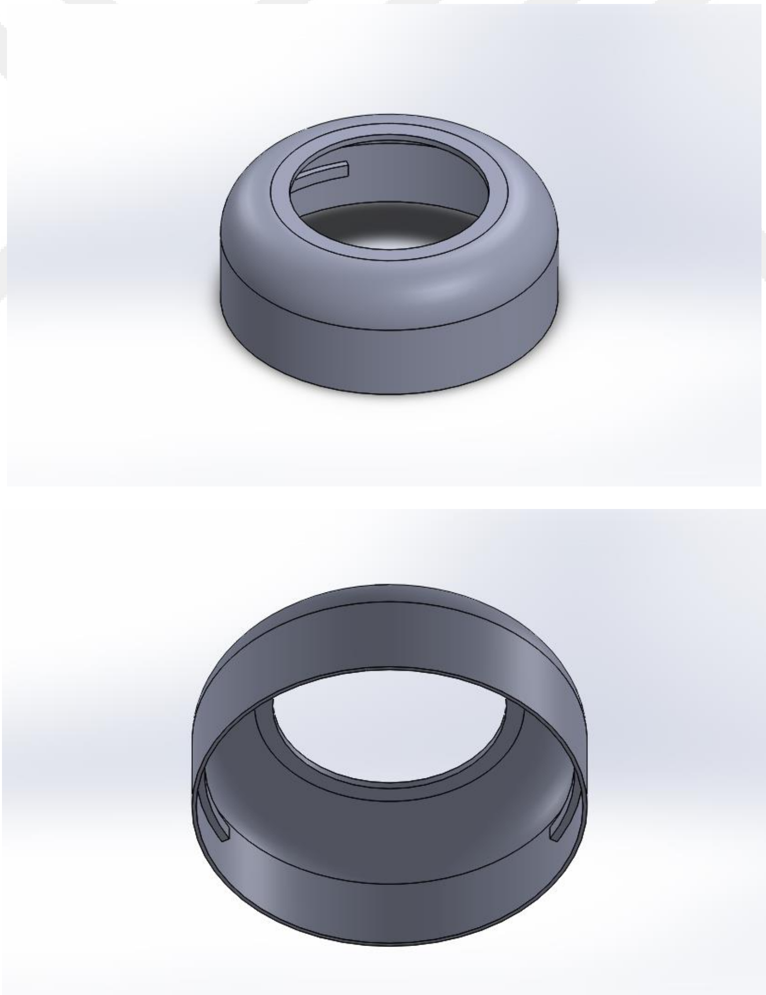


Figure 3.25: Design of the upper cap

The main function of an upper cap is to prevent the contamination of the bearing. The bearing has spherical balls made of metal and there is a type of lubricant used inside the bearing which must be protected from environmental effects in order to prevent corrosion of the bearing. The bearing allows the upper spring seat to rotate in accordance with the movements of the wheels. The assembly of the upper cap and the upper spring seat is shown in Figure 3.26 below in order to show the exact location of the upper cap in a MacPherson strut suspension system.

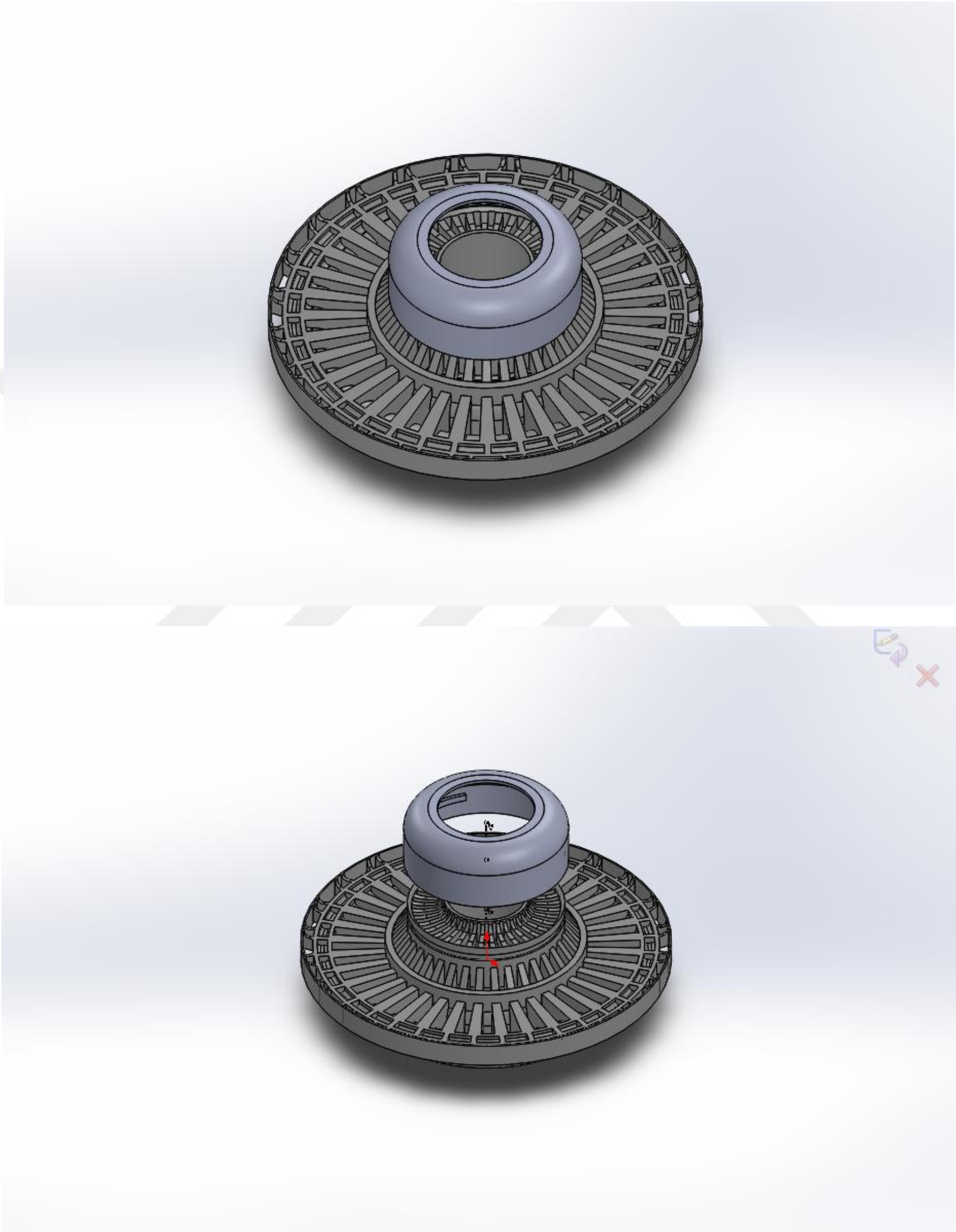


Figure 3.26: Upper spring seat and upper cap assembly

As it can be seen from these designs; upper cap has a simple geometry and there is not many features to be modified. And the relationship of the upper cap with other components in the overall assembly prevents any design changes to the upper cap without affecting the overall assembly. Therefore design improvements for the upper cap were not possible. The aim of the activities regarding the upper cap were focused on improvement via optimum material selection.

3.2.2 Moldflow Simulations

For the purpose of material selection; Moldflow software was used for upper cap as well. Upper cap design was transferred to Moldflow and the plastic flow was simulated for valuable data such as fill time, injection pressure etc. Moldflow material database was used for simulating the design with different materials. The settings used for the simulations of the upper cap were same as the settings shown in Figure 3.22 for the upper spring seat. The data obtained via Moldflow simulations along with the help of other material databases were used for the selection of the optimum material. An example of these simulations is shown in Figure 3.27 below.

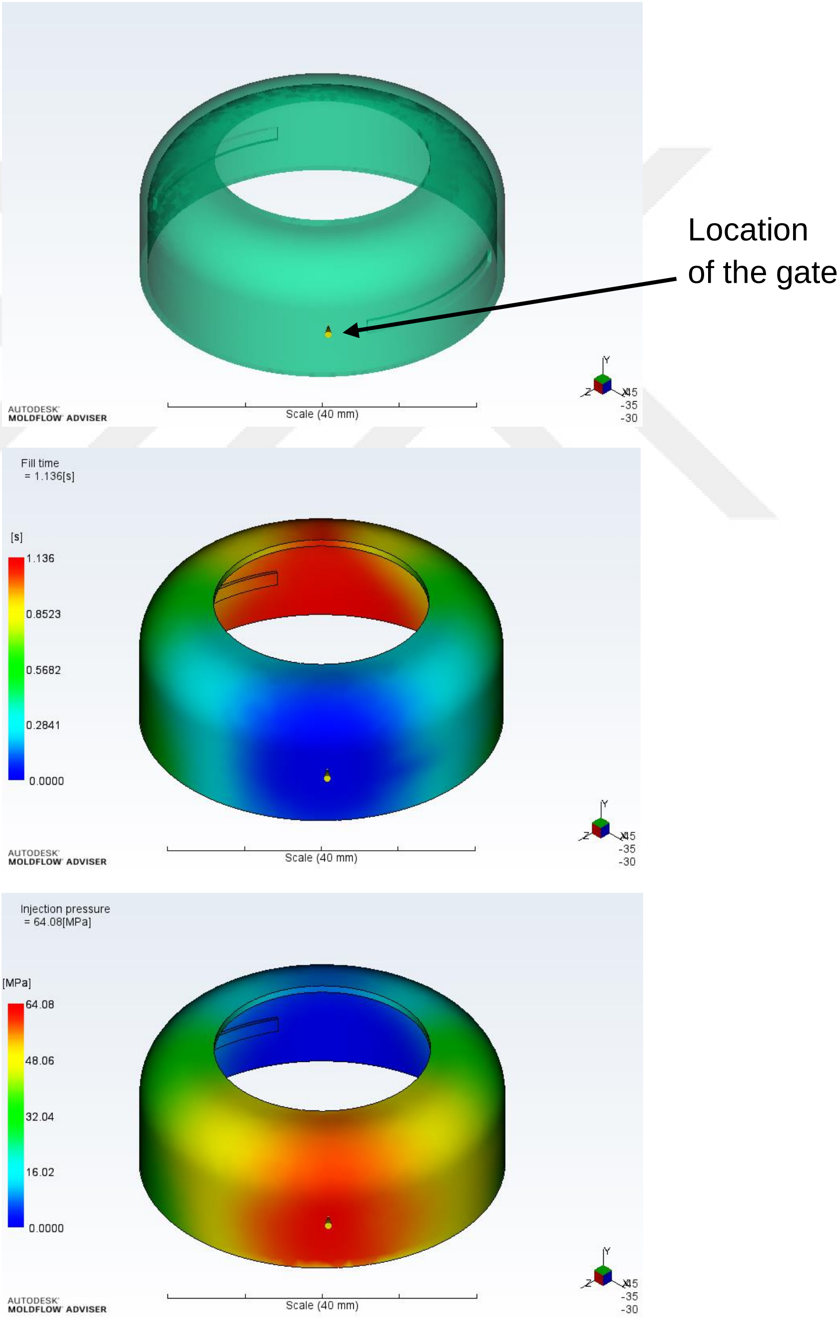


Figure 3.27: Moldflow simulations for the upper cap

4 Material Selection

In the frame of this thesis work material properties comparisons are one of the main aspects. Selecting the optimum materials which satisfy the requirements is the main object of this thesis work.

