MARMARA UNIVERSITY

FACULTY OF ENGINEERING

DESIGN AND ANALYSIS OF MECHANICAL BRAKE

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Design and Analysis of Mechanical Brake

by

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Mehmet SARIAY

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ABSTRACT

In this study, we will consider mechanical brake systems. In this, we will first draw the part using SolidWorks, and then we will make the necessary heat transfer and physical analysis using ANSYS. Our general aim is to first design the produced brake disc, then make our own 2 new designs, analyse them through the software and compare the results. While doing this, we will use the finite element method found in the software, so that we will get more accurate results about the product we have obtained, while at the same time we will see whether we can achieve an improvement in your product with our new design.

SYMBOLS

h	**:**	hour
in	**:**	Inch
kPa	**:**	Kilopascal
lbs	**:**	pound
m	**:**	meter
min (m)	**:**	minute
mm	**:**	millimetre
MPa	**:**	Megapascal
N	**:**	Newton
Pa	**:**	Pascal
s	**:**	second

ABBREVIATIONS

3D	**:**	3 Dimensions
DMLM	**:**	Direct Metal Laser Melting
DMLS	**:**	Direct Metal Laser Sintering
GB	**:**	Gigabyte
GE	**:**	General Electric
GPU	**:**	Graphics Processing Unit
Max	**:**	Maximum
Min	**:**	Minimum
RAM	**:**	Random Access Memory
SLM	**:**	Selective Laser Melting
SLS	**:**	Selective Laser Sintering
TPU	**:**	Thermoplastic polyurethane

LIST OF FIGURES

1. INTRODUCTION

1.1 Automobile Brake System and Its History

1.1.1 Its History

The hydraulic brake system, which was first used in racing cars in the world, was first patented by Malcolm Loughead in 1917. The hydraulic brake system was used in the first passenger cars by the automobile company Duesenberg. The hydraulic brake system applied to trucks by Knox Motors Company, self-energised hydraulic drum brakes, which are still used today, emerged in 1927 for the first time and has developed throughout its history and reached today. Today, hydraulic brake systems are used in many mechanical systems. [7]

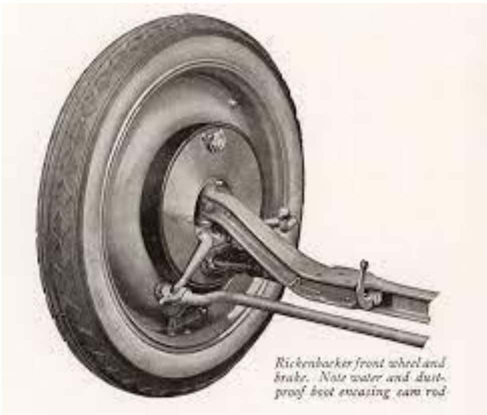


Figure 1-1 Example of the first automobile braking system [7]

Until this time, speed and safety were prioritized while producing cars. The increase in speeds and traffic has triggered the emergence of active braking systems. The best example of this is ABS brake systems. Although the ABS brake system was patented by a German company in the 1920s, this ABS brake system, which was created by technological developments, was used in different fields. It was first used on the automobile by Jansen, an Englishman, in 1967, by integrating it into the braking systems of automobiles. The ABS brake system is still present in the brake systems of automobiles by revising itself with technological developments. [7]

1.1.2 Automobile Brake System

Generally, double braking system is used in land transportation vehicles. These are hand brake and pedal (foot) brake systems. The position of the vehicle is fixed by the parking brake when the parking brake is usually in the stationary position of the vehicle. Pedal brake system is a braking system that we control with our feet when the vehicle is in motion and needs to stop or slow down.

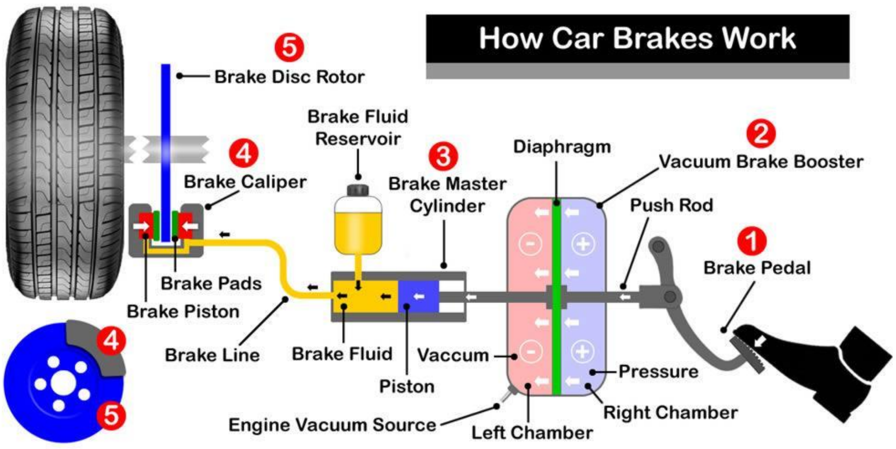


Figure 1-2 Automobile brake system working principle [10]

Disc brake systems used as automobile brake systems appear as hydraulic brakes. The main parts of this brake system are the piston, pads, caliper, brake disc and attachment points. As the working principle of hydraulic brake systems, it is based on the principle of displacing the hydraulic fluid by giving a movement by pressing the pedal. The change in this hydraulic fluid creates a frictional force on the brake disc of the caliper with the help of the pistons, causing the vehicle to stop or slow down. Although brake systems are seen as simple systems, they are among the most important systems in terms of safety in vehicles. This system, which has passed a long time from the past to the present, now provides a safer driving opportunity with electronic equipment.

1.2 CAD (Computer Aided Design)

Computer-aided design, abbreviated as CAD, is the two-dimensional or three-dimensional modelling of physical structures and material properties, using specialized software on a computer. CAD software is used by engineers, artists, and enthusiasts to create architectural designs, ray traced images, animations, and physics simulations. Pictured at right is an example of an image created with CAD software.

1.3 Solidworks

SolidWorks is a solid modelling computer-aided design (CAD) and computer-aided engineering (CAE) computer software that runs on Microsoft Windows. SolidWorks is published by Dassault Systems. For those of us having served any amount of time as a 3D CAD designer, the name SolidWorks is a name well known. Even though software packages with more complex functionality exist, SolidWorks is an industry favourite. It has a user base larger than any other 3D CAD package, almost as large as AutoCAD (which is primarily 2D drafting and drawing). This is because of SolidWorks intuitive interface, logical and smart innovations in the user experience and clean whilst thorough function set. It is literally a favourite in the sports, fashion as well as the automobile industry with small to large scale projects employing the package just the same.

Figure 1-3 Solidworks

1.4 ANSYS

ANSYS is a software package that lets you digitally model real-world phenomena. It uses computer-based numerical techniques to solve physics problems. The range of problems ANSYS can solve is immense and could be anything from fluid flow, heat transfer, stress analysis, structural optimization and more.

The real power of an FEA or CFD package such as ANSYS is that it can solve problems that are not amenable to an analytical approach. That is, they don’t have standard formulae. Now, with the arrival of cheap utility computing in the form of cloud, you can really push the limits of what can be modelled on the computer. Advantages:

- ANSYS can import all kinds of CAD geometries (3D and 2D) from different CAD software's and perform simulations, and it has the capability of creating one effortlessly. ANSYS has inbuilt CAD developing software's like Design Modeller and SpaceClaim which makes the workflow even smoother.
- ANSYS has the capability of performing advanced engineering simulations accurately and realistic in nature by its variety of contact algorithms, time dependent simulations and nonlinear material models.
- ANSYS has the capability of integrating various physics into one platform and performing the analysis. Just like integrating a thermal analysis with structural and integrating fluid flow analysis with thermal and structural, etc.,
- ANSYS now has featured its development into a product called ANSYS AIM, which can perform multi physics simulation. It is a single platform which can integrate all kinds of physics and perform simulations.
- ANSYS has its own customization tool called ACT which uses python as a background scripting language and is used in creating customised user required features in it.
- ANSYS has the capability to optimise various features like the geometrical design, boundary conditions and analyse the behaviour of the product under various criteria.

1.5 Finite Element Analysis for Software

Finite element analysis (FEA) is a computerised method for predicting how a product reacts to real-world forces, vibration, heat, fluid flow, and other physical effects. Finite element analysis shows whether a product will break, wear out, or work the way it was designed. FEA works by breaking down a real object into a large number (thousands to hundreds of thousands) of finite elements, such as little cubes. Mathematical equations help predict the behaviour of each element. A computer then adds up all the individual behaviours to predict the behaviour of the actual object.

Finite element analysis helps predict the behaviour of products affected by many physical effects, including:

- Mechanical stress
- Mechanical vibration
- Fatigue
- Motion
- Heat transfer
- Fluid flow
- Structural optimization
- Electrostatics
- Plastic injection moulding

2. DEFINITION OF BRAKE PARTS

2.1 Brake Calliper

A calliper is part of the disc brake system, the type most cars have in their front brakes. The brake calliper houses your car’s brake pads and pistons. Its job is to slow the car’s wheels by creating friction with the brake rotors.

The brake calliper fits like a drum on a wheel’s rotor to stop the wheel from turning when you step on the brakes. Inside each calliper is a pair of metal plates known as brake pads. When you push the brake pedal, brake fluid creates pressure on pistons in the brake calliper, forcing the pads against the brake rotor and slowing your car.

Figure 2-1 Disc(rotor) and Calliper

2.1.1 How does brake callipers work?

The calliper assembly is typically located inside the wheel and is linked to the master cylinder via tubes, hoses, and valves that transport brake fluid throughout the system. We could go on and on about brake callipers for days, but we'll restrain ourselves. What you really need to know is that your brake callipers are extremely important.

2.2 Rotors (Discs)

Brake rotors are the circular discs that are connected to each wheel. Rotors are designed to turn motion (kinetic energy) into thermal energy. When you press down on the brake pedal, it sends a signal via the master brake cylinder to your callipers to squeeze your brake pads together against the rotors' large surface area. This friction created by the pads pressing up against the rotors resists the spin of the wheel, which slows its rotation and halts the movement of the car.

2.2.1 Different Types of Brake Rotors

- Blank & Smooth - Blank and smooth rotors are what you'll find on most passenger vehicles and feature a smooth, blank metal surface all the way around the rotor
- Drilled - Drilled rotors feature drilled holes around the metal surface

- Slotted - Slotted rotors feature long "slots" or lines in the metal surface
- Drilled & Slotted - Drilled and slotted rotors combine the drilled holes and slots for enhanced performance

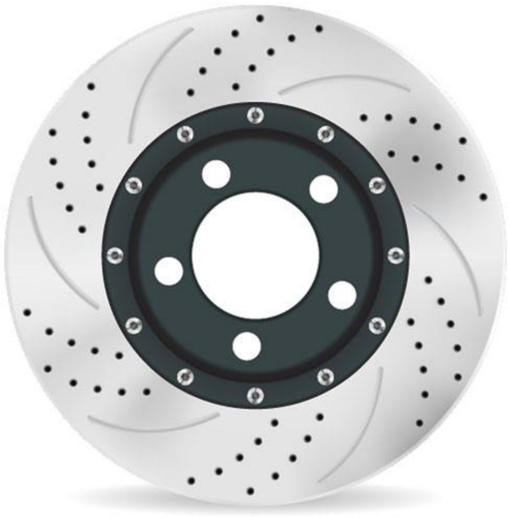


Figure 2-2 Brake Rotor

3. ANALYSIS

Our analysis will be in two stages. We will use the ANSYS software for this purpose. First, we will do the steady-state analysis, then we will connect the result here to the static structural analysis. In the first analysis, we will have temperature and convection inputs, while we will add pressure and angular velocity to our static structural analysis piece. As a result of these, we will see temperature distribution, heat distribution, stress, flexible deformation, and total deformation.

In line with the first analyses, the structural analysis will be completed with the temperature distribution and related parameters on a new brake disc without air holes. These completed analysis parameters will be connected to the structural optimization, which is an add-on of ANSYS, and the resulting values will lead to the conclusion that we need to optimize the unwanted parts of our brake disc by weight.

3.1 Design of Brake System

While designing the brake system, we took a pre-manufactured brake system as an example to take an example as a priority. This example is a Nissan car. As a result of our research on the Internet, we found a Nissan brake disc and drew this part using SolidWorks.

As a result of the main design, we designed 2 more brake discs ourselves. We designed these designs by following the brake disc design logic. In our designs, we first designed a perforated disc and combined it with the duct system used in modern sports cars.

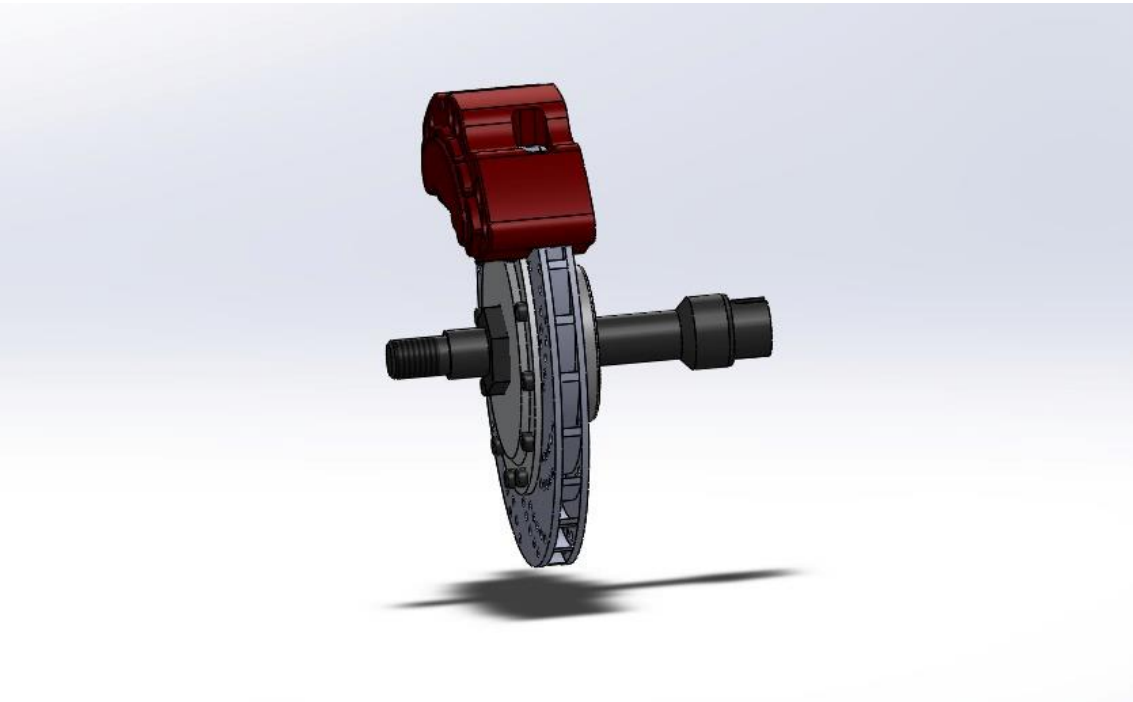


Figure 3-1 Nissan Brake System

3.1.1 Brake Disc

Before assembling the Nissan disc, we first drew the brake disc and the brake drum separately and combined them. While drawing this piece, we were inspired by the original drawing and redesigned the rest of the pieces based on that. We kept the brake disc drum the same for all designs[5].