Firstly design activities were conducted. Different possible designs were created and the effect of those changes were analysed accordingly. Secondly analysis activities were conducted. Created designs were analysed structurally under loads and boundary conditions in order get values such as stress, strain, deformation etc. Lastly Moldflow simulations were conducted in order to simulate the flow of the molten plastic during plastic injection process.

In addition to those activities; various material databases were used to evaluate different materials and their properties. Selection of the optimum material will be carried out as a result of combining all the design, analysis, simulation and material database results.

There are various material databases available. Some of the material databases that were used are listed below:

- Moldflow material database
- SolidWorks material database
- Campusplastics (campusplastics.com)
- Matweb (matweb.com)
- Ulprospector (ulprospector.com)

All these databases were used for comparing material properties for the upper spring seat and the upper cap. Particularly for the upper spring seat various databases were used and different material properties were compared. Values such as density, strength and modulus of elasticity were important parameters during these comparisons.

The work carried out in this thesis work can be summarized as evaluating different designs if a weight reduction would be possible and then by using software such as Ansys and Moldflow conducting analysis and simulations to obtain values such as stress and strain to select the optimum materials via material databases. Ansys analysis activities provide data such as how much stress will occur in the upper spring seat and that stress value later was used as a reference point for selecting a material - either providing the same strength values as the current material or another material with better strength values – by comparing material properties of different materials via material databases. The process flow of this thesis work is illustrated in Figure 4.1 to summarize the overall study.

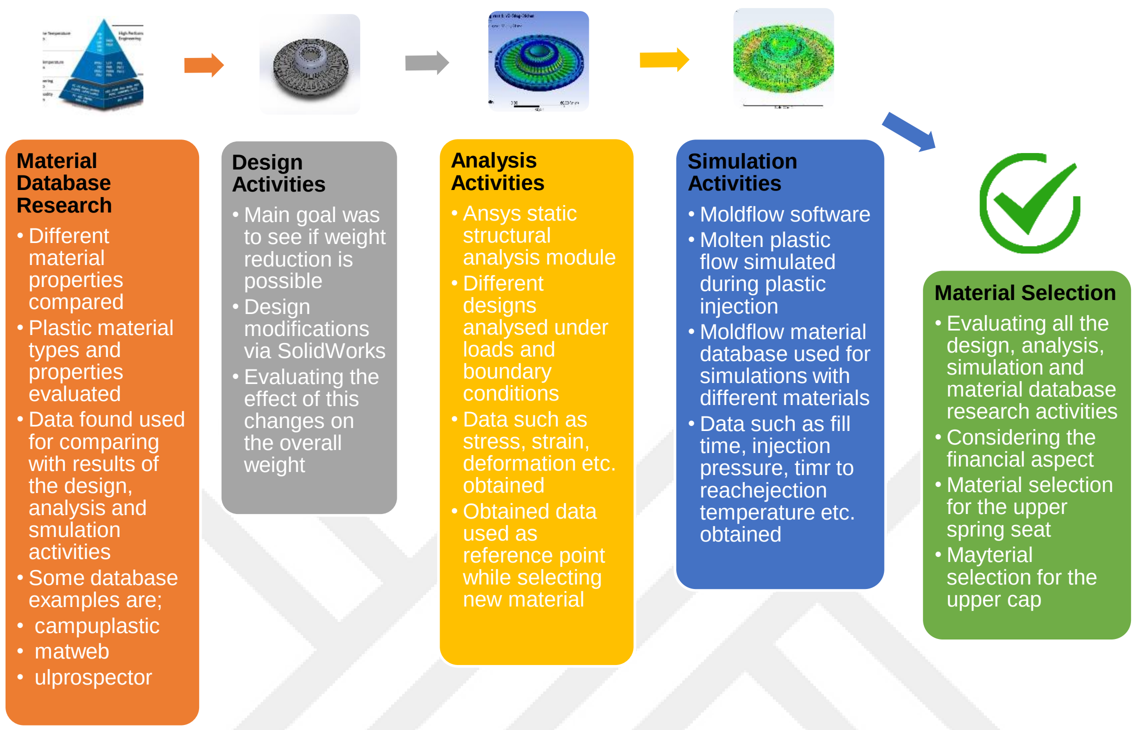


Figure 4.1: Process flow of this thesis work

Every step in this process flow is a vital aspect of the study. All the activities conducted at each step was evaluated again according to the data obtained on the other steps. For example the strength value of a material according to material databases was further analysed by appointing that material to the designs and then Ansys analysis and Moldflow simulation activities were conducted.

5 Results

Design and analysis activities were conducted via SolidWorks and Ansys software in order to evaluate various designs and the effect of these designs on the properties of the final product. Design modifications were conducted on the upper spring seat and these designs were analysed in Ansys using static structural module under applied loads and defined boundary conditions. Due to its simple geometry and lack of features in its design; activities regarding the upper cap were not as extensive. Finally Moldflow software was used for both parts in order to simulate the plastic flow. The following results were used with data from the aforementioned material databases which is explained in the next chapter for selecting the optimum material.

5.1 Upper Spring Seat

The upper spring seat's design was modified mainly via changing the number of channels and the degree between these channels. Number of channels and the degree between them are shown in Figure 5.1 below to clarify the design changes. SolidWorks software was used for the design activities. Since the aim was to see if weight reduction is possible or not; the overall weight of each design was measured. Table 5.1 - 3 shows the overall weight for each design modification. In these designs; a random material was appointed to the designs and the appointed material was same for all designs so the density was a constant since the aim is to evaluate the effect of the design changes.

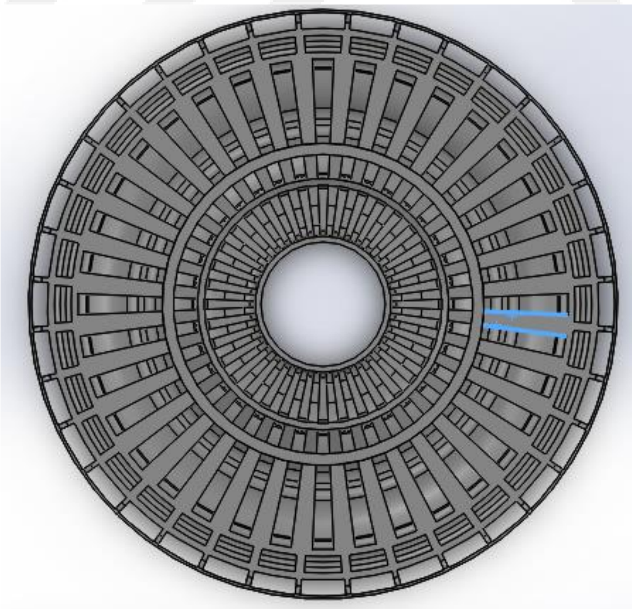


Figure 5.1: Illustration of the channels on the top surface of the upper spring seat

As it can be seen from the figure above; the hollow sections on the top surface are called channels and they follow a circular pattern. The degree between the two faces of these channels which are highlighted in the figure are referred as the degree between channels. Table 5.1 – 3 show the evaluation of all the designs regarding the overall weight.

Table 5.1: Overall Weight of Design Modifications – Design Version 1

Design Identification	Degree Between Channels (°)	Number of Channels	Overall Weight (gram)
Design Version 1 – 1 (Current Design)	5	36	111,44
Design Version 1 – 2	8	24	109,64
Design Version 1 – 3	10	20	108,44
Design Version 1 – 4	12	18	106,05
Design Version 1 – 5	15	15	104,69
Design Version 1 – 6	18	14	100,63
Design Version 1 – 7	20	12	102,42

Table 5.2: Overall Weight of Design Modifications – Design Version 2

Design Identification	Degree Between Channels (°)	Number of Channels	Overall Weight (gram)
Design Version 2 – 1	5	36	111,03
Design Version 2 – 2	8	24	109,23
Design Version 2 – 3	10	20	108,04
Design Version 2 – 4	12	18	105,63
Design Version 2 – 5	15	15	104,28
Design Version 2 – 6	18	14	100,24
Design Version 2 – 7	20	12	102,05

Table 5.3: Overall Weight of Design Modifications – Design Version 3

Design Identification	Degree Between Channels (°)	Number of Channels	Overall Weight (gram)
Design Version 3 – 1	36	8	99,81
Design Version 3 – 2	36	8	100,22

After evaluating all the design modifications based on the effect of the design changes on the overall weight; Ansys analysis were conducted to evaluate the effect of these design changes on the mechanical properties. Table 5.4 – 6 shows the result of Ansys static structural analysis shown in Figure 3.16 - 20. As it was the case with the design evaluations; for the Ansys analysis the same material was appointed to each design for having only the design as a variable. Therefore; different designs were analysed with the same appointed material to see which design version offers the best mechanical properties and the lowest overall weight. Safety factor was a deciding parameter for these evaluations. Safety factor is defined as the yield stress of the appointed material divided by the maximum Von Mises stress occurring in the part.