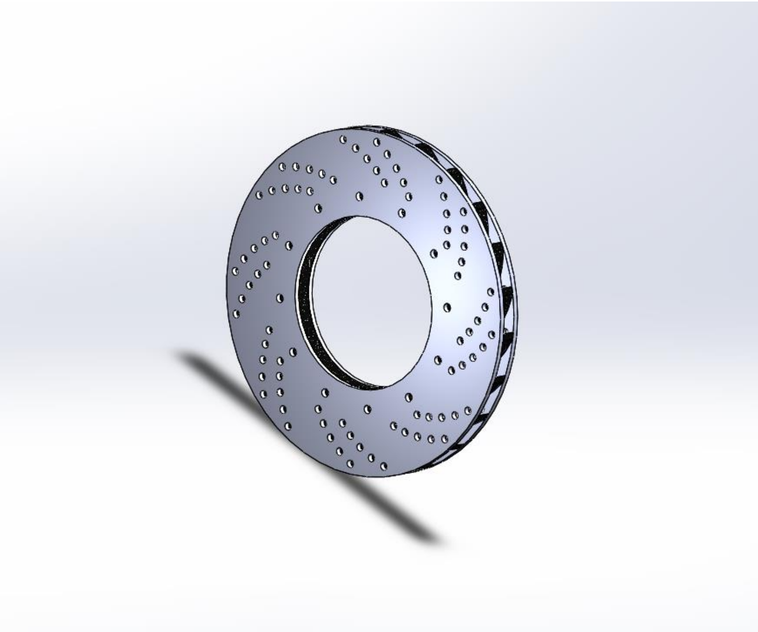


Figure 3-2 Nissan Brake Disc[5]

Figure 3-3 Brake Drum for Brake Disc

We thought about the designs we could make because of the research we did by taking this original piece as an example. If you wanted high efficiency from the brake, we had to preserve the perforated structure in the brake disc. Flat brake discs are also available, but they are generally used for slow cars.

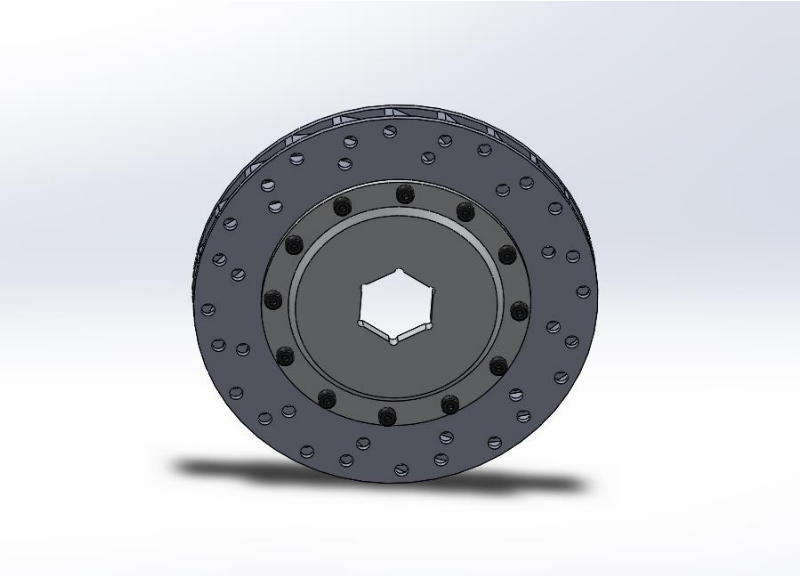


Figure 3-4 Our own design named Design #1

After creating a new design in this perforated structure, we discovered that both perforated and slotted discs were made at the same time. As a result, our second design emerged.

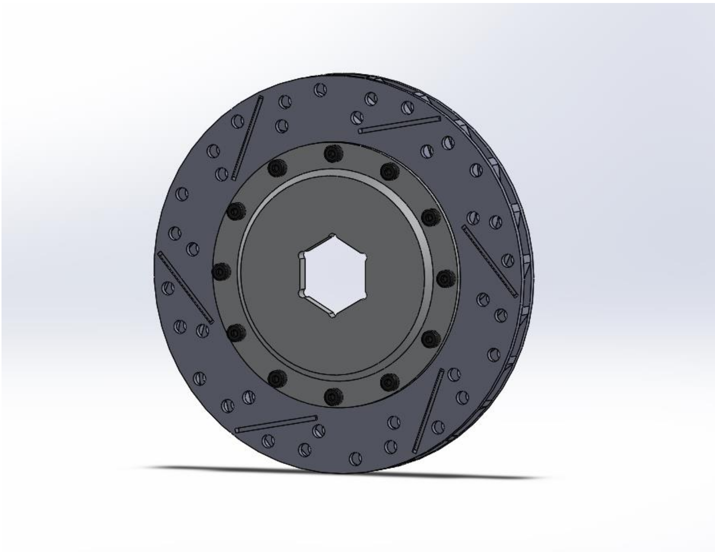


Figure 3-5 Our own design named Design #2

It was made for our brake disc to reduce weight and reveal a design with pressure area and cooling channels.

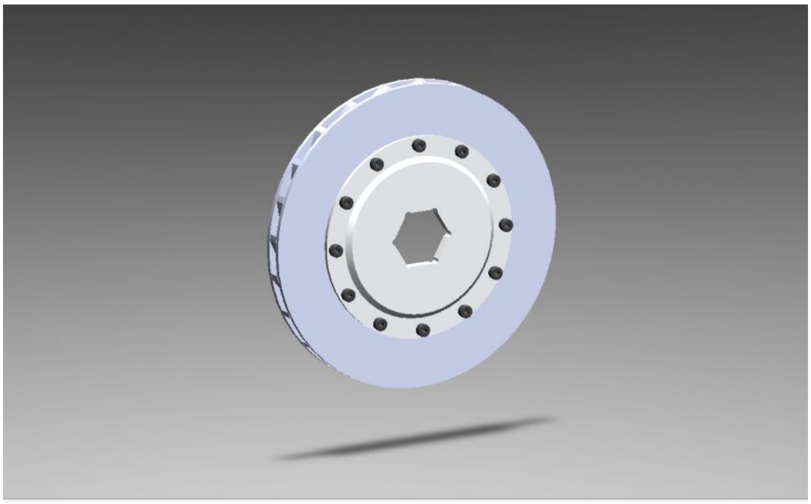


Figure 3-6 For Structural Optimization Design

3.2 Material Selection

Before starting the analysis, we first researched which materials are used in brake disc systems, and as a result, we learned that ceramic, gray cast iron and stainless steel are used in brake discs. All of these have their own advantages and disadvantages. Ceramic is mostly used in luxury cars. For this reason, it can reach higher temperature levels. We used stainless steel and gray cast iron in our own designs.

3.2.1 Gray Cast Iron

When it comes to brake rotors, this is the epitome of old school. It comes in one or two pieces and does the job. It's the most common material for brake rotors, in fact. Even a high-performance vehicle can benefit from the right design. It is, however, the heaviest option, which has an impact on your car's overall weight and handling because the weight is right up there with your front wheels.

	A	B	C
1	Property	Value	Unit
2	Material Field Variables	Table	
3	Density	7200	kg m^-3
4	Isotropic Secant Coefficient of Thermal Expansion		
6	Isotropic Elasticity		
7	Derive from	Young's Modulus and Poisson...	
8	Young's Modulus	1,1E+11	Pa
9	Poisson's Ratio	0,28	
10	Bulk Modulus	8,3333E+10	Pa
11	Shear Modulus	4,2969E+10	Pa
12	Tensile Yield Strength	0	Pa
13	Compressive Yield Strength	0	Pa
14	Tensile Ultimate Strength	2,4E+08	Pa
15	Compressive Ultimate Strength	8,2E+08	Pa
16	Isotropic Thermal Conductivity	52	W m^-1 C^-1
17	Specific Heat, C_p	447	J kg^-1 C^-1
18	Isotropic Relative Permeability	10000	
19	Isotropic Resistivity	9,6E-08	ohm m

Figure 3-7 Material Properties of Gray Cast Iron

3.2.2 Stainless Steel

It is provided a stainless steel for a brake disc that is less susceptible to material property deterioration, particularly hardness deterioration, when heated to temperatures exceeding 500°C during braking, while maintaining the abrasion resistance, rusting resistance, and toughness of conventional steel.

	A	B	C
1	Property	Value	Unit
2	Material Field Variables	Table	
3	Density	7750	kg m^-3
4	Isotropic Secant Coefficient of Thermal Expansion		
6	Isotropic Elasticity		
7	Derive from	Young's Modulus and Poisson...	
8	Young's Modulus	1,93E+11	Pa
9	Poisson's Ratio	0,31	
10	Bulk Modulus	1,693E+11	Pa
11	Shear Modulus	7,3664E+10	Pa
12	Tensile Yield Strength	2,07E+08	Pa
13	Compressive Yield Strength	2,07E+08	Pa
14	Tensile Ultimate Strength	5,86E+08	Pa
15	Compressive Ultimate Strength	0	Pa
16	Isotropic Thermal Conductivity	15,1	W m^-1 C^-1
17	Specific Heat, C_p	480	J kg^-1 C^-1
18	Isotropic Relative Permeability	1	
19	Isotropic Resistivity	7,7E-07	ohm m

Figure 3-8 Material Properties of Stainless Steel

3.3 Meshing

One of the most important stages in mesh analysis, proper mesh definition and compliance with its standards. For this reason, we ran multiple trials for the mesh and ran multiple analyses to see that the analysis results were mesh independent.

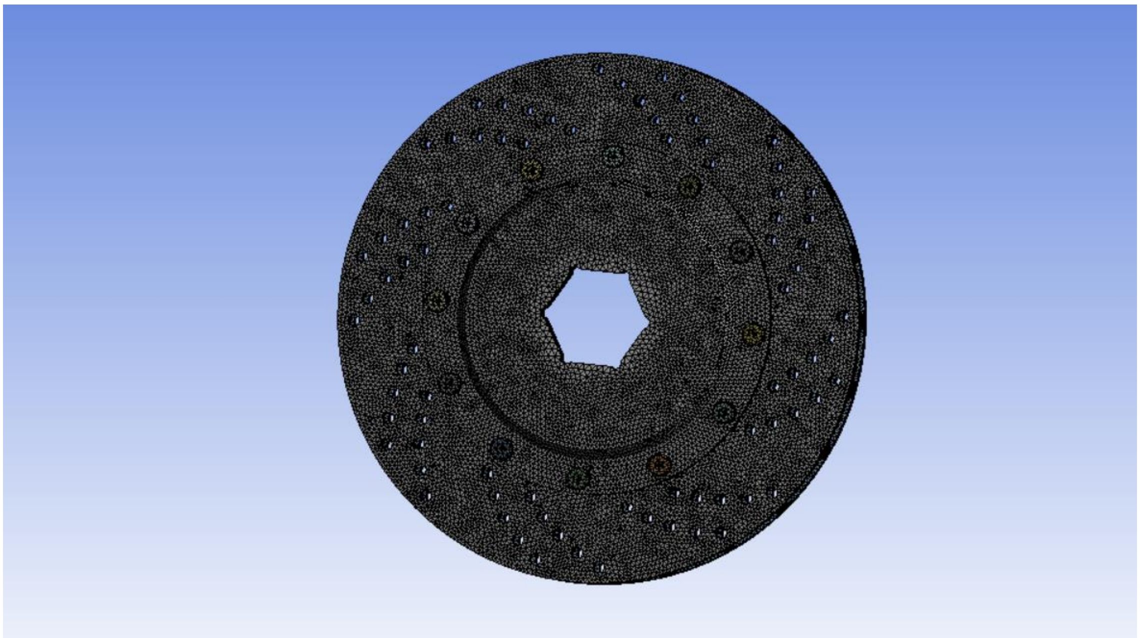
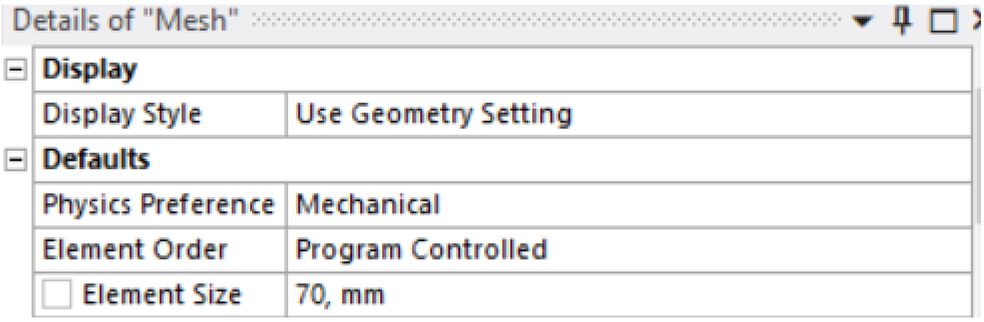


Figure 3-9 Brake Disk After Meshing

There are multiple options in the software when meshing. While doing this, we have taken the element as 70mm. The reason for this was that this range was found to be the most suitable range because of multiple trials.

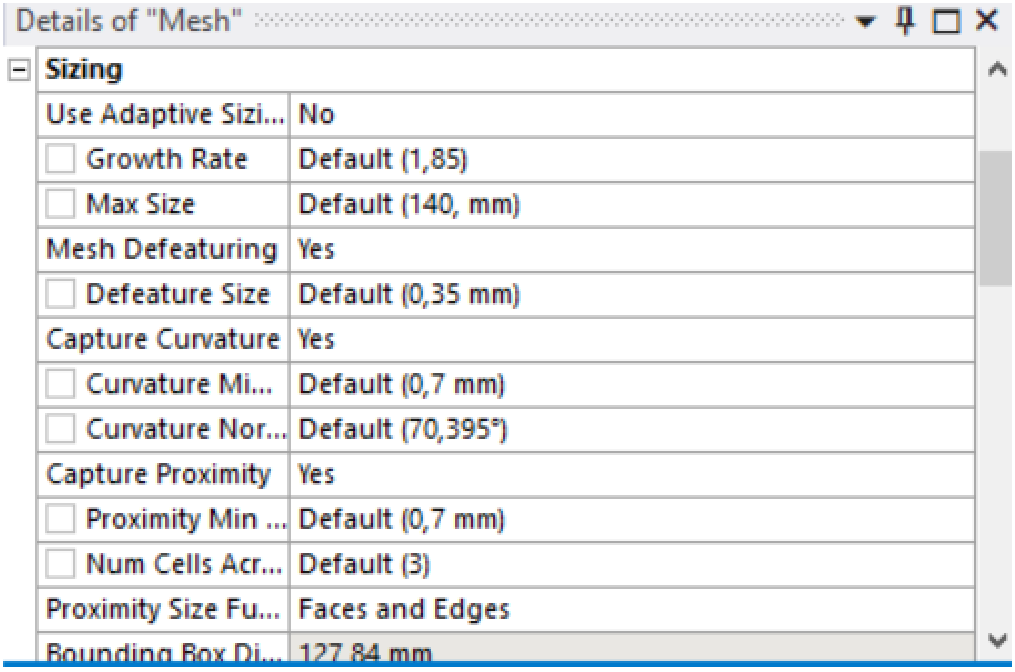


Details of "Mesh"

Display	
Display Style	Use Geometry Setting
Defaults	
Physics Preference	Mechanical
Element Order	Program Controlled
Element Size	70, mm

Figure 3-10 Mesh Element Size

While doing my analysis, we turned off adaptive sizing to keep mesh sizes close to each other and turned-on convergence and curvature capture feature to assign better mesh, which gave us the chance to assign more meshes.



Details of "Mesh"

Sizing	
Use Adaptive Sizi...	No
Growth Rate	Default (1,85)
Max Size	Default (140, mm)
Mesh Defeaturing	Yes
Defeature Size	Default (0,35 mm)
Capture Curvature	Yes
Curvature Mi...	Default (0,7 mm)
Curvature Nor...	Default (70,395°)
Capture Proximity	Yes
Proximity Min ...	Default (0,7 mm)
Num Cells Acr...	Default (3)
Proximity Size Fu...	Faces and Edges
Bounding Box Di...	127,84 mm

Figure 3-11 Sizing Options for Meshing

Then we checked whether our meshing was up to standards using the mesh metric. According to the standards, when the mesh is cast in the tetrahedron structure, the meshes should be close to 1. When we checked the quality, we found that our meshes met these standards.

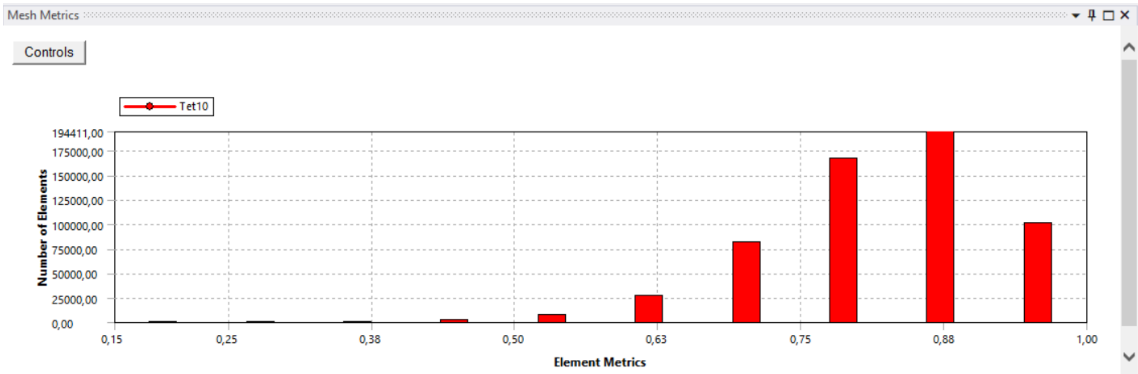


Figure 3-12 Element Quality of Meshing

We used this tactic in all our mesh assignments, although only the first piece is visible in the image, we used all these stages in other designs.

- **The Structural Optimization**

A different meshing technique was used together with the mesh intervals brought by the structural optimization studies. Although the increase in the number of mesh and the corresponding numerical models are predicted to give more accurate results, the change in the meshing method has supported the structural optimization studies, as many analyses made for the lack of hardware for structural optimization studies were inconclusive.

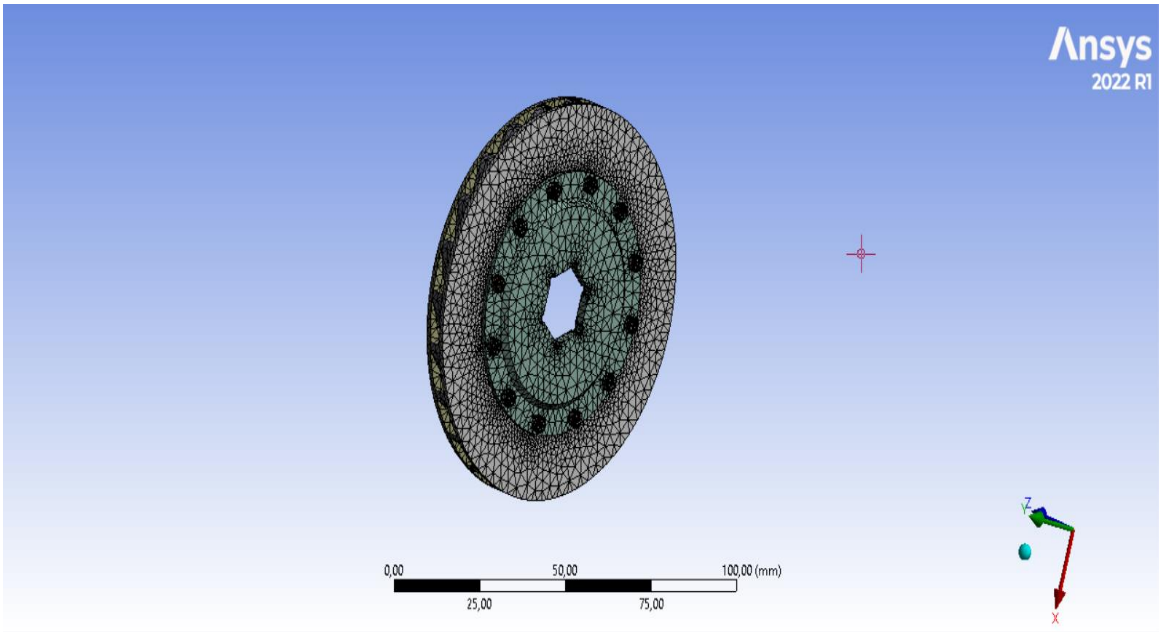


Figure 3-13 Brake Disk After Meshing (for Structural Optimization)

The mesh spacing for structural optimization is 2 mm. The reason for this is that no results can be obtained due to insufficient hardware.

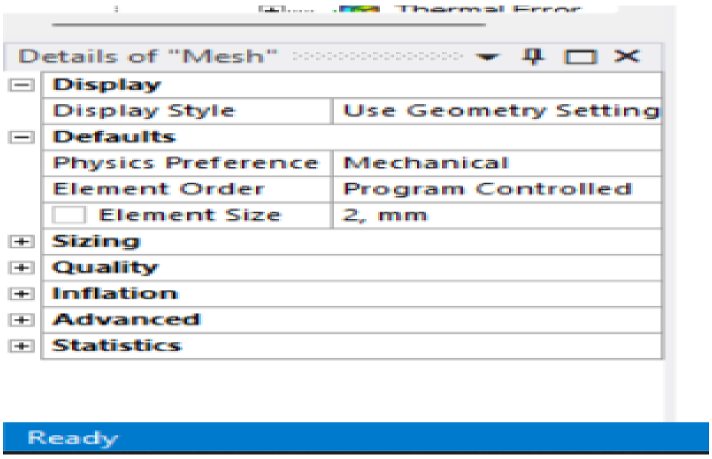


Figure 3-14 Mesh Element Size (for Structural Optimization)

3.4 Disk Analysis

In this section, we first analysed the piece we took as an example, and while doing this, we will do steady state and structural analysis. In this piece, we chose the disc as gray cast iron and the rest as stainless steel.

3.4.1 Steady-State Thermal Analysis

The average operating temperature of the brake discs is in the range of 200-300 degrees. This value can go up to 500-700 degrees with frequent braking or aggressive driving. For this reason, we adhered to the average temperature during our analysis and gave our brake disc a temperature of 300 degrees.

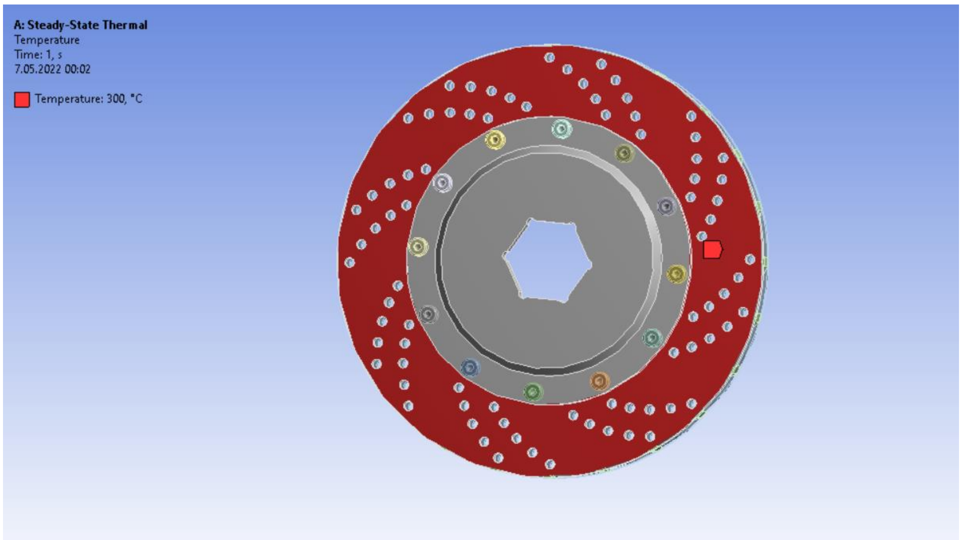


Figure 3-15 Temperature Applied on Front Disc

We applied the heat to the front disc, and our purpose was to do this. Brake callipers work as 2-piston or single-piston. During our analysis, we analysed our disc as if we had a single-piston calliper. For this reason, we only applied heat to the front surface.

Then we added convection as other parts will be affected by both the ambient temperature and the heat emitted by your brake disc. We added warmth to the front surface and defined the remaining disc parts as affected by convection. While doing this, we added the option depending on the temperature so that they are affected by the temperature.

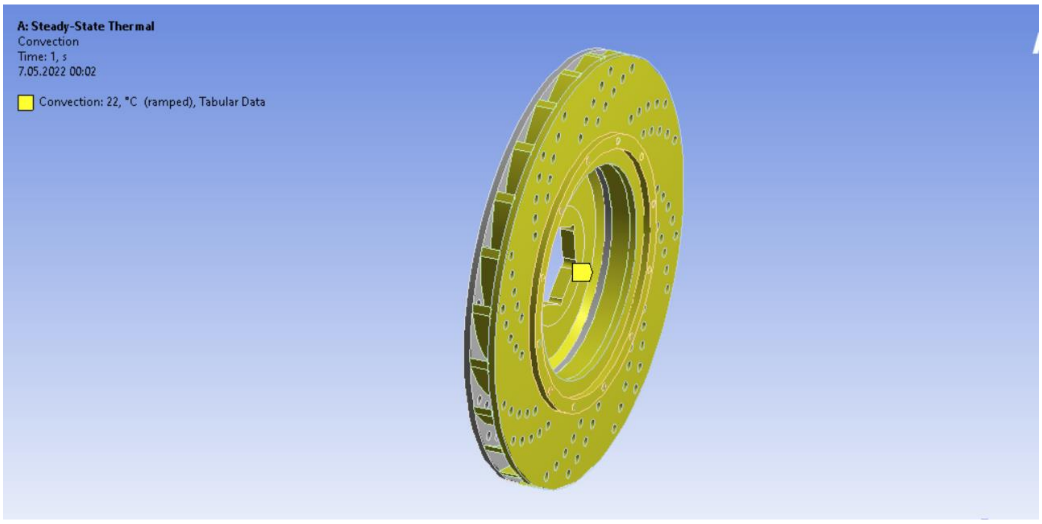


Figure 3-16 Parts Affected by Convection

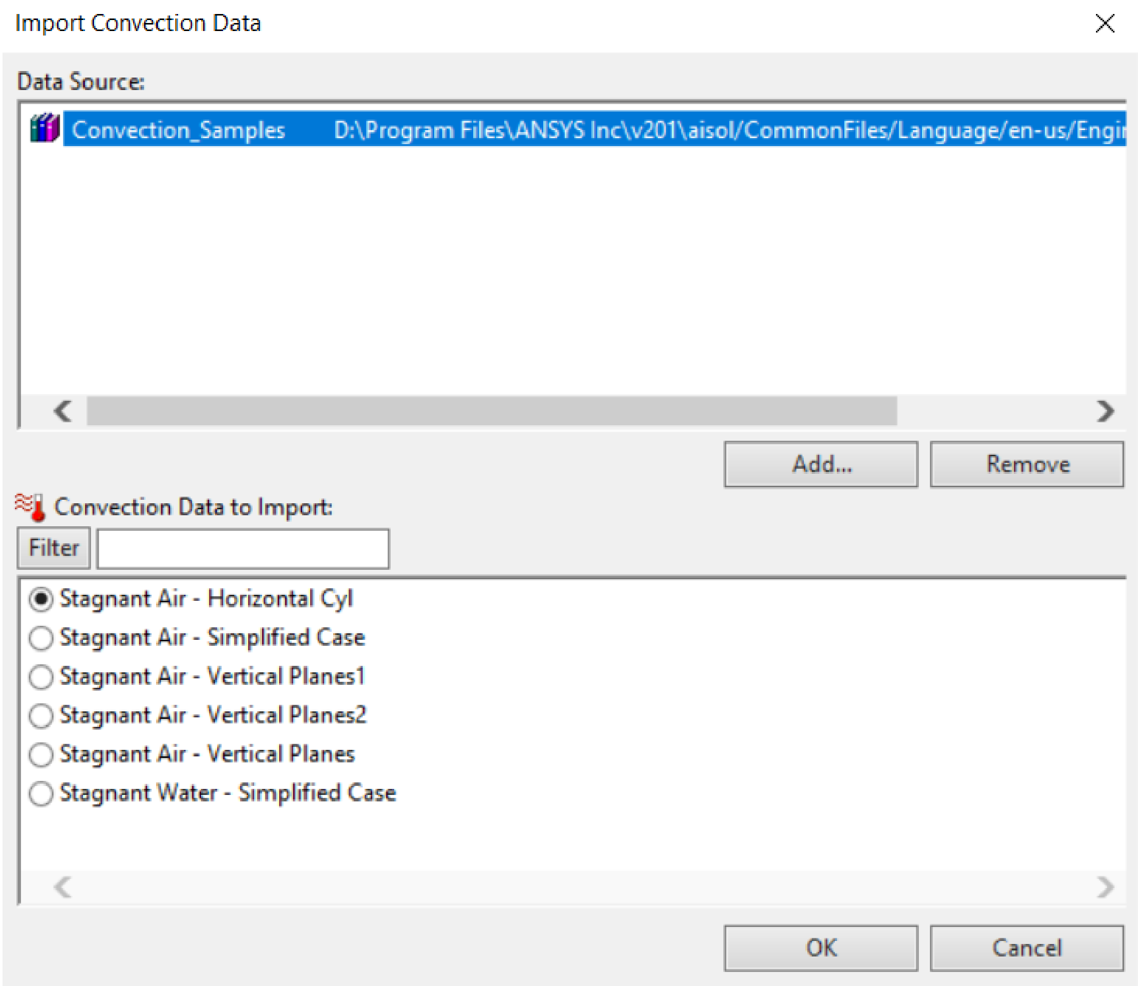


Figure 3-17 Temperature Dependent Convection

3.4.2 Static Structural Analysis

When we come to static structural, our inputs are fixed point, angular velocity and pressure applied to the surface. While doing this, we discussed the average car values. As a result of our research, we have seen that the pressure applied to the brake disc is below 800 PSI. For the accuracy of our analysis, we applied a pressure of 5 MPa, which is approximately 725 PSI.