Table 5.4: Ansys Static Structural Analysis Results – Design Version 1

Design Identification	Max Equivalent Von Mises Stress (MPa)	Max Shear Stress (MPa)	Min Safety Factor
Design Version 1 – 1 (Cur. Design)	74,51	38,6	3,22
Design Version 1 – 2	83,03	43,29	2,89
Design Version 1 – 3	80,78	43,49	2,97
Design Version 1 – 4	86,81	47,32	2,76
Design Version 1 – 5	88,88	48,5	2,7
Design Version 1 – 6	100,4	55,43	2,39
Design Version 1 – 7	97,34	51,25	2,47

Table 5.5: Ansys Static Structural Analysis Results – Design Version 2

Design Identification	Max Equivalent Von Mises Stress (MPa)	Max Shear Stress (MPa)	Min Safety Factor
Design Version 2 – 1	77,39	40,36	3,01
Design Version 2 – 2	79,34	42,09	3,03
Design Version 2 – 3	80,85	41,09	2,97
Design Version 2 – 4	84,55	43,74	2,84
Design Version 2 – 5	88,47	45,93	2,71
Design Version 2 – 6	99,46	54,84	2,41
Design Version 2 – 7	100,31	52,37	2,39

Table 5.6: Ansys Static Structural Analysis Results – Design Version 2

Design Identification	Max Equivalent Von Mises Stress (MPa)	Max Shear Stress (MPa)	Min Safety Factor
Design Version 3 – 1	118,61	66,41	2,02
Design Version 3 – 2	119,26	65,25	2,01

5.1.1 Material Selection

According to the information provided by Oyak Renault; the current material used for the upper spring seat is PA6T/6I with %50 glass fibre content by EMS Grivory. The material used before that was PA6 with %60 glass fibre content by Lanxess. The designation of those materials according to the material databases mentioned before are shown below and these materials was also used as reference values:

- Grivory® HT1V-5 HY black 9205
- Durethan® DPBKV60H2.0EF 900116

Table 5.7 below gives shows some material properties of those materials according to the data provided on the material databases.

Table 5.7: Material Properties of Grivory PA6T/6I %50 GF and Durethan PA6 %60 GF [56] [57]

Property	Grivory PA6T/6I %50 GF	Durethan PA6 %60 GF
Density (g/cm^3)	1,65	1,71
Tensile Modulus (23°C) (MPa) Dry / Conditioned	18000 / 17500	20500 / 13100
Tensile Stress (Break, 23°C) (MPa) Dry / Conditioned	250 / 240	230 / 150
Tensile Strain (Break, 23°C) (%) Dry / Conditioned	2 / 2	2.4 / 3.1
Water Absorption (%)	3	3.6
Melt Temperature (°C)	325	270 - 290

As it can be seen from Table 5.7; the current material and the previously used one offers a tensile stress between 150 and 240 MPa. Therefore; the material selected at the end of this thesis work; must also offer properties in this range. Another important parameter is the density as it affects the weight of the part.

The material databases were investigated for evaluating possible materials that satisfy the necessary property requirements. Properties of the materials that might be selected were later evaluated according to the data from the design and analysis activities. In Table 5.8; possible materials and some of their properties are listed.

Table 5.8 - a: Possible Materials for the Upper Spring Seat and Their Properties [58]

Number / Material Designation	Product Family / Filler %	Density (g/cm^3)	Tensile Mod. (MPa) Dry/Condi.	Stress at Break (MPa) Dry/Condi.
1) Akulon IG-HG10	PA46+PA6 / %50 GF	-	16000/-	240/-
2) Alcom PC 740/1.1 CF20	PC / %20 CF	1,28	13800	160
3) Celanex2300 GV1/50	PBT / %50 GF	1,71	17000	165
4) Durethan BKV40H2.0EF 900116	PA6 / %40 GF	1,45	12200/7200	190/110
5) Durethan BCF30H2.0EF 900111	PA6 / %30 CF	1,26	23000/11500	225/135
6) Celstran TPU-GF50-01-US	TPU / %50 GF	1,63	15100	230
7) Celstran PP-GF45M15-04CN15/10	PP / %45 GF	1,52	12300	150
8) Celstran PA6-GF50-01	PA6 / %50 GF	1,56	16000/-	245/-
9) EcoPaXX Q-DWX10	PA410 / %50 GF	1,56	16500/16000	240/210
10) EcoPaXX Q-HG10	PA410 / %50 GF	1,52	16000/12000	220/170

Table 5.8 - b : Possible Materials for the Upper Spring Seat and Their Properties

Material Designation	Product Family / Filler %	Density (g/cm^3)	Tensile Mod. (MPa) Dry/Condi.	Stress at Break (MPa) Dry/Condi.
11) EcoPaXX Q-HG8	PA410 / %40 GF	1,43	12500/9500	195/140
12) ForTii Ace MX52	PPA / %40 GF	1,55	14500/14500	220/220
13) ForTii MX15HR	PPA / %35 GF	1,49	12500/12500	240/220
14) ForTiiWF11 (P788A)	PPA+PTFE/ %35GF	1,57	13000/13000	210/185
15) Fortron 1140L4	PPS / %40 GF	1,65	14700	195
16) enestarG1500A-M61	PA9T / %50 GF	1,58	16400	250
17) Genestar GT2330-1	PA9T / %33 GF	1,58	12200	199
18) Grilamid1SVX-50H black 9288	PA1010 / %50 GF	1,51	14500/13000	200/160
19) GrilamidLBV50H FWA black 9225	PA12 / %50 GF	1,47	13500/12500	170/160
20) GrilamidXE 4105 black 9992	PA610 / %50 GF	1,53	15500/12500	205/160
21) GrilamidXE 4108 black 9992	PA612 / %50 GF	1,52	15500/12500	185/150
22) GrilamidXE 4176 black 9288	PA1010 / %50 GF	1,5	14000/12200	170/150
23) Grilon BG-50 FC	PA6 / %50 GF	1,58	17200/11500	240/155
24) GrivoryHT1V-45 HY black 9205	PA6T/6I / %45 GF	1,59	16000/15500	230/225

Table 5.8 - c: Possible Materials for the Upper Spring Seat and Their Properties

Material Designation	Product Family / Filler %	Density (g/cm^3)	Tensile Mod. (MPa) Dry/Condi.	Stress at Break (MPa) Dry/Condi.
25) Stanyl DiabloHDT2700	PA46 / %40 GF	1,48	13500/7000	220/130
26) TechnylstarSX218 V50	PA6 / %50 GF	1,55	17000/11600	230/130
27) Tedur L 9200-1	PPS %30GF + %30MF	1,9	17000	150
28) Ultramid B3WG10 bk 564	PA6 / %50 GF	1,55	16700/11000	225/150
29) Ultramid T KR 4355 G10 bk 23215	PA6T/6 / %50 GF	1,62	17000/16000	240/190
30) Ultramid T KR 4355 G7	PA6T/6 / %35 GF	1,43	12000/12000	210/200
31) XytronG4010E (P952N)	PPS-I / %40 GF	1,53	12000	160
32) Zytel 73G40T BK416	PA6-I / %40 GF	1,44	13000/8000	210/150
33) Zytel HTN51G35HSL BK083	PA6T/XT / %35 GF	1,47	12000/11500	210/210
34) Zytel HTN51G45HSL BK083	PA6T/XT / %45 GF	1,57	15000/15500	240/230
35) Novamid 1013GH451NA/BK701	PA6 / %45 GF	1,49	13600/9000	220/150
36) Radilon S RV500W Black	PA610 / %50 GF	1,56	17000/11500	230/160
37) Stanyl 46HF4550	PA46 / %50 GF	1,62	16000/11000	250/170

Evaluation of the data from design modifications listed in Table 5.1 – 6 shows that modifications in design group 3 result in higher stress values whereas some modified designs from design groups 1 and 2 result in lower stress values and lower overall weight. The designs that show less stress values and lower overall weight are listed below:

- Design Version 1 – 1
- Design Version 1 – 3
- Design Version 2 – 1
- Design Version 2 – 2
- Design Version 2 – 3

The overall weight ant the safety factor which is the tensile strength of the material divided by the maximum Von Mises stress values for the materials listed in Table 5.7 – Grivory %50 GF and Durethan %60 GF – with the stress values above are shown in Table 2.9 below.

Table 5.9: Overall Weight and Safety Factor Values of Grivory %50 GF and Durethan %60 GF for Selected Design Modifications

Design	Grivory %50 GF		Durethan %60 GF	
	Overall Weight (gr)	Safety Factor Cond.	Overall Weight (gr)	Safety Factor Cond.
Design Version 1 – 1 (Cur. Design)	111,44	3,22	115,49	2,01
Design Version 1 – 3	108,44	2,97	112,38	1,86
Design Version 2 – 1	111,03	3,1	115,06	1,94
Design Version 2 – 2	109,23	3,03	113,22	1,89
Design Version 2 – 3	108,04	2,97	111,97	1,86

The data listed in Table 5.9 - which shows that the safety factor varies between 1,8 and 3,2 for the conditioned case - were considered as reference values. The possible materials that were selected were investigated based on their properties to see what would be the safety factor for the conditioned case values and the overall weight for the selected design modifications above as it can be seen in Table 5.10. Results of this evaluation will be used to see which of the selected materials would result in lowest weight and highest safety factor combination.

Table 5.10 - a: Safety Factor and Overall Weight Values of Selected Designs Based on Possible Materials and Their Properties

Material	Design Version 1 – 1		Design Version 1 – 3		Design Version 2 – 1		Design Version 2 – 2		Design Version 2 – 3	
	Safety Factor Con.	Overall Weight (gr)	Safety Factor Con.	Overall Weight (gr)	Safety Factor Con.	Overall Weight (gr)	Safety Factor Con.	Overall Weight (gr)	Safety Factor Con.	Overall Weight (gr)
1	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
2	2,15	86,45	1,98	84,12	2,07	86,13	2,02	84,75	1,98	83,81
3	2,21	115,49	2,04	112,38	2,13	115,07	2,08	113,22	2,04	111,97
4	1,48	97,93	1,36	95,29	1,42	97,57	1,39	96,00	1,36	94,95
5	1,81	85,10	1,67	82,81	1,74	84,79	1,70	83,42	1,67	82,50
6	3,09	110,09	2,85	107,12	2,97	109,68	2,90	107,92	2,84	106,73
7	2,01	102,66	1,86	99,89	1,94	102,28	1,89	100,64	1,86	99,53
8	NA	105,36	NA	102,52	NA	104,97	NA	103,29	NA	102,15
9	2,82	105,36	2,60	102,52	2,71	104,97	2,65	103,29	2,60	102,15
10	2,28	102,66	2,10	99,89	2,20	102,28	2,14	100,64	2,10	99,53
11	1,88	96,58	1,73	93,98	1,81	96,22	1,76	94,68	1,73	93,64
12	2,95	104,69	2,72	101,87	2,84	104,30	2,77	102,63	2,72	101,49
13	2,95	100,63	2,72	97,92	2,84	100,26	2,77	98,65	2,72	97,57
14	2,48	106,04	2,29	103,18	2,39	105,65	2,33	103,95	2,29	102,80
15	2,62	111,44	2,41	108,44	2,52	111,03	2,46	109,25	2,41	108,04
16	3,36	106,71	3,09	103,84	3,23	106,32	3,15	104,61	3,09	103,46
17	2,67	106,71	2,46	103,84	2,57	106,32	2,51	104,61	2,46	103,46
18	2,15	101,99	1,98	99,24	2,07	101,61	2,02	99,98	1,98	98,87
19	2,15	99,28	1,98	96,61	2,07	98,92	2,02	97,33	1,98	96,26
20	2,15	103,34	1,98	100,55	2,07	102,95	2,02	101,30	1,98	100,18
21	2,01	102,66	1,86	99,89	1,94	102,28	1,89	100,64	1,86	99,53
22	2,01	101,31	1,86	98,58	1,94	100,94	1,89	99,32	1,86	98,22

Table 5.10 - b: Safety Factor and Overall Weight Values of Selected Designs Based on Possible Materials and Their Properties

Material	Design Version 1 – 1		Design Version 1 – 3		Design Version 2 – 1		Design Version 2 – 2		Design Version 2 – 3	
	Safety Factor Con.	Overall Weight (gr)	Safety Factor Con.	Overall Weight (gr)	Safety Factor Con.	Overall Weight (gr)	Safety Factor Con.	Overall Weight (gr)	Safety Factor Con.	Overall Weight (gr)
23	2,08	106,71	1,92	103,84	2,00	106,32	1,95	104,61	1,92	103,46
24	3,02	107,39	2,79	104,49	2,91	106,99	2,84	105,27	2,78	104,11
25	1,74	99,96	1,61	97,27	1,68	99,59	1,64	97,99	1,61	96,91
26	1,74	104,69	1,61	101,87	1,68	104,30	1,64	102,63	1,61	101,49
27	NA	128,33	NA	124,87	NA	127,85	NA	125,80	NA	124,41
28	2,01	104,69	1,86	101,87	1,94	104,30	1,89	102,63	1,86	101,49
29	2,55	109,41	2,35	106,47	2,46	109,01	2,39	107,26	2,35	106,08
30	2,68	96,58	2,48	93,98	2,58	96,22	2,52	94,68	2,47	93,64
31	2,15	103,34	1,98	100,55	2,07	102,95	2,02	101,30	1,98	100,18
32	2,01	97,26	1,86	94,64	1,94	96,90	1,89	95,34	1,86	94,29
33	2,82	99,28	2,60	96,61	2,71	98,92	2,65	97,33	2,60	96,26
34	3,09	106,04	2,85	103,18	2,97	105,65	2,90	103,95	2,84	102,80
35	2,01	100,63	1,86	97,92	1,94	100,26	1,89	98,65	1,86	97,57
36	2,15	105,36	1,98	102,52	2,07	104,97	2,02	103,29	1,98	102,15
37	2,28	109,41	2,10	106,47	2,20	109,01	2,14	107,26	2,10	106,08

Evaluation of the data shows that the highlighted materials in the Table 5.10 are the materials that offer the best combination regarding the safety factor values and the overall weight. Regarding the modified designs that were selected; designs named "design version 1 – 3 " and "design version 2 – 3" offer the lowest overall weights and therefore the highlighted materials in Table 5.11 will be further evaluated for these designs.

Table 5.11: Evaluation of the Best Possible Material Selections and Design Modifications for the Upper Spring Seat

Material	**Product Family / Filler %**	**Design Version 1 – 3**		**Design Version 2 – 3**	
		Safety Factor Con.	**Overall Weight (gr)**	**Safety Factor Con.**	**Overall Weight (gr)**
9) EcoPaXX Q-DWX10	PA410 / %50 GF	2,6	102,52	2,6	102,15
10) EcoPaXX Q-HG10	PA410 / %50 GF	2,1	99,89	2,1	99,53
12) ForTii Ace MX52	PPA / %40 GF	2,72	101,87	2,72	101,49
13) ForTii MX15HR	PPA / %35 GF	2,72	97,92	2,72	97,57
14) ForTiiWF11 (P788A)	PPA+PTFE/%35GF	2,29	103,18	2,29	102,8
19) GrilamidLBV50H FWA black 9225	PA12 / %50 GF	1,98	96,61	1,98	96,26
23) Grilon BG-50 FC	PA6 / %50 GF	1,92	103,84	1,92	103,46
24) GrivoryHT1V-45 HY black 9205	PA6T/6I / %45 GF	2,79	104,49	2,78	104,11
29) Ultramid T KR 4355 G10 bk 23215	PA6T/6 / %35 GF	2,35	106,47	2,35	106,08
30) Ultramid T KR 4355 G7	PPS-I / %40 GF	2,48	93,98	2,47	96,64
33) Zytel HTN51G35HSL BK083	PA6T/XT / %35 GF	2,6	96,61	2,6	96,26
34) Zytel HTN51G45HSL BK083	PA6T/XT / %45 GF	2,85	103,18	2,84	102,8

Evaluation of the materials listed in Table 5.11 shows that the differences between them are quite narrow. Especially regarding the safety factor; values for 2 designs are almost equal whereas the overall weight values have a wider range between 2 designs. Therefore the distinguishing feature is the overall weight and since designs named “design version 2 – 3” offers lower overall weights; it is chosen as the final design for the upper spring seat.

As for the safety values; the highest values for the conditioned case are offered by the materials numbered 34, 24 and 13 which are 2,84 for material numbered 34, 2,78 for material numbered 24 and 2,72 for material numbered 13. The overall weights of the design named “Design Version 2 – 3” which is the final design selection for the upper spring seat with these materials are 102,8 gr, 104,11 gr and 97,57 gr respectively. Since the difference between their safety values is quite little; the overall weight of the selected design with these 3 materials was chosen as the defining criteria.

But before deciding on the material selection; Moldflow simulations were conducted to have all the research, design, analysis and simulation results. ForTii MX15HR was not available on the Moldflow material database so ForTii AceMX52 was used instead whose properties were closest to ForTii MX15HR. Moldflow simulations are illustrated in Figure 5.2 - 4. Moldflow simulation settings are same as the settings shown in Chapter 3. Current material simulation is shown in Figure 5.5.