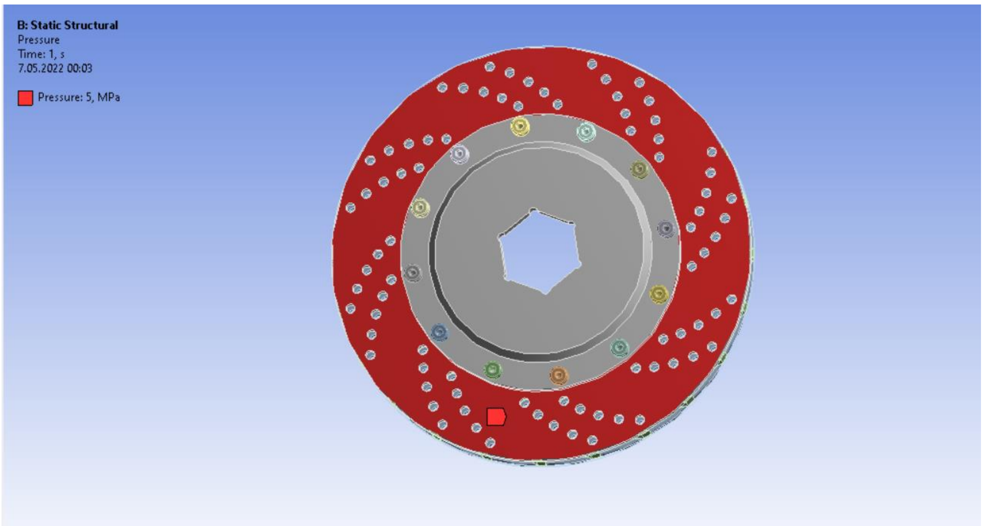


Figure 3-18 Pressure Applied on Front Disc

Apart from that, we had to choose a fixed point before adding angular velocity. The most accurate part of this was the front disc drum. We considered the front disc drum fixed.

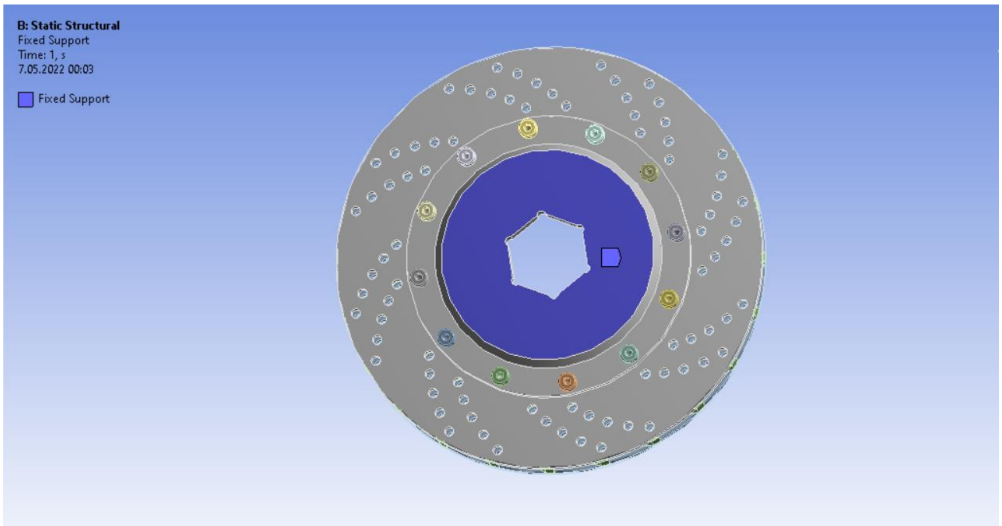


Figure 3-19 Fixed Support for Brake Disc

After making these settings, it's time to show the angular velocity. While doing this, we got the value of 130 rad/s. The reason for this is that it evolves to a speed of about 90 MPH for a car. In this way, we would be able to reach the values of a vehicle traveling at 90 MPH on a disc that had reached 300 degrees.

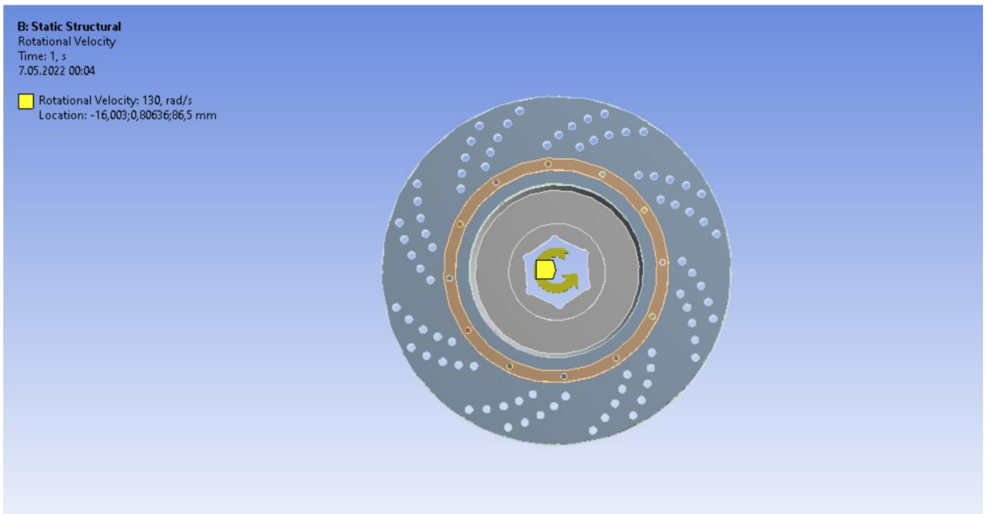


Figure 3-20 Rotational Velocity for Brake Disk

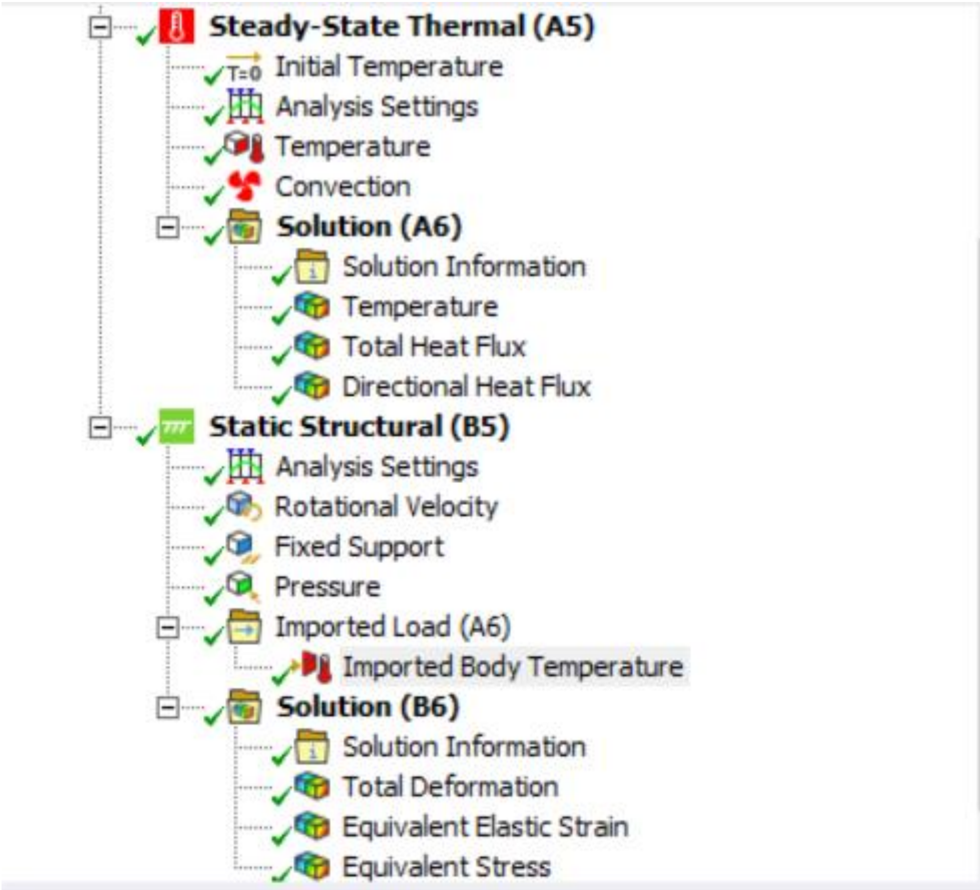


Figure 3-21 Outline Part of ANSYS

3.5 First Design of Brake Disc

In our first design, we changed not only the design but also the disc material. The main purpose of the design was to reduce the number of holes on the disc but also to increase the diameter of the holes. In this way, we wanted to see how the size of the arrangement of the holes and the change of material affected our result. In this piece, we chose the disc material as stainless steel.

3.5.1 Steady-State Thermal Analysis

We kept our input values the same during our analysis. The reason for this was to reach more concrete results when comparing the analysis results. For this reason, we applied a temperature of 300 degrees to the front disc surface in this disc.

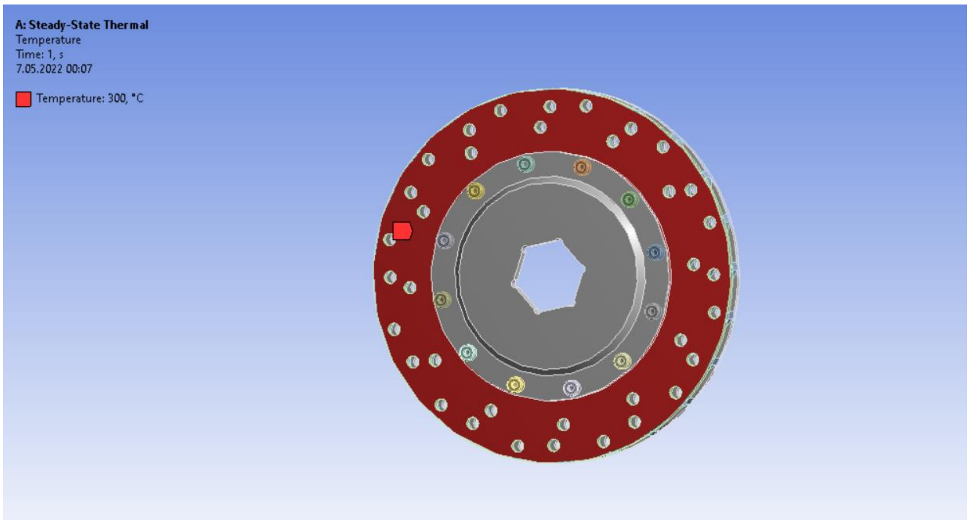


Figure 3-22 Temperature Applied on Front Disc of Design #1

As in the previous analysis, we selected the same parts as affected by convection and made it dependent on temperature.

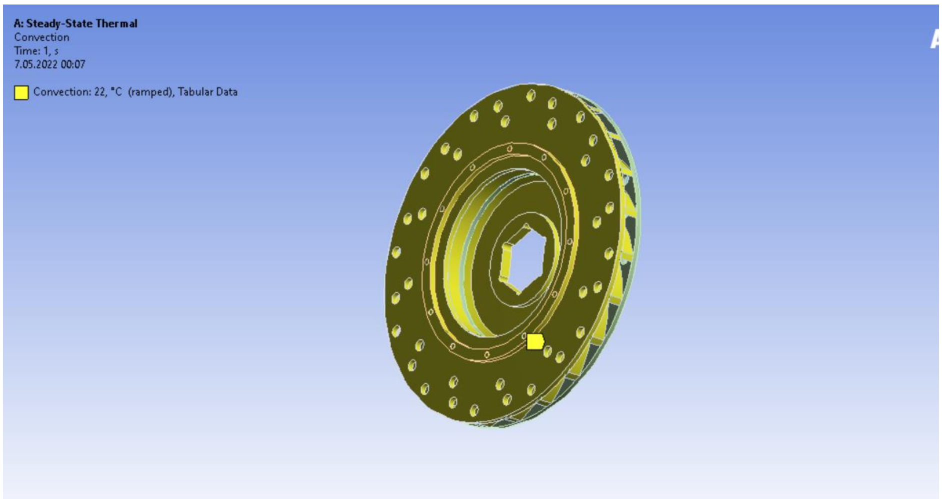


Figure 3-23 Convection for Brake Disc

3.5.2 Static Structural Analysis

In this design, we have chosen our rotational speed as 130 rad/s and our pressure on the disc as 5 MPA.

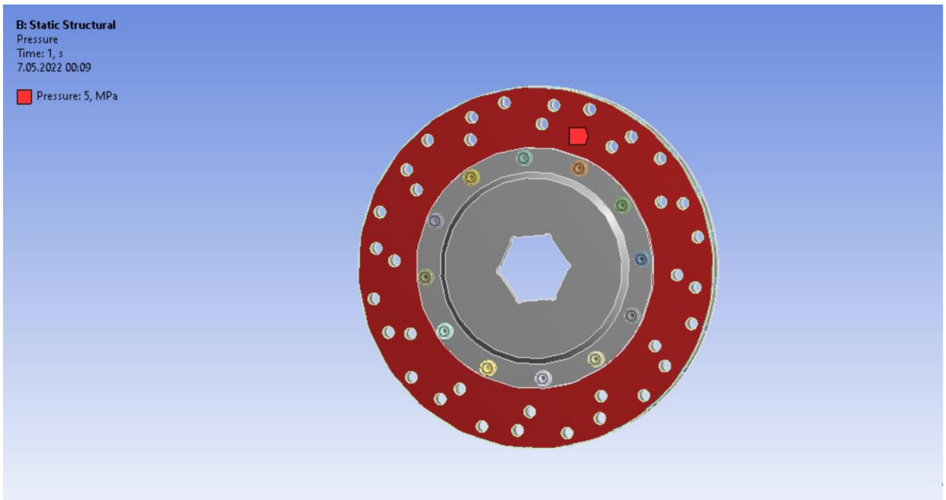


Figure 3-24 Pressure Applied on Front Disc of Design #1

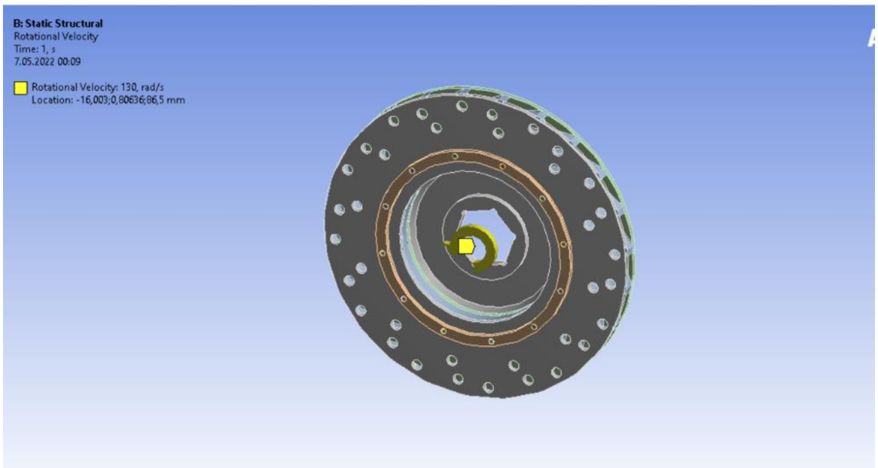


Figure 3-25 Rotational Speed for Design #1

In this design, we wanted to see if the wider holes have an effect on extra deformation and stress, but it should also be taken into account when we make a difference in material selection. For more accurate inferences, we will have to examine the 2nd design.