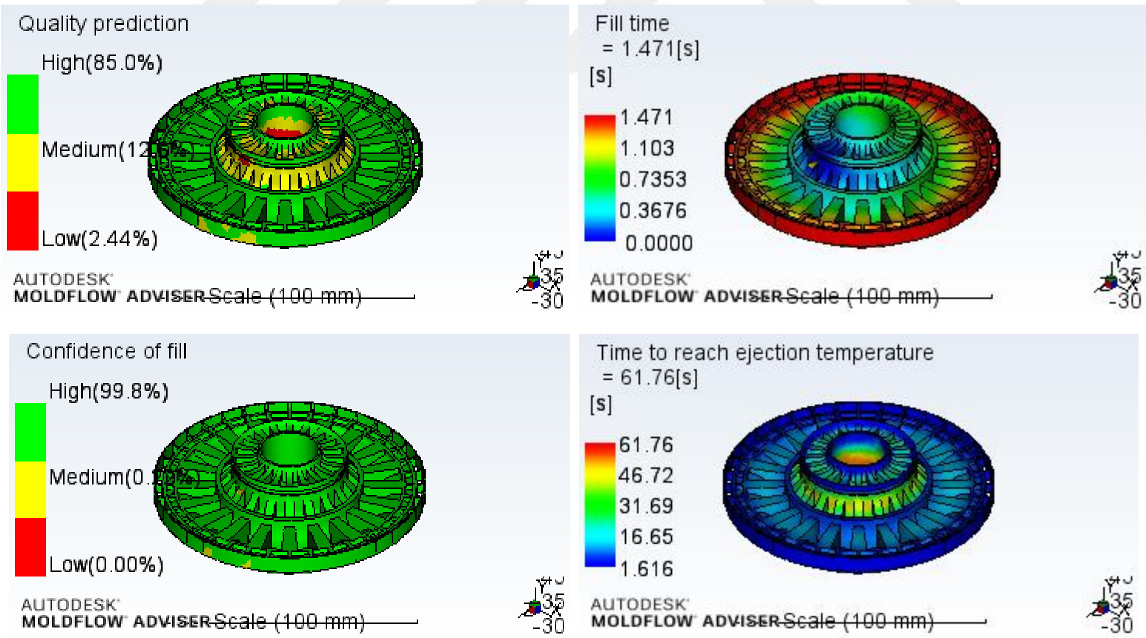


Figure 5.2: Moldflow simulations with Zytel HTN 51G45HSL BK083

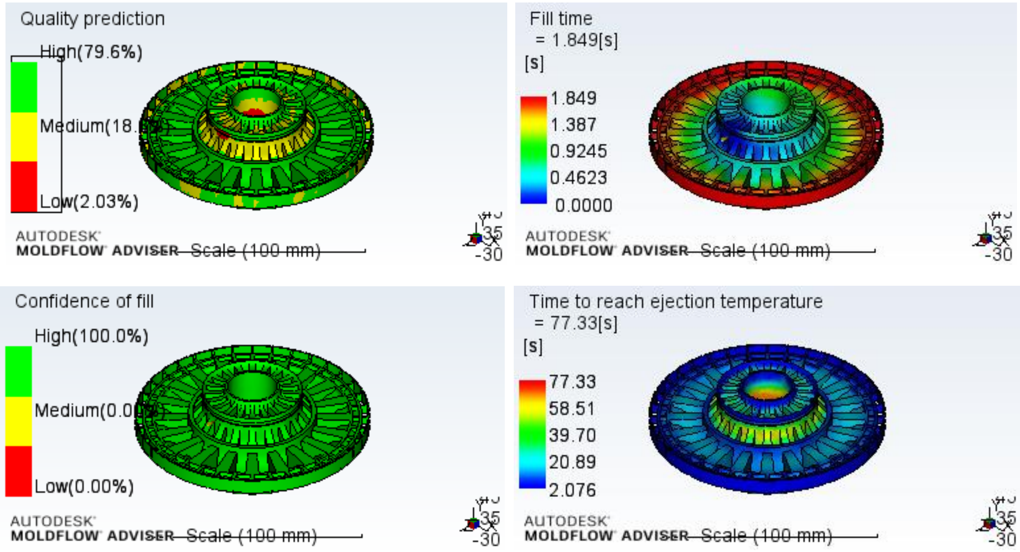


Figure 5.3: Moldflow simulations with Grivory HT1V-45 HY black 9205

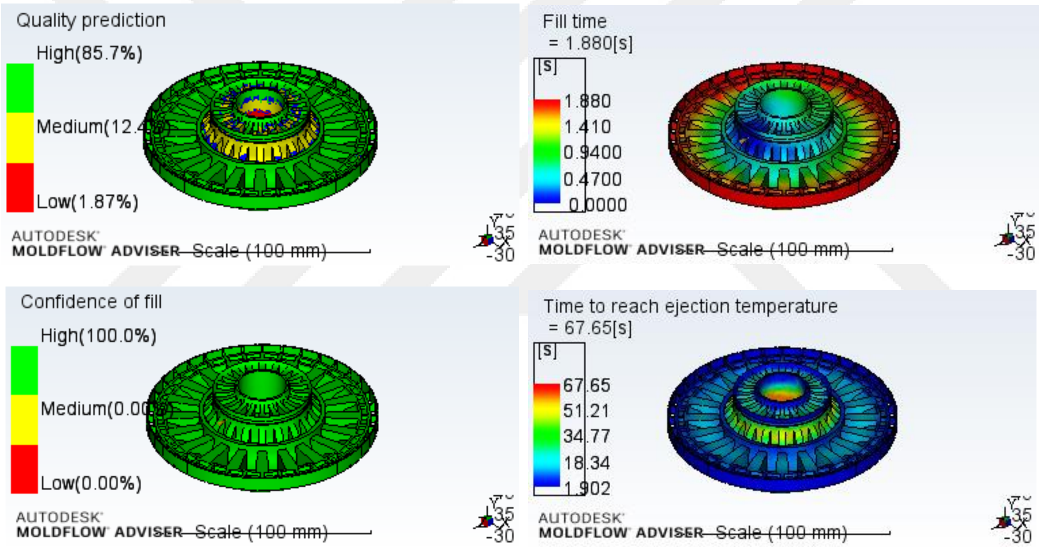


Figure 5.4: Moldflow simulations with ForTii Ace MX52

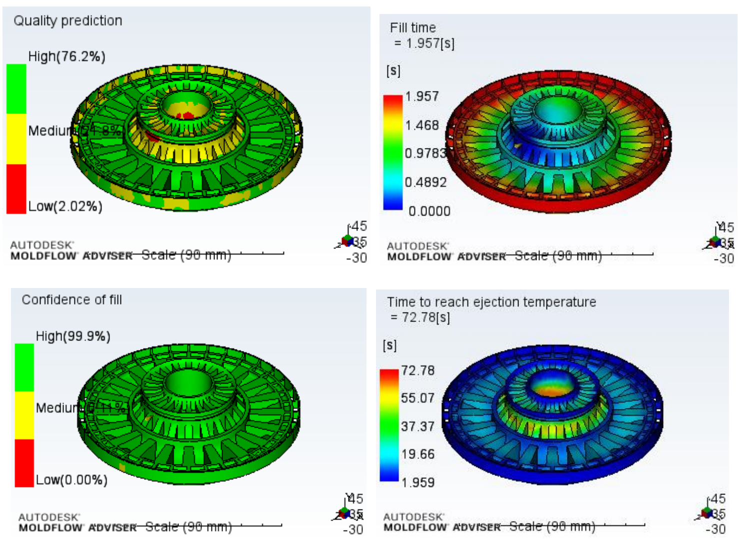


Figure 5.5: Moldflow simulation results of the current material

Moldflow simulations shown in these figures shows that the simulation results are usually quite similar to each other for these 3 materials. Particularly confidence of fill and quality prediction results vary in a very narrow range. Fill time and time to reach ejection temperature results have a relatively wider range. Zytel material offers the lowest fill time with the fill times of Grivory and ForTii being almost same whereas time to reach ejection temperature values show that Zytel and ForTii have the shortest time requirement while Grivory requires a bit longer for ejection. As it was stated earlier the Moldflow material database does not have ForTii MX15HR so ForTii Ace MX52 was selected as it offers the closest properties only for these simulation purposes so that comparison activities could be conducted successfully. These Moldflow simulations show that each of these material offer good properties and each of them has their advantages. The fill time and time to reach ejection temperature values of the current material are respectively 1,96 s and 72,78 s which will be used to compare with the selected material.

If the material selection were to be made based only on the Moldflow simulations; all 3 materials could be selected as the optimum choice. But after evaluating all the research, design, analysis and simulation activities all together; a new material was selected as the optimum choice – low overall weight and good mechanical properties - for the upper spring seat. The selected material and alternatives to it are listed below:

- **Design Selection:** Design Version 2 – 3
- **Material Selection:** Material Number 13 – ForTii MX15HR
- **2nd Material Choice:** Material Number 24 – Grivory HT1V-45 HY black 9205
- **3rd Material Choice:** Material Number 34 – Zytel HTN 51G45HSL BK083

The selected material ForTii MX15HR by DSM Engineering Plastics is a %35 glass fibre reinforced plastic belonging to the Polyphthalamide (PPA) family based on the PA4T chemistry. It offers good mechanical properties such as strength, stiffness and chemical resistance. Figure 5.6 illustrates some charts regarding ForTii MX15HR properties.

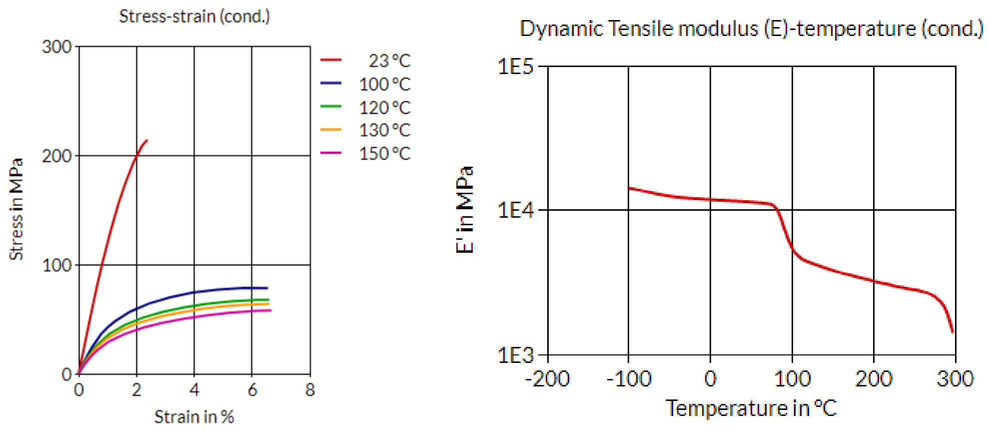


Figure 5.6: Graphs illustrating the properties of ForTii MX15HR [59]

Figure 5.7 below shows the Ansys analysis of the final design with the selected material where it can be seen the selections – design and material - results in good mechanical properties for the upper spring seat.

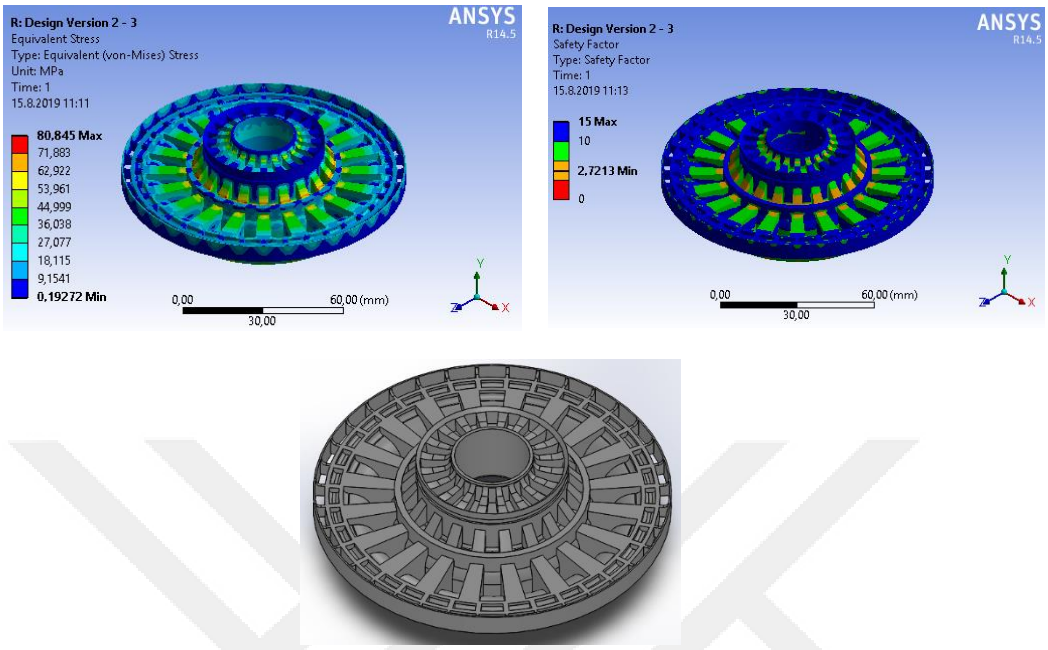


Figure 5.7: Final design selection and analysis results with the selected material

5.2 Upper Cap

It was stated before that the activities regarding the upper cap were not as extensive as the upper spring seat due to its simple geometry and its function. Therefore the process of material selection for the upper cap comprises evaluating the material properties of the current material and then comparing those values via material databases to find a material with better properties.

5.2.1 Material Selection

The current material for the upper cap is Akrotek PK – VM 4774 by Akro Plastics. It is an unreinforced Polyketone (PK) and has a tensile modulus of 1500 MPa, a yield stress of 60 MPa and a density of 1,24 g/cm^3 which means the weight of the upper cap is 4,45 gr currently. Since its property values are not that high; there are plenty of plastics that offer the same properties. Therefore the aim will be to find a material with similar properties but lower density as that would result in weight reduction. Material databases were analysed and the list of possible materials and their main properties are listed in Table 5.12 below.