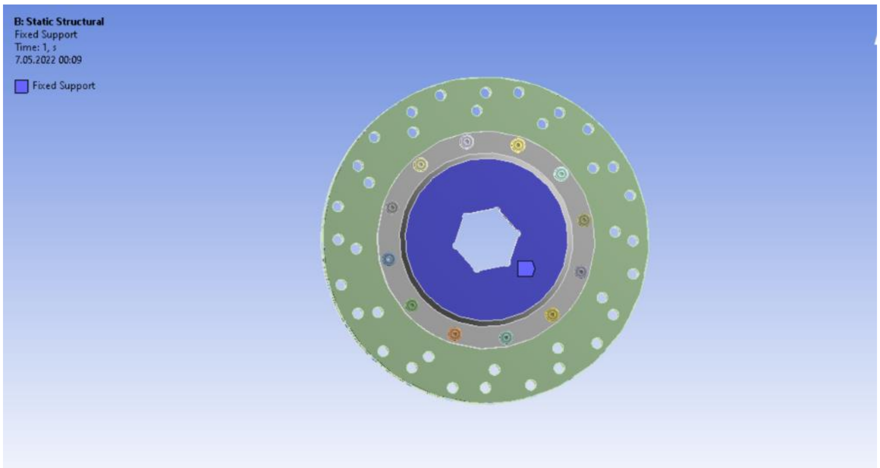


Figure 3-26 Fixed Support for Design #1

3.6 First Design of Brake Disc Version #2

Our aim in this design was to examine the first design with two different materials and see the differences in the results. For this reason, we kept the geometry in the first design constant and chose gray cast iron as the raw material.

3.6.1 Steady-State Thermal Analysis

As we mentioned before, we keep the input values in the analysis of the designs constant at every stage. For this reason, we applied a temperature of 300 degrees to the front surface here.

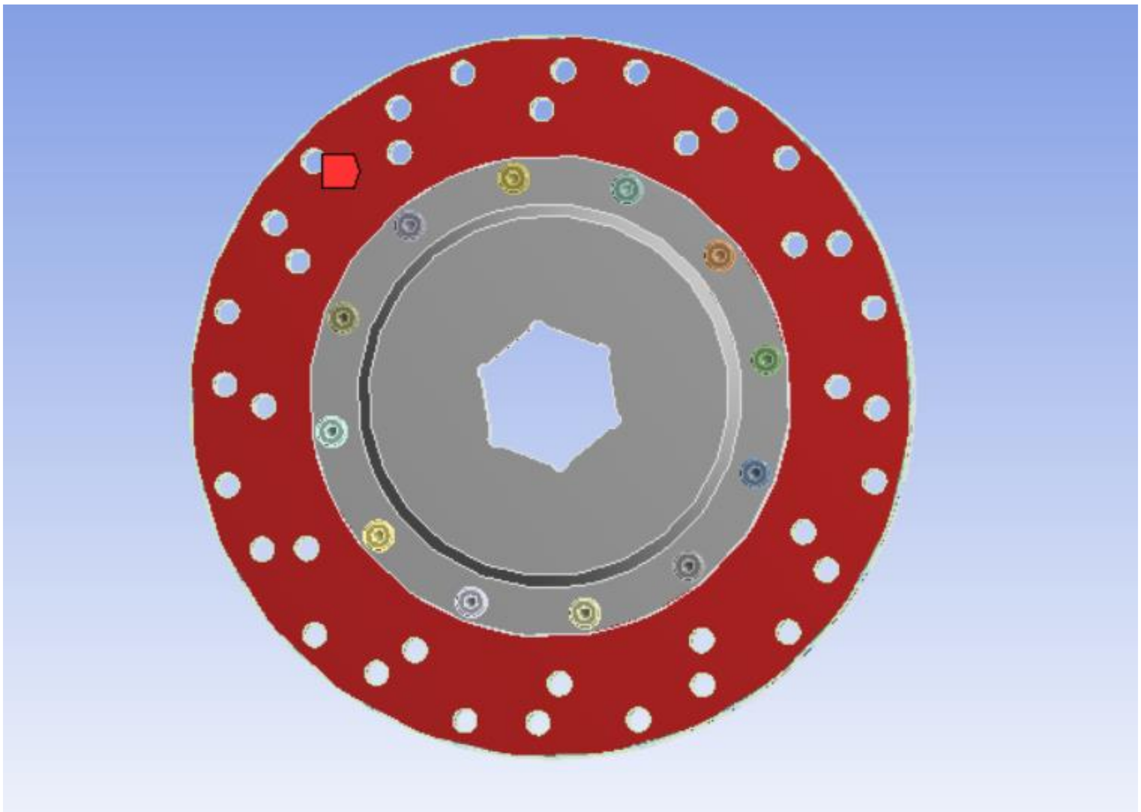


Figure 3-27 Temperature Applied on Front Disc of Design #1 Version #2

In the same way as in the previous designs, we chose the parts affected by convection and adjusted it depending on the temperature.

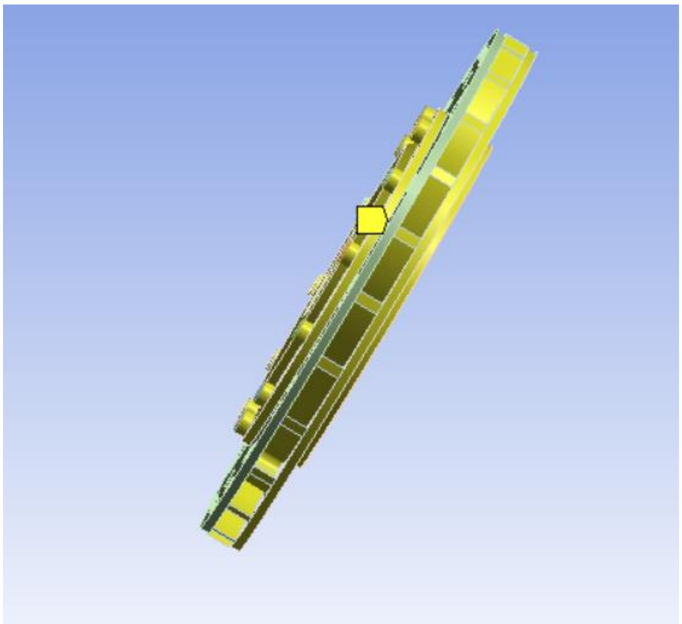


Figure 3-28 Convection for Design #1 Version #2

3.6.2 Static Structural Analysis

In this design, we have chosen our rotational speed as 130 rad/s and our pressure on the disc as 5 MPA.

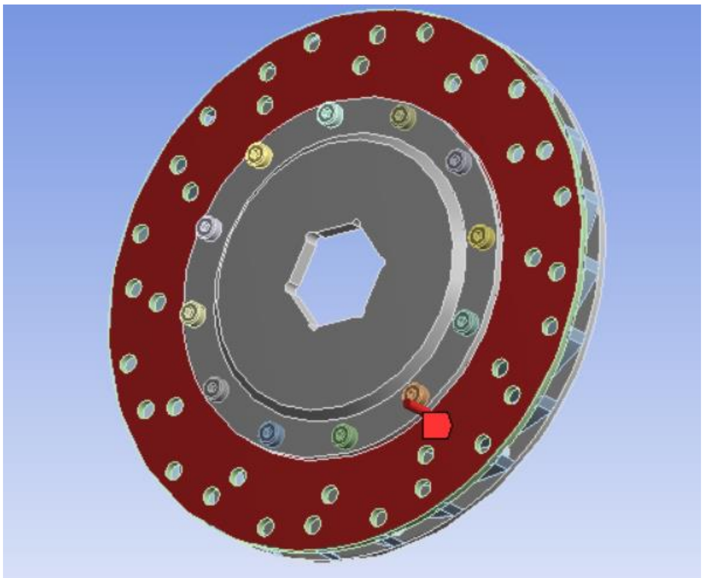


Figure 3-29 Pressure Applied on Front Disc of Design #1 Version #2

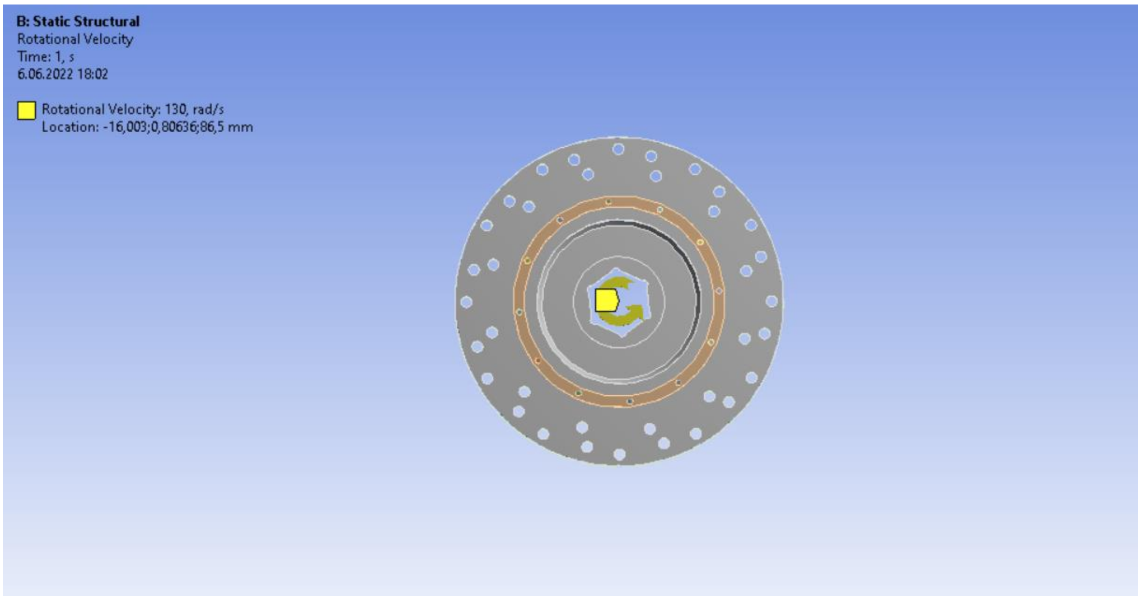


Figure 3-30 Rotational Speed for Design #1 Version #2

In this design, we expect to see differences in expectation static analysis as the material changes and the design remains constant. At the same time, we also need to choose a fixed point.

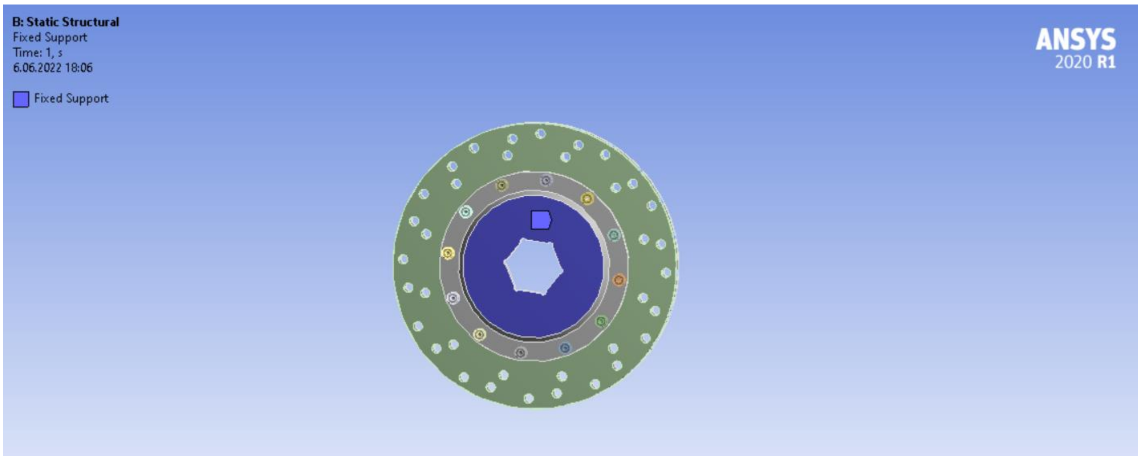


Figure 3-31 Fixed Support for Design #1 Version #2

3.7 Second Design of Brake Disc

In the third design, our main goal is to stay true to the second design and add channels to the design. Under normal circumstances, such a complex disc is only found in luxury cars or racing cars. In this way, the brakes of the cars can better withstand extreme conditions. In this design, we have made a design with a perforated and slotted structure.

3.7.1 Steady-State Thermal Analysis

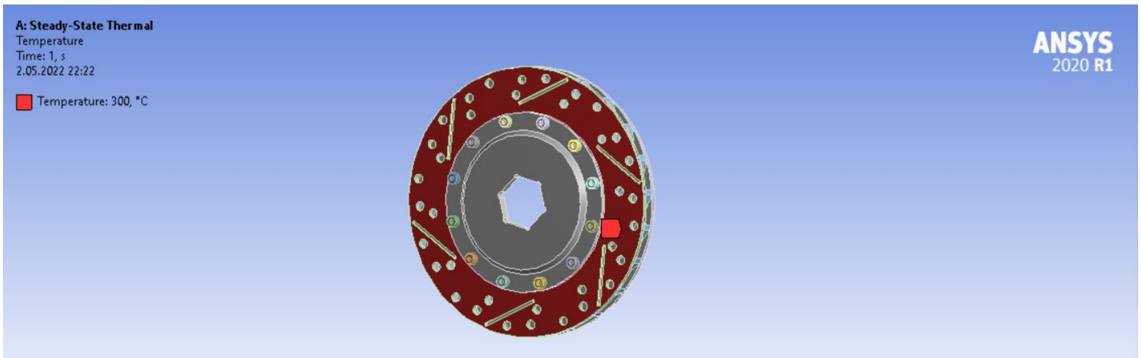


Figure 3-32 Temperature on Front Disc for Design #2

In this design, we kept the inputs constant for analysis, so it would be more realistic for us to compare designs related to the original design. We added the 300-degree temperature front disc. Apart from that, we designed the remaining parts to be affected by convection.

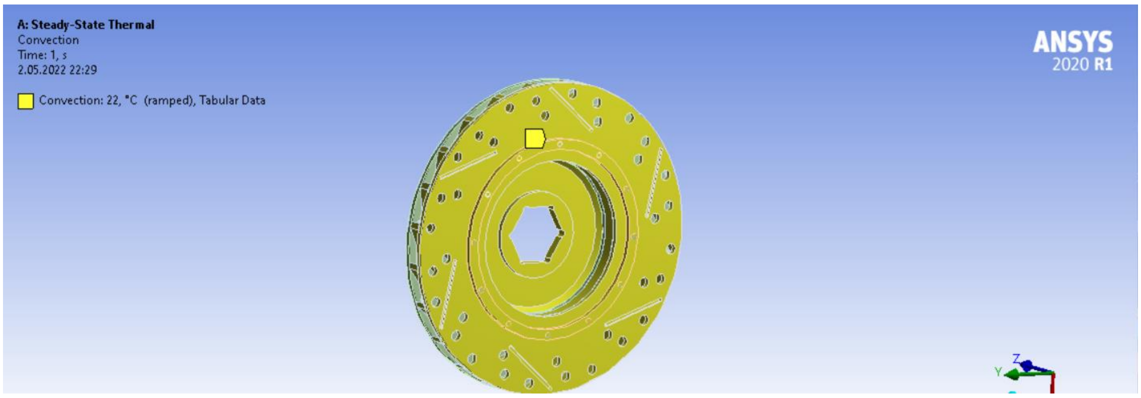


Figure 3-33 Part for Convection Design #2

3.7.2 Static Structural Analysis

In this design, too, we stuck to the inputs and set the rotational speed to 130 rad/s and the front surface pressure to 5 MPa. Our main aim is to see the difference in the stress and deformation of the channel structure.

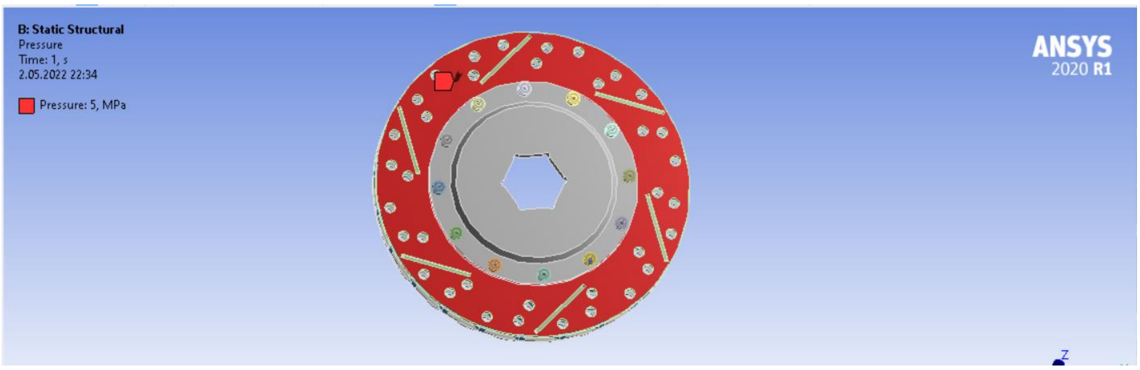


Figure 3-34 Pressure on Front Disc Surface of Design #2

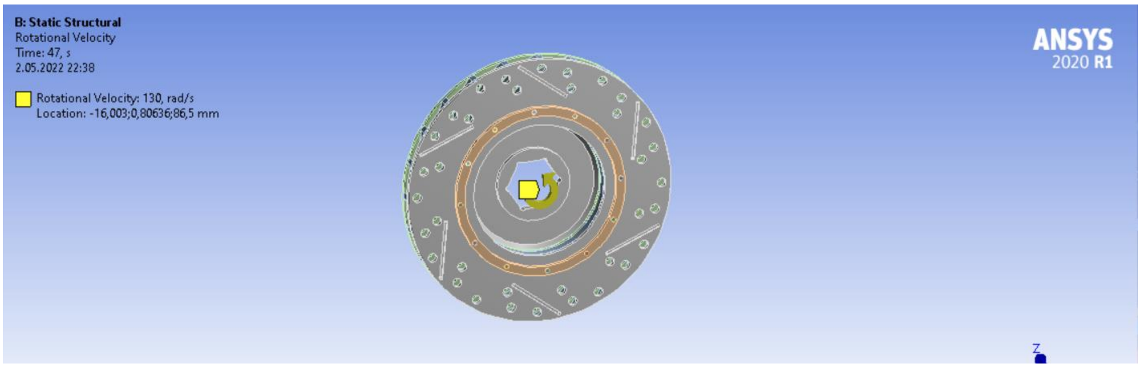


Figure 3-35 Rotational Speed for Design #2

3.8 The Structural Optimization

Before starting the structural optimization, a brake disc without air vents was created. Our aim here is to demonstrate the functionality of the air vents and to come up with a design for structural optimization. Structural optimization is done to help the designs by optimizing the structure created through the ANSYS software.

3.8.1 Steady-State Thermal Analysis

One of the most important points of brake discs is that the temperature distribution and maximum temperature distribution can be predicted. Air holes used for cooling are not used in this brake disc design.

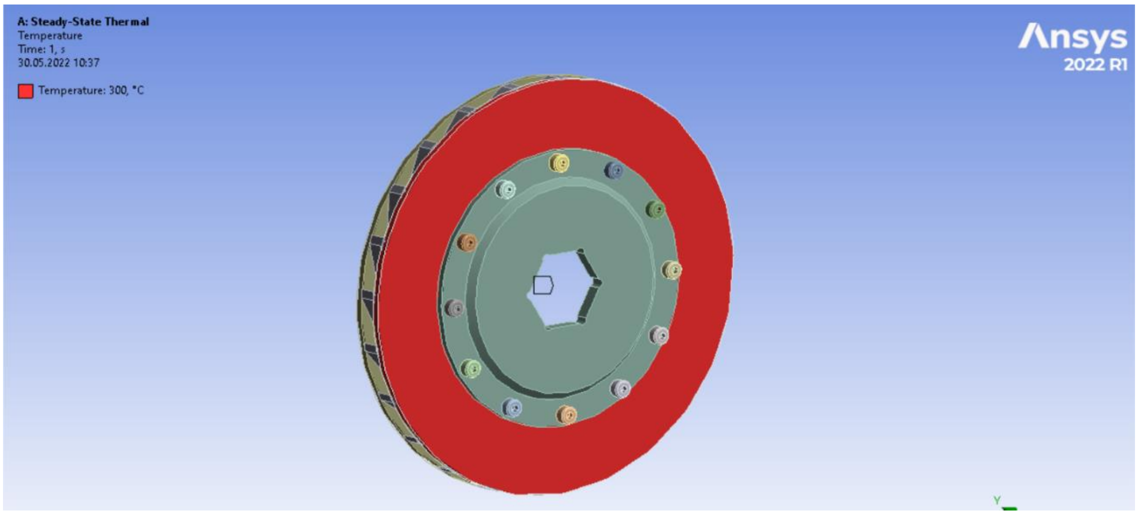


Figure 3-36 Temperature on Front Disc for Structural Optimization

Since pressure and temperature value will occur on the front of the brake disc, a one-sided temperature value is given. This temperature value is 300 C.

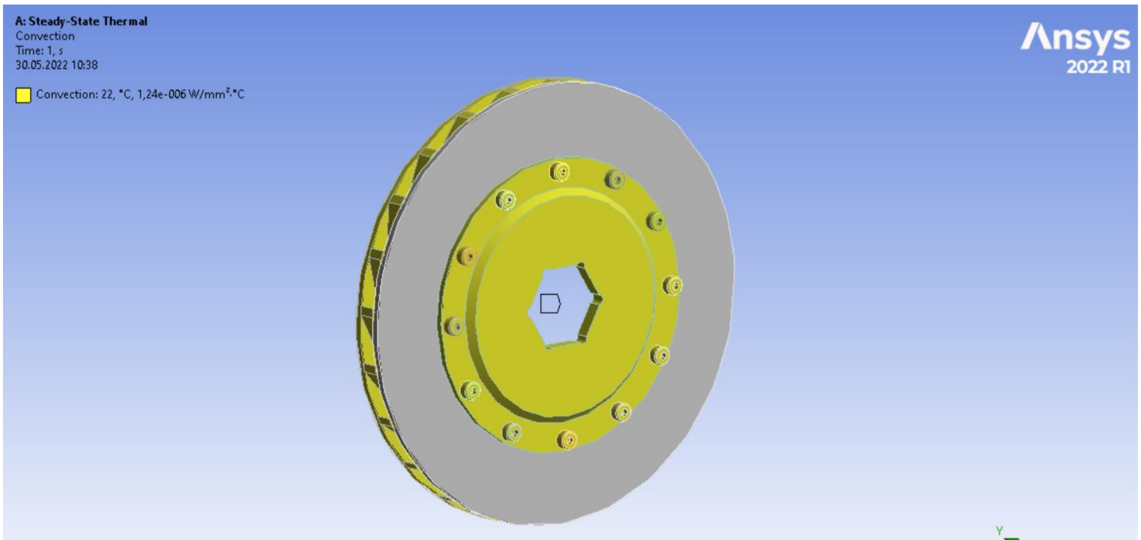


Figure 3-37 Part for Convection Design Structural Optimization

All parts except the front brake disc, which is heated in the convection definition section, have been selected.

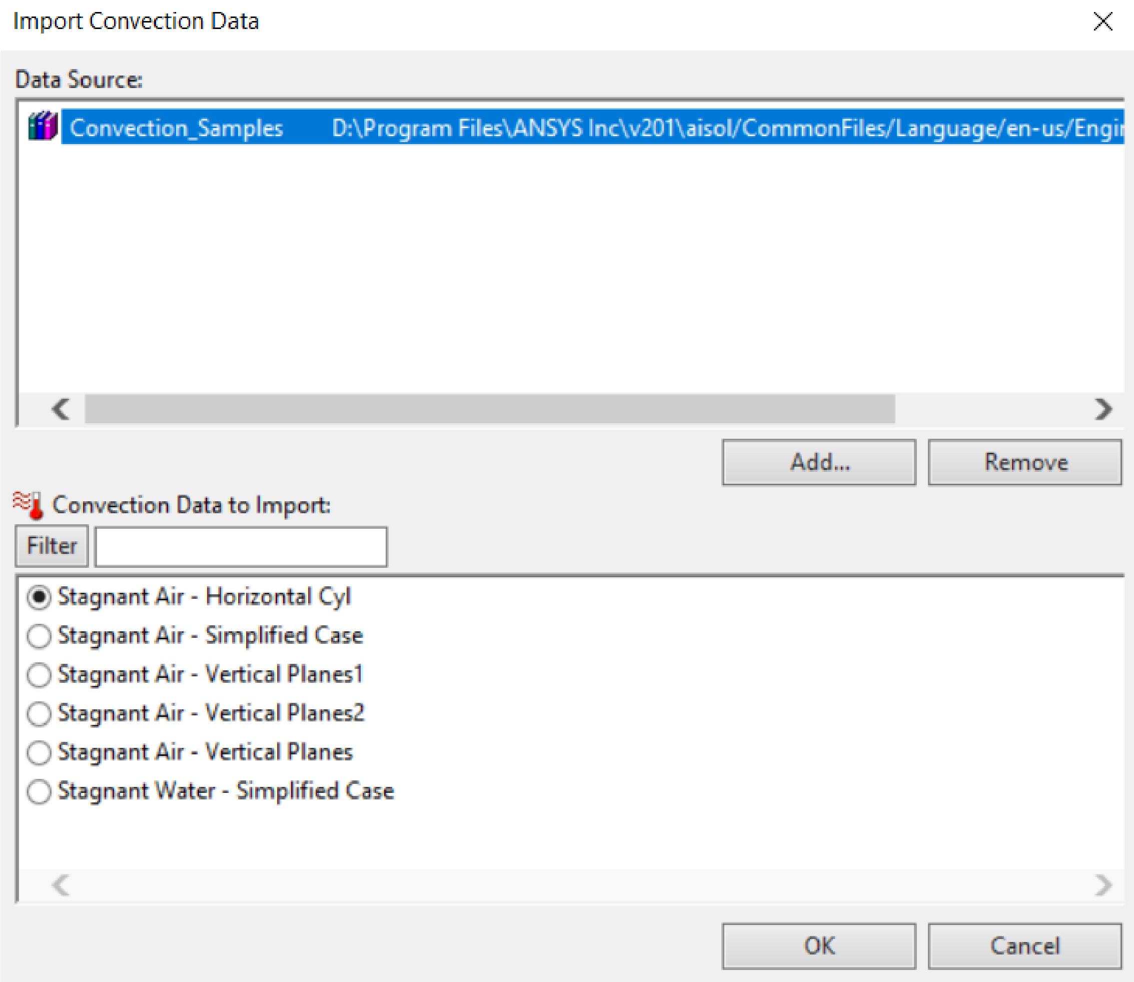


Figure 3-38 Temperature Dependent Convection

3.8.2 Static Structural Analysis

In our structural analysis part, we need to complete the last step before structural optimization. At this point, we linked the results of our heat transfer analysis to our structural analysis tree. After checking the accuracy of the results, the necessary parameters for the structural analysis were entered. Fixed point, pressure and rotational velocity values of the entered parameters were entered.

Our rotational velocity value was given as 130 rad/s and it was given over the rear brake disc. This is because the first contact point of the movement is the rear brake disc.

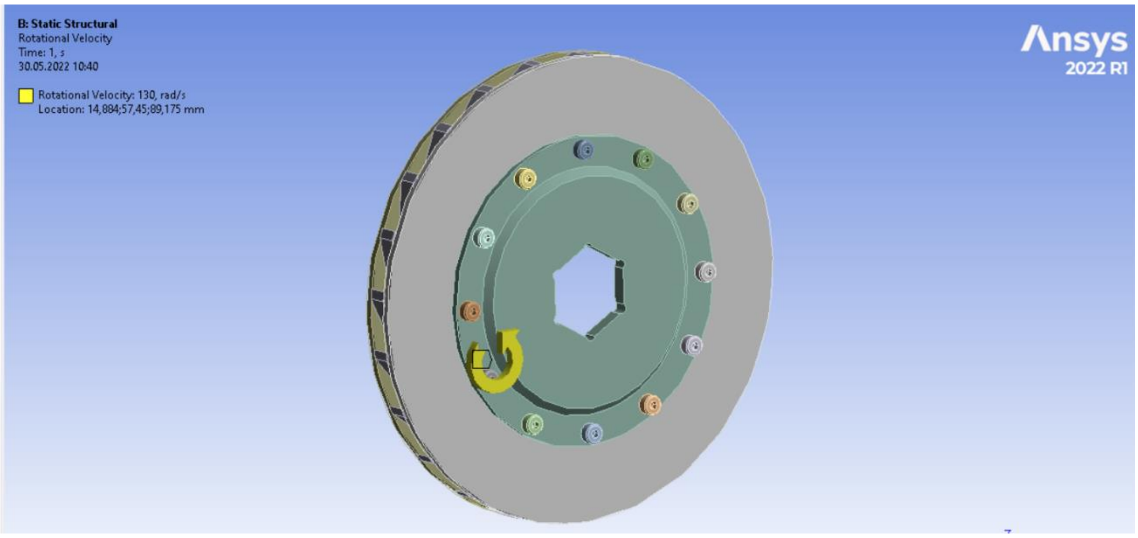


Figure 3-39 Rotational Velocity Values

Our braking force is about 5 Mpa. Our brake system, which makes one-sided braking, is pressed on our front brake disc.