Table 5.12: Possible New Materials for the Upper Cap [58]

Material	**Product Family**	**Tensile Modulus (MPa)**		**Yield Stress (MPa)**		**Density (g/cm^3)**	**Weight (gr)**
		Dry	**Condi.**	**Dry**	**Condi.**		
Novamid® 1010C2	PA6	3400	1700	87	54	1,13	4,06
Grilamid TR 55	PA12	2200	2200	75	75	1,06	3,81
EcoPaXX® Q150-D	PA410	3100	1700	85	60	1,09	3,91
Genestar™ N1000A-M41	PA9T	2720	-	85	-	1,14	4,09
Bayblend® CG100	PC + ABS	2500	-	62	-	1,14	4,09
ALCOM LD2 PC 1000 UV 17004WT1004-17	PC	2400	-	66	-	1,19	4,27
SCHULAKETON NV	PK	1450	-	65	-	1,24	4,45

At first glance of the data in Table 5.12; it is seen that the differences between these materials are really narrow. The weight of the upper cap with these materials vary between 3,81 gr and 4,45 gr. So in order to have more comparable data Moldflow simulations were conducted. The simulation settings were same as the settings shown in Chapter 3. The results of those simulations are given in Table 5.13 below.

Table 5.13: Moldflow Simulation Results of Possible Materials For The Upper Cap

Material	**Fill Time (s)**	**Injection Pressure (MPa)**	**Confidence of Fill (%)**	**Quality Prediction (%)**	**Time to Reach Ejection Temp. (s)**	**Volumetric Shrinkage at Ejection (%)**
Novamid® 1010C2	0,44	23,68	100	High:100	6,77	9,11
Grilamid TR 55	1,16	115,7	100	Low: 40,8	7,05	1,93
EcoPaXX® Q150-D	0,55	44,52	100	High: 100	2,73	10,35
Genestar™ N1000A-M41	0,77	43,32	100	High: 100	3,1	7,3
Bayblend® CG100	0,79	43,41	100	High: 75,8	7,61	6,37
ALCOM LD2 PC 1000 UV 17004WT1004-17	0,44	51,17	100	High: 99,4	5,04	2,91
SCHULAKETON NV	1,13	58,63	100	High: 57,2	5,03	5,73

Evaluation of the data in Table 5.12 and 5.13 show that Grilamid TR55 offers the lowest weight but does not result in a high quality product according to Moldflow simulations. Next material with the lowest weight is EqoPaXX Q150–D and it shows good simulation results. Novamid 1010C2 also offers a good combination of low weight and good simulation results but EqoPaXX Q150–D seems to be a better choice regarding the time to reach ejection temperature results. These simulation results are shown in Figure 5.8 as well. As a result of evaluation of these data; the material selection was made and the results are listed below:

- **1st Material Choice:** EqoPaxx Q-150-D
- **2nd Material Choice:** Novamid 1010C2

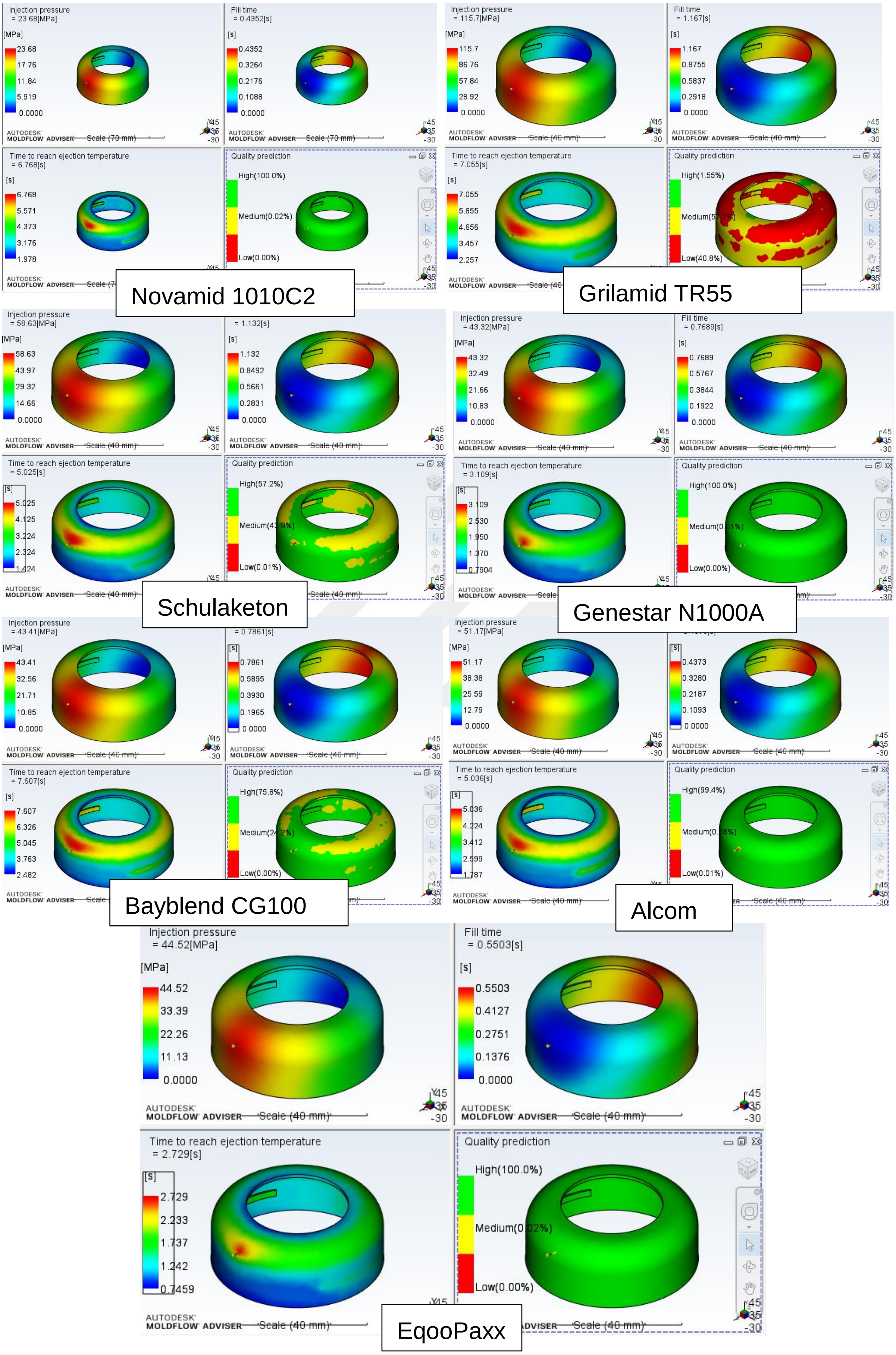


Figure 5.8: Moldflow simulations of the possible materials for the upper cap

As a result of all the research, design and simulation activities conducted; the optimum material for the upper cap is EqoPaXX Q-150–D by DSM Engineering Plastics. EqoPaXX Q-150–D is a PA410 plastic belonging to the Polyamide family. It offers very good performances in harsh environments. EqooPaXX Q-150-D offers very good chemical resistance in addition to very low moisture absorption. Figure 5.9 shows the illustration of the stress – strain properties of the EqooPaXX Q-150-D. [60]

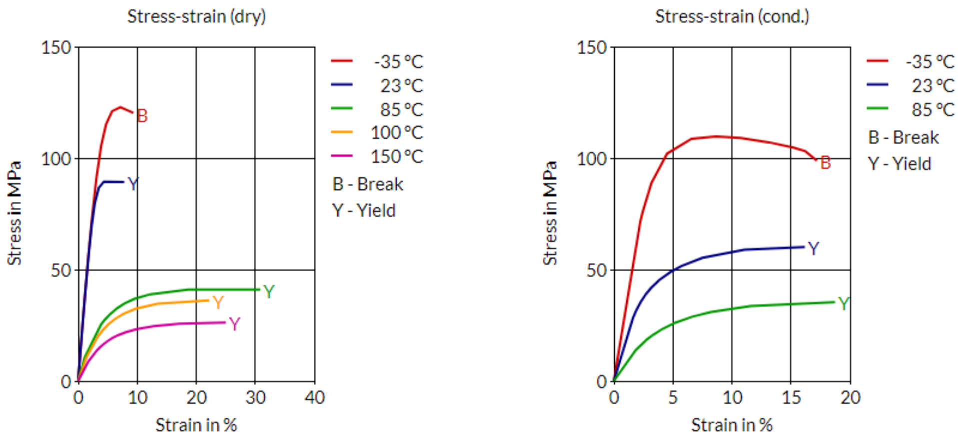


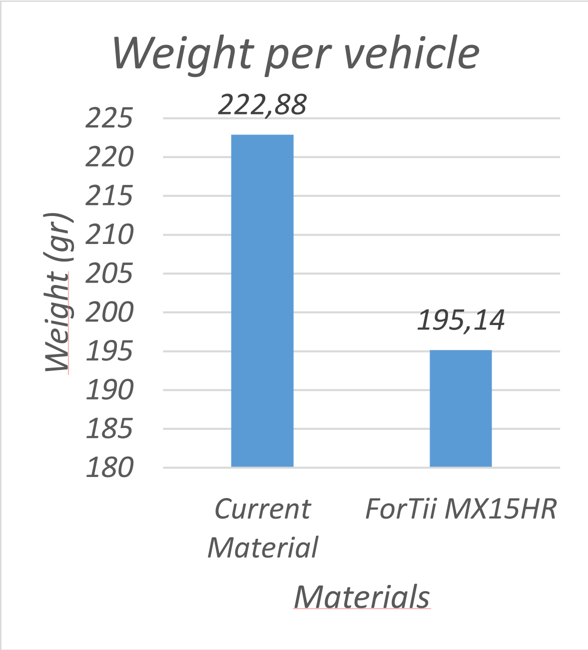
Figure 5.9: Stress – strain values of EqooPaXX Q-150-D [60]

5.3 Evaluation of The Selected Materials and Design Improvements

5.3.1 Upper Spring Seat

The upper spring seat design was analysed and the analysis activities showed that the current design can be improved. This improvement and the selection of the ForTii MX15HR as the optimum material for the upper spring seat offers a %12,4 weight reduction from 111,44 gr to 97,57 gr. ForTii MX15HR also offers high mechanical properties so the safety factor value with the new design and the new material is 2,72 which is quite good. Another outcome of those choices was the fibre content reduction from %50 to %35. These outcomes result in a very good design and a material selection. It is also important to mention that there are 2 front suspensions so there are 2 upper spring seats which means approximately 28 gr less plastic compound per vehicle.