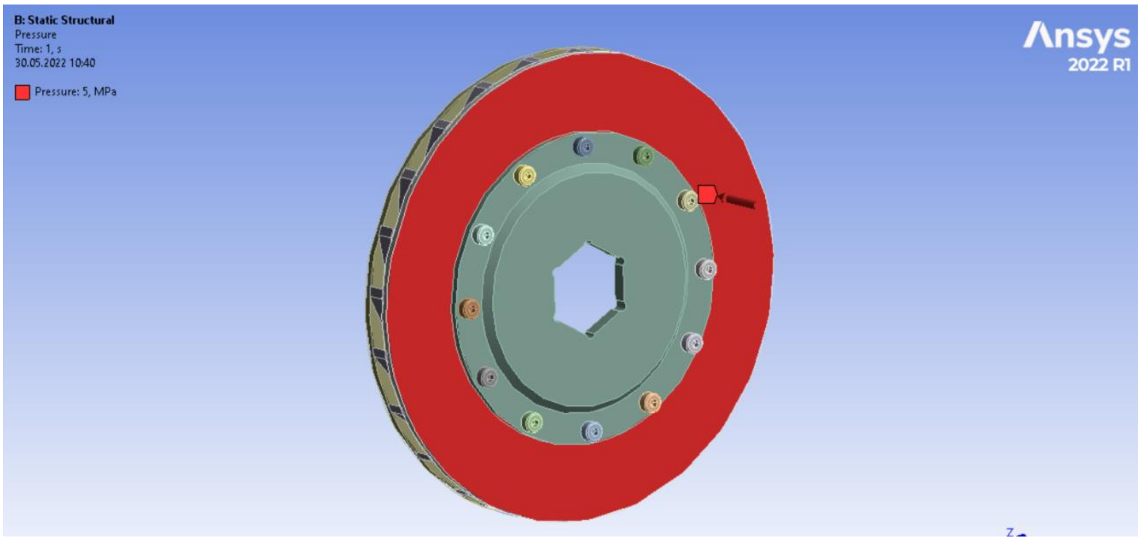


Figure 3-40 Pressure on Front Disc Surface

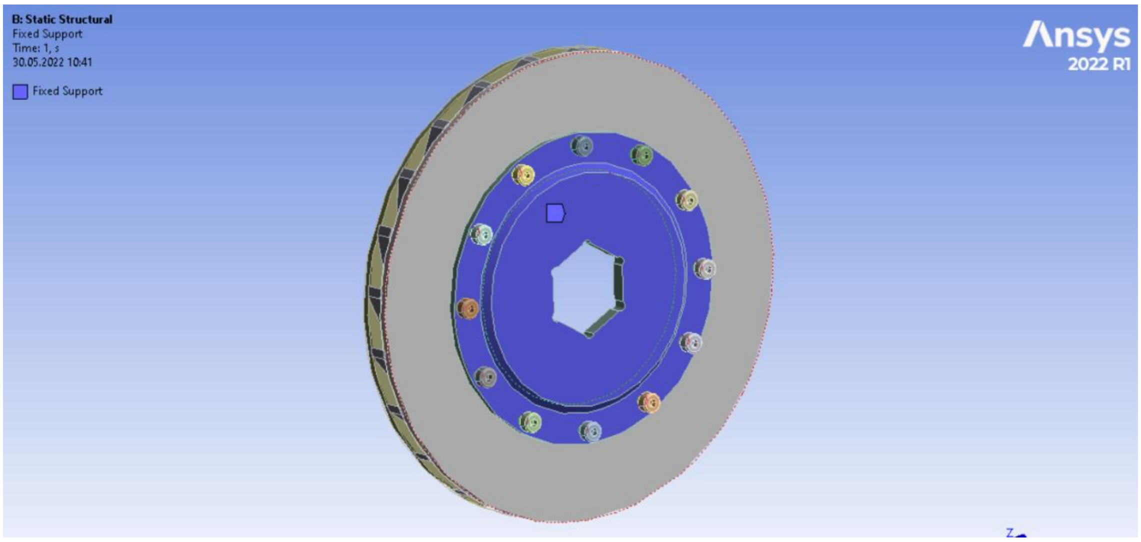


Figure 3-41 Fixed Support

3.8.3 Structural Optimization

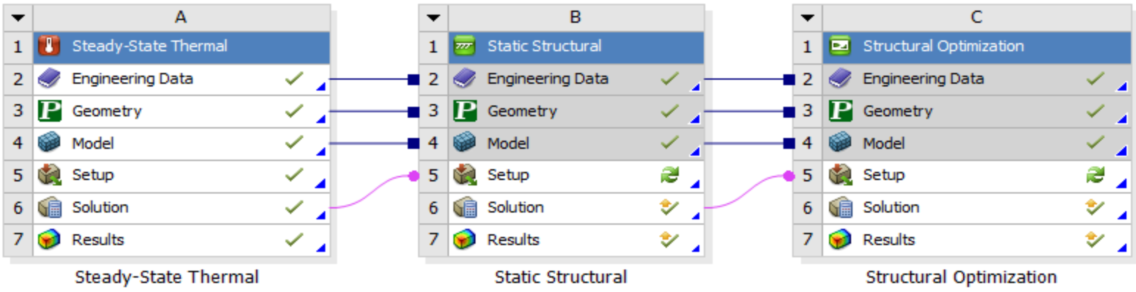
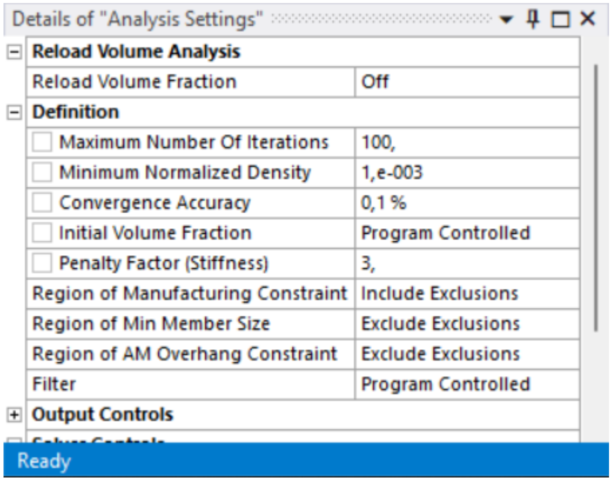


Figure 3-42 Structural Optimization Analysis Tree



Reload Volume Analysis	
Reload Volume Fraction	Off
Definition	
Maximum Number Of Iterations	100,
Minimum Normalized Density	1,e-003
Convergence Accuracy	0,1 %
Initial Volume Fraction	Program Controlled
Penalty Factor (Stiffness)	3,
Region of Manufacturing Constraint	Include Exclusions
Region of Min Member Size	Exclude Exclusions
Region of AM Overhang Constraint	Exclude Exclusions
Filter	Program Controlled
Output Controls	

Figure 3-43 Analysis Settings (Max Number of Iterations 100)

In general, structural optimization problems can be examined under four headings: size, shape, topology, and terrain optimization. The oldest known structural optimization method in the literature is size optimization (also called parameter optimization). Next up is shape optimization and finally is topology and terrain optimization.

Structural optimization process: It can be defined starting from a particular design topology, under certain boundary conditions and constraints, by changing the material distribution or boundary shape to reach an optimum design. The design process was carried out in three stages.

- Create the best initial topology using existing methods.
- This topology is processed and converted into a design with the help of computer imaging techniques.

- Then by applying shape optimization give a smooth shape to the contours and holes of the structure and, if necessary, by size optimization determine the final size of the structure.

Topology optimization should first include analyses that will occur at the boundary conditions of the material. While we were doing our structural optimization, we defined our values such as temperature, pressure, angular velocity, and then connected the results of these analyses to our analysis tree for our structural optimization analysis. While doing these steps, we revealed an analysis for weight reduction for structural optimization.

Details of "Optimization Region"

Design Region	
Scoping Method	Geometry Selection
Geometry	All Bodies
Exclusion Region	
Define By	Boundary Condition
Boundary Condition	All Boundary Conditions
Definition	
Suppressed	No
Optimization Option	
Optimization Type	Topology Optimization - Density Based

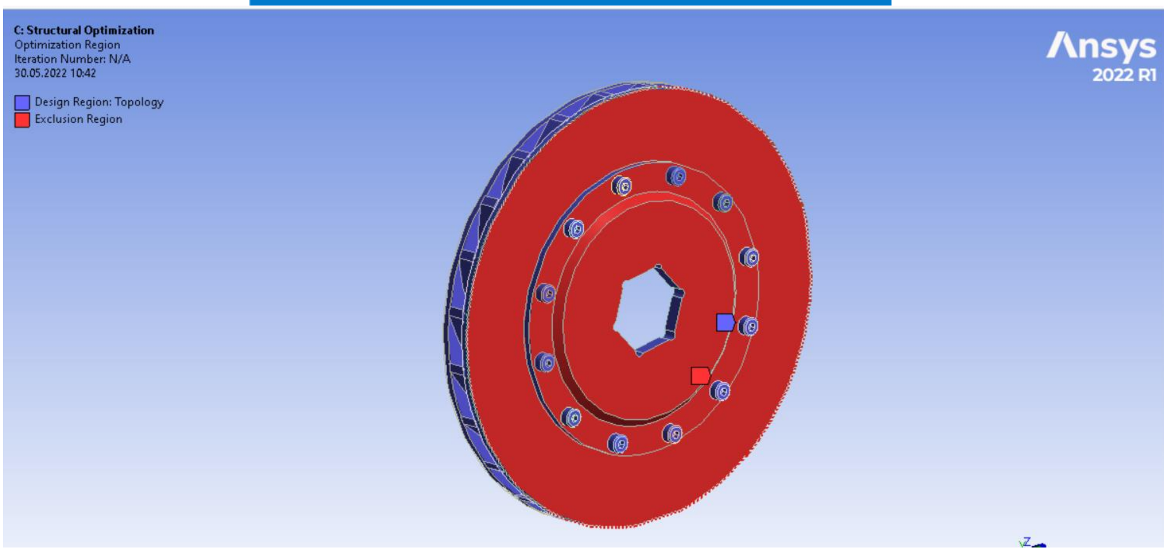


Figure 3-44 Optimization Region

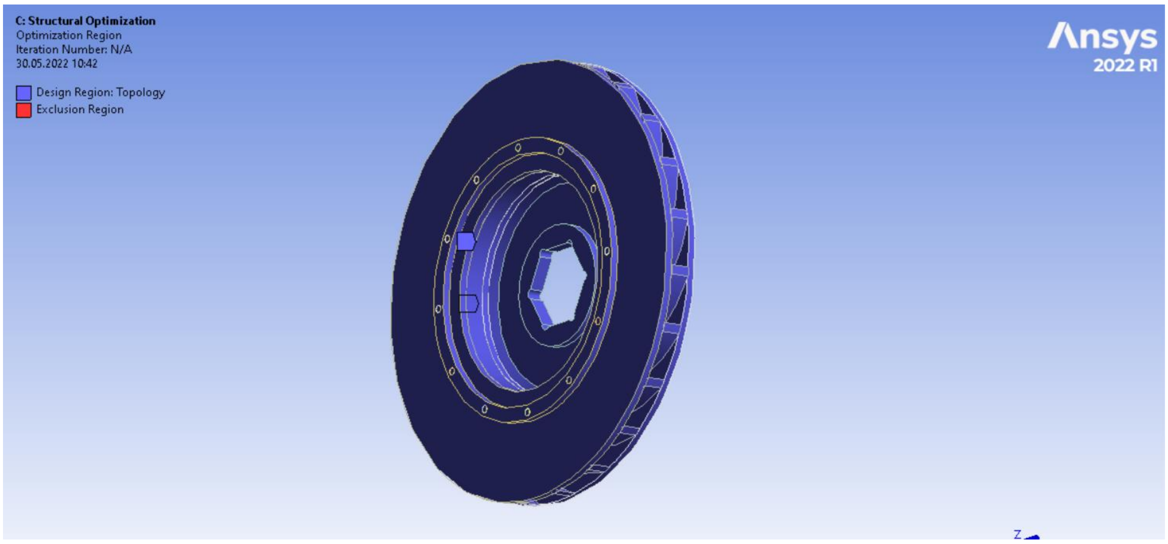


Figure 3-45 Defined Points for Structural Optimization

Details of "Response Constraint"

Scope	
Scoping Method	Optimization Region
Optimization Region Selection	Optimization Region
Definition	
Type	Response Constraint
Response	Mass
Define By	Constant
Percent to Retain	50 %
Suppressed	No

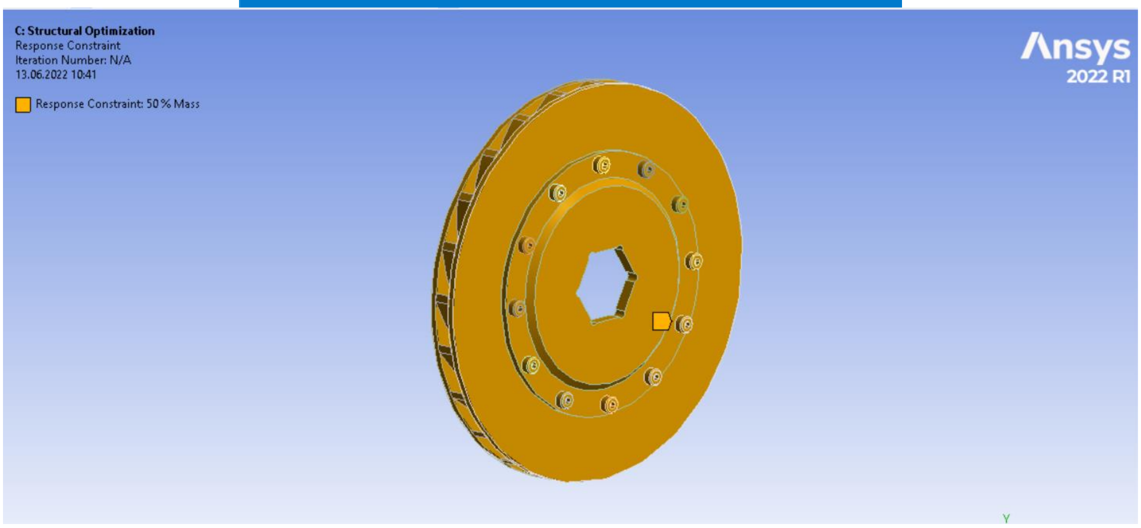


Figure 3-46 Response Constraint for %50 mass

For structural optimization, 50% weight reduction was achieved in the first analysis. All parameters are the same until the Response Constraint section. In the Response Constraint section, 50%, 67% and 82% were completed for 3 analyses, respectively. Details will be discussed in the Results section.