The selected material ForTii MX15HR along with the improved design leads to a %12,4 weight reduction. Since there are two front suspensions on each vehicle; that would mean a weight reduction of 28 gr per vehicle from the upper spring seats. Oyak Renault plant in Bursa has a production capacity of 350000 vehicles per year. With two upper spring seats per vehicle; the company purchases 700000 upper spring seats per year. The effect of the design improvement and the material selection according to those numbers are shown in Figure 5.10.



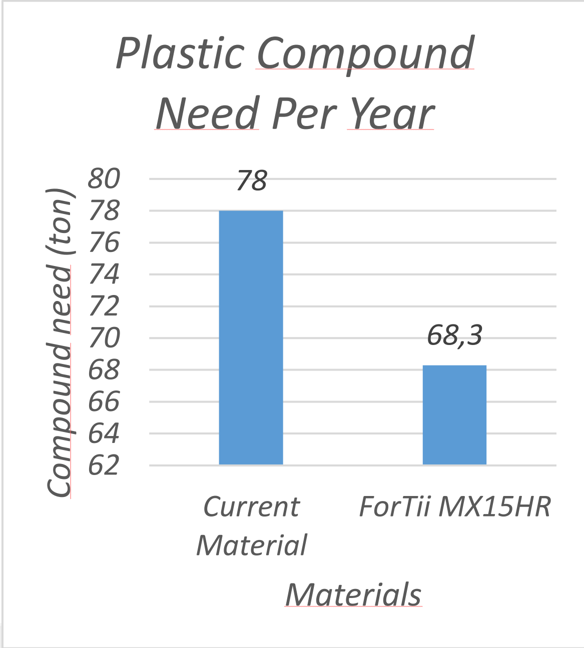


Figure 5.10: Charts illustrating the effects of design and material changes

As it can be seen from the charts above; the new material result in a plastic compound need reduction of approximately 10 ton. The material selection and the design change were also compared to the current version according to Moldflow simulations. Fill time and time to reach ejection temperatures were assumed as the cycle time for 1 part and the total time needed for production of 700000 was calculated as it can be seen in Table 5.14 below.

Table 5.14: Comparisons Between The Current Material and The ForTii MX15HR

Materials	**Cycle Time**		
	Fill Time (s)	**Time to reach ejection temperature (s)**	**Total (s)**
Current Material	1,96	72,78	74,74
ForTii MX15HR	1,88	67,65	69,53
		Time saved per part (s)	**5,21**
Cars manufactured per year	350000		
Spring seats per car	2		
Total time saved (s)	3647000	350000x2x5,21	
Total time saved (h)	1013,06		
Total time saved (day)	**45,02**	Acc. to 22,5 h working time per work day	

5.3.2 Upper Cap

The selected material for the upper cap was EqoPaXX Q – 150 – D. According to the mechanical properties and the simulation results; the EqooPaXX Q – 150 – D offers the same properties such as yield stress as the current material whereas the EqooPaXX also offers a %12 weight reduction from 4,45 gr to 3,91 gr. This is a pretty good ratio for a very light part. Finally there are again 2 upper caps as there are 2 front suspensions. Figure 5.11 below illustrates the result of the material selection for the upper cap.

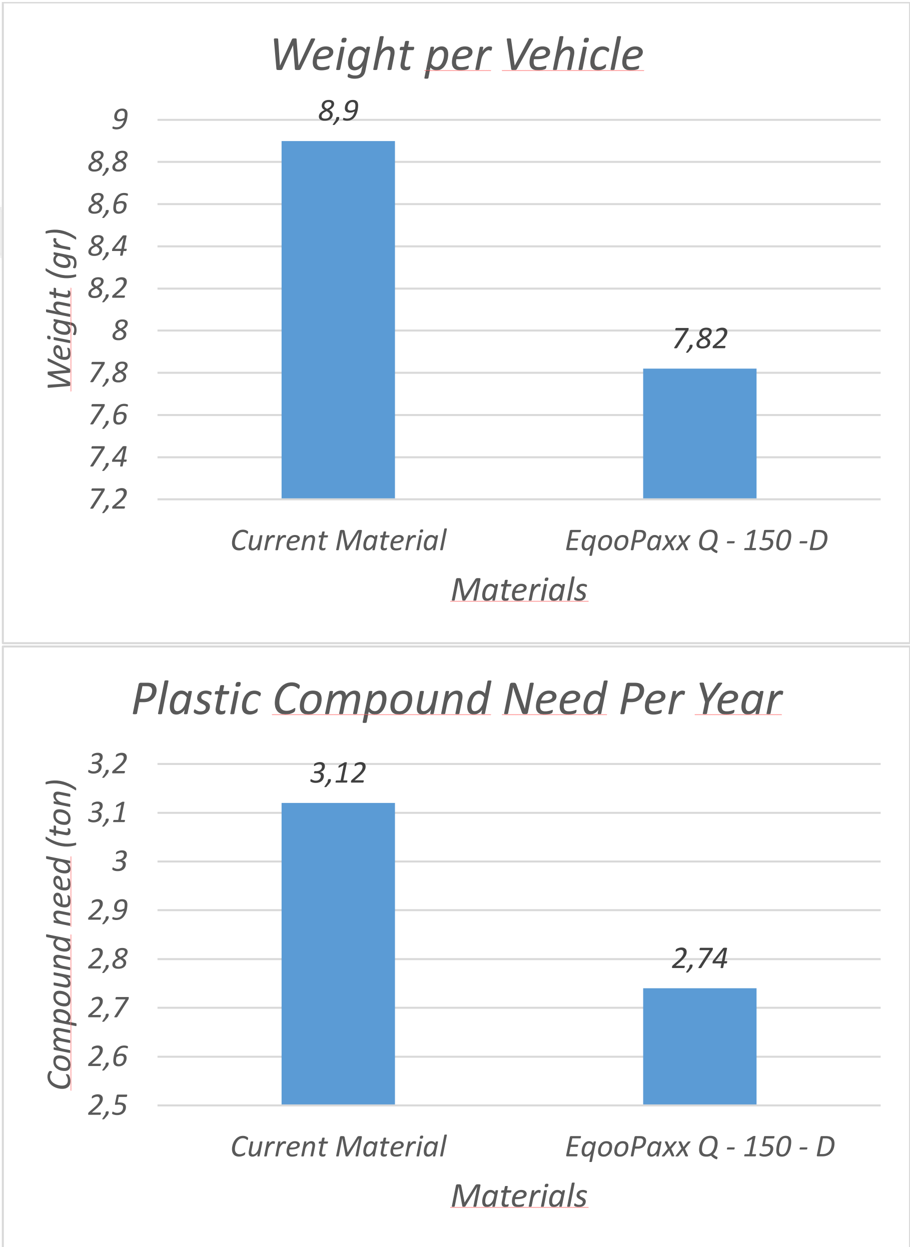


Figure 5.11: Charts illustrating the effects of material selection for the upper cap

6 Conclusion and Outlook

6.1 Conclusion

The aim of this thesis work conducted at Oyak Renault plant in Turkey was to select alternative materials for the components called upper spring seat and the upper cap which are used in a MacPherson strut suspension system which is a very popular front suspension for many modern passenger vehicles and modify their design in a way that overall weight could be reduced without effecting their mechanical properties in a negative way.

In the frame of this thesis work; first literature research activities were conducted. Plastic materials, composite plastics and plastic injection process was studied to have the necessary background for the material selection. Then suspension systems used in vehicles were researched. The function of the suspension system, its main components and different types of suspension systems were studied to understand the function of the components which are the topic of this thesis.

After the literature research was completed; design activities were conducted. Current designs were created using SolidWorks and then by changing parameters such as number of channels and the degree between the channels; different design versions were created for the upper spring seat as the upper cap has a quite simple geometry without many possibilities for a design change. In order to evaluate the effects of those design changes on the upper spring seat; Ansys static structural analysis were conducted to find out which design version offers the lowest overall weight in combination with good mechanical properties such as high safety factor. During those analysis activities a randomly selected material was appointed to the designs and so each material was analysed with the same material to have the design as the only variable.

Once the design versions were evaluated; it was time for finding new materials for the two parts. Material databases were investigated to find possible materials that would offer satisfactory mechanical properties. The properties of the current materials used were taken as reference values. The possible replacements found were analysed based on parameters such as tensile stress, density, filler content etc. Then the list of possible materials were further reduced after comparisons among those materials. For example; materials with higher density values were eliminated as higher density would lead to higher weight. Another important parameter for the comparisons was the safety factor which is the ratio of the yield stress to the maximum Von Mises stress value occurring as a result of the applied loads. Higher safety factor simply means a safer part.

When the possible material options were reduced; the remaining options were compared by using the Moldflow simulations to simulate the flow of the plastic. Final design selection of the upper spring seat was simulated for the remaining possible materials in order to get data such as fill time, injection pressure, quality prediction etc. The simulations were conducted under the same conditions for all the materials and the results were evaluated to see which of the possible materials would be the optimum choice for the upper spring seat. The final material selection was made as a result of all these activities.

As a result of all the research, design, analysis and simulation activities; the optimum material for the upper spring seat was chosen as the material designated as ForTii MX15HR.

Regarding the upper cap; as mentioned design changes were not very likely and because of that the aim was to select a material which would offer the same properties as the current material. Since the weight reduction via design change was not possible; a material with lower density was the preferred choice.

Material database research activities were conducted once again for possible materials. These possible materials were later appointed to the upper cap and Moldflow simulations were conducted. After comparing the Moldflow results and comparing their mechanical properties; the optimum material for the upper cap was chosen as the material designated as EqooPaXX Q – 150 – D.

6.2 Outlook

The upper spring seat and the upper cap are both outsourced by Oyak Renault. So any physical tests or experiments was not a possibility for this thesis work. It would be quite useful if the analysis and simulation results were verified by conducting the regarding experiments.

The selected material usage for prototypes to conduct physical tests to evaluate values such as stress and deformation would be very interesting as it would allow to compare the physical test results with the analysis and simulation results. Using the prototypes in the suspension system to evaluate the offered outcome of this thesis in its working environment could also be used to further verify the activities conducted for this thesis. Observing the plastic injection process to see if any improvements could be made would also be valuable addition to this work.

Finally; the selected materials as a results of the activities conducted could be investigated from the economical aspect. The comparison between the prices of different plastic composites would allow to evaluate the financial outcome of the study. Because the offered materials weight less and also the glass fibre percentage is also less than the current material selection. So a comparison regarding the price of the new material which requires less compound with lower glass fibre content would clearly show the economic advantages and disadvantages of this thesis work.

7 Bibliography

[1] Campbell, F. C. (2010): Structural composite materials. Materials Park Ohio: ASM International

[2] https://www.plasticseurope.org/en/resources/market-data

[3] http://www.injectionmoulding.org/plastic-parts-in-automotive-industry.html, checked on 7/6/2019

[4] Shrivastava, Anshuman (2018): Introduction to Plastics Engineering. In : Introduction to Plastics Engineering: Elsevier

[5] R.J.Crawford (1998): Plastics Engineering 3rd Edition: Butterworth - Heinemann

[6] Carraher, Charles E.; Seymour, Raymond B. (2003): Seymour Carraher's Polymer Chemistry, 6th Edition

[7] https://www.plasticseurope.org/en/resources/market-data

[8] Rolf Klein (2011): Laser Welding of Plastics: Wiley-VCH Verlag GmbH & Co. KGaA.

[9] Melton, George H.; Peters, Edward N.; Arisman, Ruth K. (2011): Engineering Thermoplastics. In : Applied Plastics Engineering Handbook: Elsevier

[10] Osswald, Tim A.; Menges, Georg (2012): Material Science of Polymers for Engineers; 3rd edition; Cincinnati; Hanser Publishers

[11] http://polymers.com.au/thermoplastics/, checked on 7/6/2019

[12] http://polymers.com.au/elastomers/, checked on 7/6/2019

[13] Gazi Basar Kocabas (2014): Cam Elyaf Takviyeli PA 6.6 Enjeksiyon Prosesinin Simulasyon Yoluyla Analizi. M.Sc. Science Institute, Corum / Turkey. Mechanical Engineering

[14] Sabu Thomas, Kuruvilla Joseph, Sant Kumar Malhotra, Koichi Goda, Meyyarappallil Sadasivan Sreekala (Ed.) (2012): Polymer Composites: Volume 1: Wiley-VCH Verlag GmbH & Co. KGaA

[15] Callister, William D. (2007): Materials science and engineering. An introduction. 7th ed. New York: John Wiley & Sons

[16] Hahladakis, John N.; Velis, Costas A.; Weber, Roland; Iacovidou, Eleni; Purnell, Phil (2018): An overview of chemical additives present in plastics: Migration, release, fate and environmental impact during their use, disposal and recycling. In Journal of hazardous materials 344, pp. 179–199. DOI: 10.1016/j.jhazmat.2017.10.014

[17] https://www.martins-rubber.co.uk/blog/advantages-and-disadvantages-of-injection-moulding/, checked on 17/7/2019

[18] https://www.linkedin.com/pulse/injection-molding-machine-history-sajjad-hussain/, checked on 17/7/2019

[19] http://www.preview-project.eu/a-guide-to-injection-moulding/blog/, checked on 7/6/2019

[20] http://fordhamplastics.com/wp-content/uploads/2016/08/HANDBOOK-REILOY-USA-BARREL-SCREW.pdf, checked on 17/7/2019

[21] https://schoolworkhelper.net/vehicle-systems-overview/, checked on 7/6/2019

[22] Yakup Putgul; Duran Altiparmak (2015): Vehicle Suspension System Types and Their Effects on Front Axle Geometry. In Journal of Polytechnic 19 (2), pp. 195–202. DOI: 10.2339/2016.19.2

[23] https://106sttire.com/blog/view/when-does-your-car-s-suspension-need-repair-part-2, checked on 7/6/2019

[24] https://accurate-alignment.com/vehicle-suspension-service, checked on 7/6/2019

[25] Tandel, Anand; Deshpande, A. R.; Deshmukh, S. P.; Jagtap, K. R. (2014): Modeling, Analysis and PID Controller Implementation on Double Wishbone Suspension Using SimMechanics and Simulink. In Procedia Engineering 97, pp. 1274–1281. DOI: 10.1016/j.proeng.2014.12.406

[26] Prof. S.C.Jain; Dr. Pushpendra kumar Sharma; Dhara Vadodaria (2014): MCPHERSON SUSPENSION SYSTEM -A REVIEW. In nternational Journal For Technological Research In Engineering Volume 1 (12)

[27] Shpetim LAJQI; Stanislav PEHAN; Naser LAJQI; Afrim GJELAJ; Jože PŠENIČNIK; Sašo EMIN (2013): DESIGN OF INDEPENDENT SUSPENSION MECHANISM FOR A TERRAIN VEHICLE WITH FOUR WHEELS DRIVE AND FOUR WHEELS STEERING. In International Journal of Engineering

[28] Reimpell, Jörnsen; Stoll, Helmut; Betzler, Jürgen W. (2001): The automotive chassis. Engineering principles ; chassis and vehicle overall, wheel suspensions and types of drive, axle kinematics and elastokinematics, steering, springing, tyres, construction and calculations advice. 2. ed. Oxford: Butterworth Heinemann

[29] https://www.bilgiustam.com/suspansiyon-sistemi-nedir-nasil-calisir/, checked on 7/6/2019

[30] Michael Gifford; Tanner Landis; Cody Wood (2015): Design and Manufacture of an Adaptive Suspension System. B.Sc. WORCESTER POLYTECHNIC INSTITUTE, Worcester, USA

[31] https://www.macksprings.com/leaf-springs-vs-coil-springs-which-suspension-system-is-better/, checked on 7/6/2019

[32] https://www.monroe.com.au/trade-corner/tech-info/suspension-systems/rear-suspension.html, checked on 7/6/2019

[33] http://www.unipedi.com/otomoto/2015/12/24/genel/otomobillerde-kullanilan-suspansiyon-sistemleri/, checked on 7/6/2019

[34] https://www.diesel-electric.co.za/shock-absorber-maintenance-tips/, checked on 7/6/2019

[35] https://www.carthrottle.com/post/how-do-anti-roll-bars-actually-work/, checked on 7/6/2019

[36] Dishant; Er.Parminder Singh; Er.Mohit Sharma (2017): Suspension Systems: A Review. In International Research Journal of Engineering and Technology 04 (04)

[37] Zulkarnain, N.; Zamzuri, H.; Mazlan, S. A. (2014): RIDE AND HANDLING ANALYSIS FOR AN ACTIVE ANTI-ROLL BAR: CASE STUDY ON COMPOSITE NONLINEAR CONTROL STRATEGY. In Int. J. Automot. Mech. Eng. 10, pp. 2122–2242. DOI: 10.15282/ijame.10.2014.28.0179

[38] Avesta Goodarzi; Amir Khajepour (2017): Vehicle Suspension System Technology and Design: Morgan&Claypool Publishers

[39] Rajashekhar Sardagi; Dr. Kallurkar Shrikant Panditrao (2014): Design and Optimization of Passenger Car Torsion Bar. In Journal of Mechanical and Civil Engineering

[40] Vikas V.Yalasangi; Prof. A.M.Naniwadekar (2016): Analysis of Torsion Bar of Light Motor Vehicle Car Using Alternative Material. In International Journal of Engineering Science and Computing 6 (7)

[41] https://www.allpar.com/mopar/torsionaire.html, checked on 7/6/2019

[42] Naveen Sankar; Manikantan R; Anshadh A (Eds.) (2016): Adaptive Air Suspension in Automobiles: A Case Study. Kerala Technological Congress

[43] PROF. D. A. MORE; RAJENDRA HIRAVE; AJAY JADHAV; RASHID PINJARI; SURAJ PISAL (2017): AUTOMATIC AIR SUSPENSION IN CARS. In JOURNAL OF INFORMATION, KNOWLEDGE AND RESEARCH IN 04 (05)

[44] http://psgautomotive.com/favorites-and-top-brands-static/mini_dsc_0417/, checked on 7/6/2019

[45] Reddy, K. Vikranth; Kodati, Madhu; Chatra, Kishen; Bandyopadhyay, Sandipan (2016): A comprehensive kinematic analysis of the double wishbone and MacPherson strut suspension systems. In Mechanism and Machine Theory 105, pp. 441–470. DOI: 10.1016/j.mechmachtheory.2016.06.001

[46] Satyajit S. Dhore; Hredeya Mishra (2015): SELECTION AND MODIFICATION OF INDEPENDENT SUSPENSION MECHANISM FOR A TERRAIN VEHICLE WITH FOUR WHEELS DRIVE. In IJARIIE 1 (5)

[47] Nikita Gawai; Deepak Yadav; Shweta Chavan; Apoorva Lele; Shreyash Dalvi (2016): Design, Modelling and Analysis of Double Wishbone Suspension System. In International Journal on Mechanical Engineering and Robotics 4 (1)

[48] https://medium.com/@you_wheel/automobile-suspension-design-101-part-iii-double-wishbone-suspension-1edbcbe29232, checked on 7/6/2019

[49] https://www.carthrottle.com/post/what-actually-is-double-wishbone-suspension/, checked on 7/6/2019

[50] Revolvy; LLC: "Earle S. MacPherson" on Revolvy.com. Available online at https://www.revolvy.com/page/Earle-S.-MacPherson, checked on 7/6/2019

[51] Prof. Sameer Verma; Parvez Raza (2016): Theoretical Analysis of Macpherson Suspension System. In IJSART 2 (3)

[52] https://eu.monroe.com/en-emea/shockopedia/shocks-vs-struts, checked on 7/6/2019

[53] http://www.importautoexpert.com/index.php?p=1_5_Suspension-Alignment-Services, checked on 7/6/2019

[54] https://www.autozone.com/repairguides/Toyota-Celica-Corolla-ECHO-MR2-1999-05/Front-Suspension/Strut-MacPherson-Strut-Assembly/_/P-0996b43f80380342, checked on 7/6/2019

[55] https://www.monroe.com.au/trade-corner/tech-info/struts/strut-design.html, checked on 7/6/2019

[56] https://www.campusplastics.com/campus/en/datasheet/Grivory+HT1V-5+HY+black+9205/EMS-GRIVORY/61/7b63edf9/SI?pos=0, checked on 7/8/2019

[57] https://www.campusplastics.com/campus/en/datasheet/Durethan+%252E0EF+900116/LANXESS/99/4a180572/SI?pos=0, checked on 7/8/2019

[58] https://www.campusplastics.com/campus/list, checked on 7/8/2019

[59] https://plasticsfinder.com/en/datasheet/ForTii%C2%AE%20MX15HR/aWpjQ, checked on 7/8/2019

[60] https://plasticsfinder.com/en/datasheet/EcoPaXX%C2%AE%20Q150-D/22Rw4, checked on 7/8/2019