4. RESULTS

In this section, we will examine the results of our analyses more closely and comment on them.

4.1 Results of Disc Analysis

4.1.1 Steady-State

When we look at the results, we see that the maximum temperature is 300.07 degrees, and the min temperature is 284.05 degrees. Our average temperature value is 298.2 degrees.

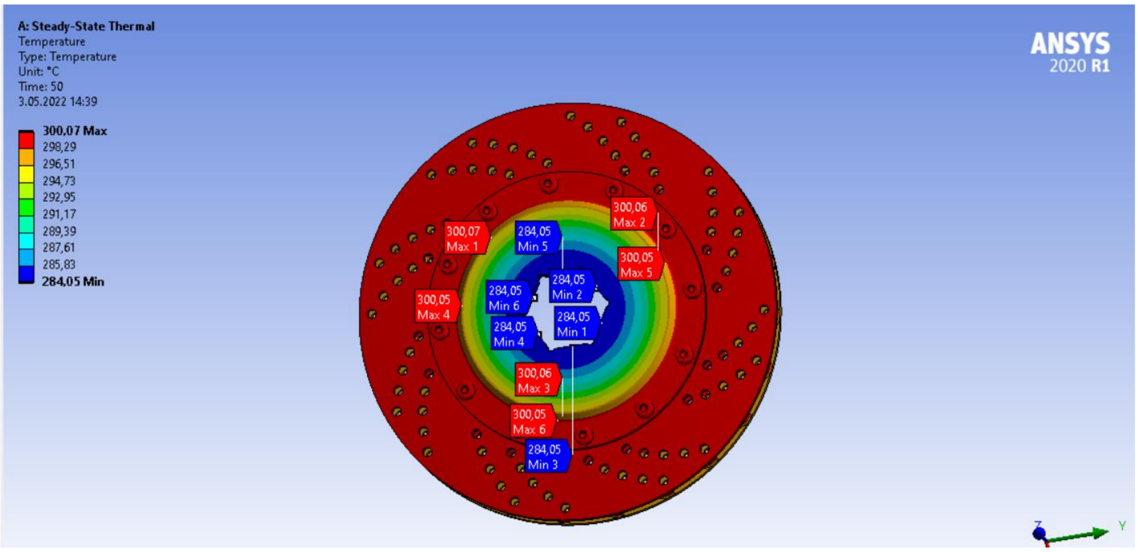


Figure 4-1 Local Max and Min Point of Disc

When we examined the front disc, the results were as expected, while the maximum temperature on the disc was found, the disc drum was the coldest part. When we examine the piece from the side, we can see the effect of air channels. As can be seen in the figure, as it gets closer to the rear disc, there is a colder temperature transition towards the rear disc with the effect of the air channels.

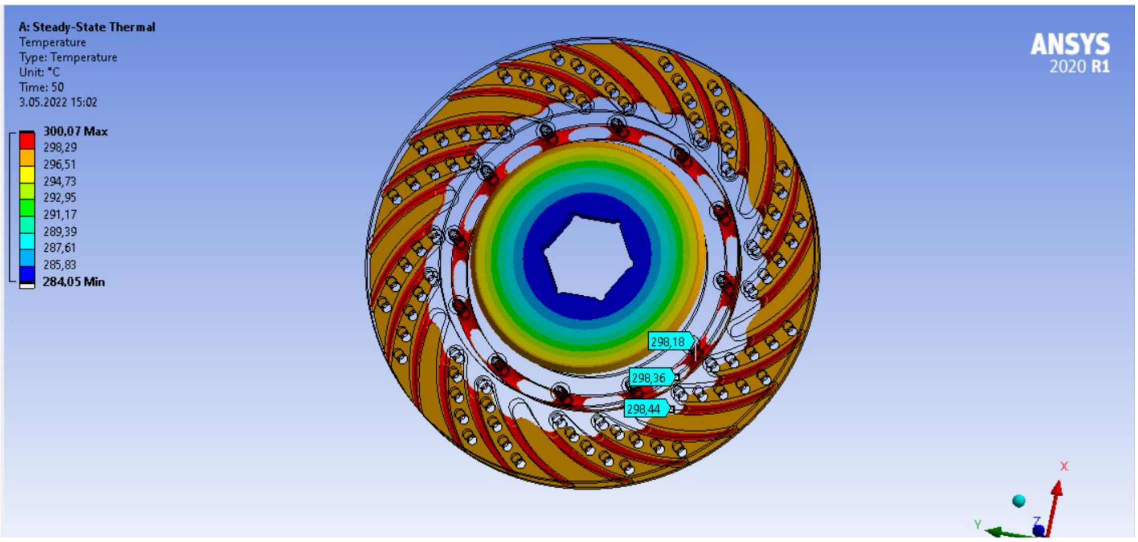


Figure 4-2 Inner Canal View of Disc

Results	
Minimum	284,05 °C
Maximum	300,07 °C
Average	298,2 °C

Figure 4-3 Temperature Values of Disc

When we examine the heat flux, we see that it is lower than the general in the perforated areas on the surface, because of the reduced surface area thanks to the perforated structure. When we look at the maximum value, it is striking that the difference between the minimum value and the minimum value is large, but the maximum value occurs only in very small areas at the ends of the channels. For this reason, the average value is closer to the minimum value.

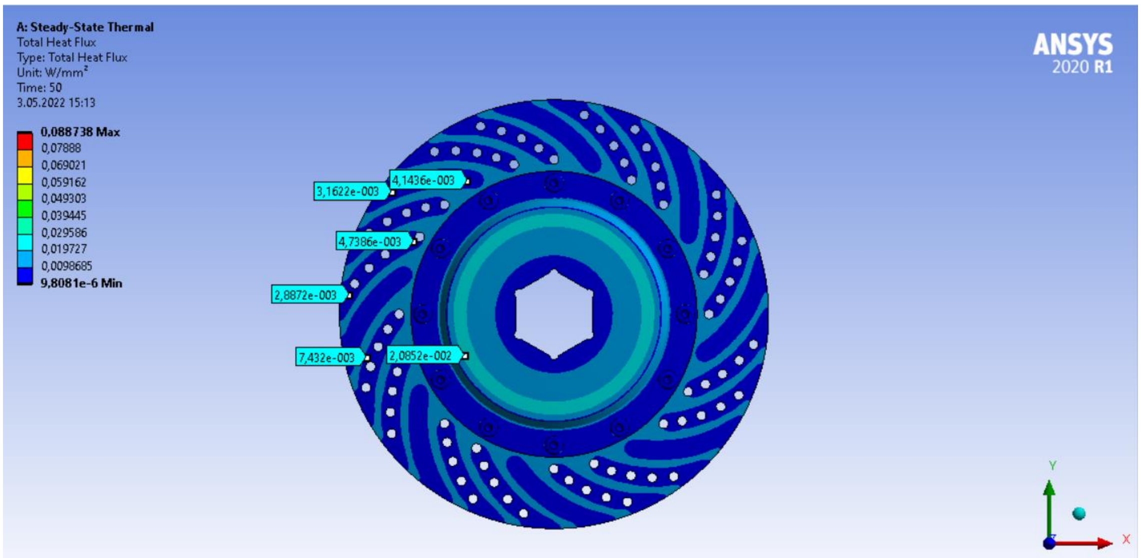


Figure 4-4 Heat Flux of Disc

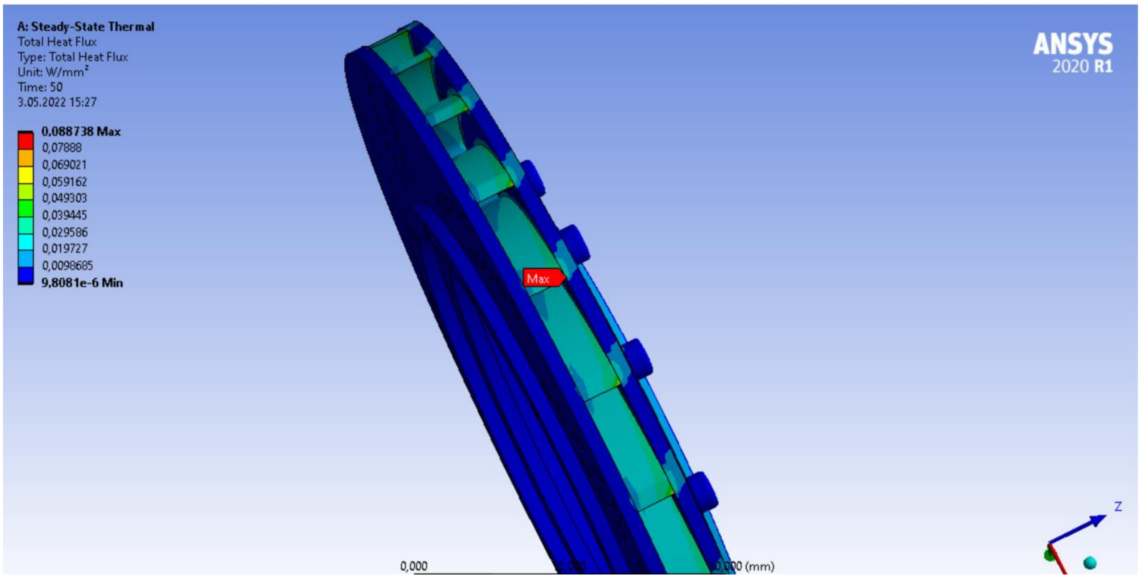


Figure 4-5 Max Heat Flux on Disc

4.1.2 Static Structural

When we look at the deformation analysis, we see that the most deformation occurs at the disc ends and the brake disc drum is least affected by this deformation.

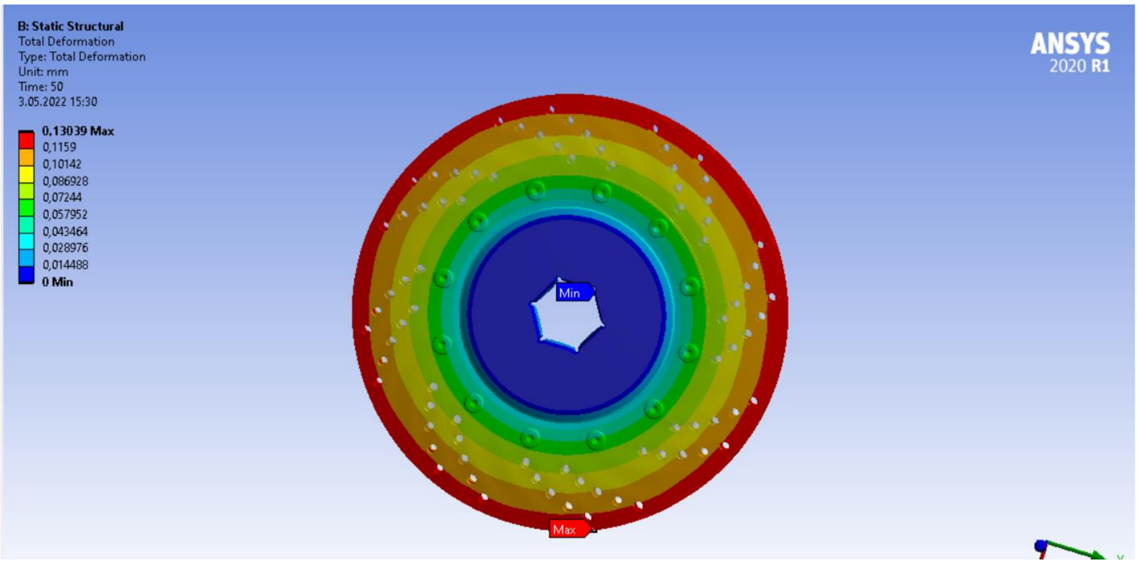


Figure 4-6 Deformation on Disc

When we look at the deformation values, we see that it gives results as at least 0 mm, maximum 13039 mm and on average 0.008207 mm.

Results	
Minimum	0, mm
Maximum	0,13039 mm
Average	8,2077e-002 mm

Figure 4-7 Deformation Values of Disc

When we move on to the stress analysis, we see that the stress on the disc surface is generally lower. In addition, the stress on the anterior disc surface is higher than the stress on the posterior surface. Average stress is 228.01 MPa.

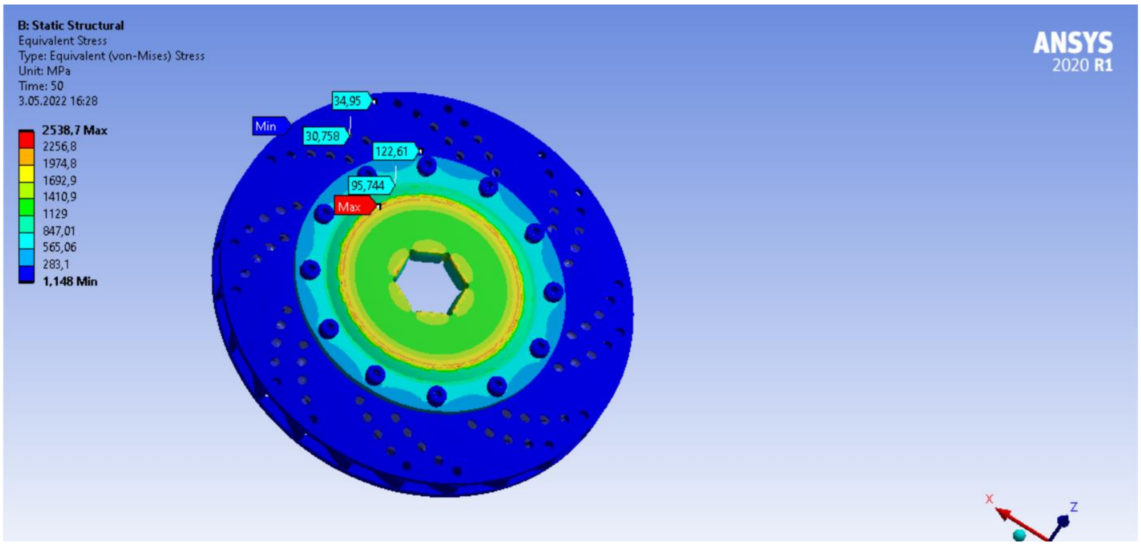


Figure 4-8 Equivalent Stress of Disc

The values in the image were taken from approximately the same points as can be seen in the figure.

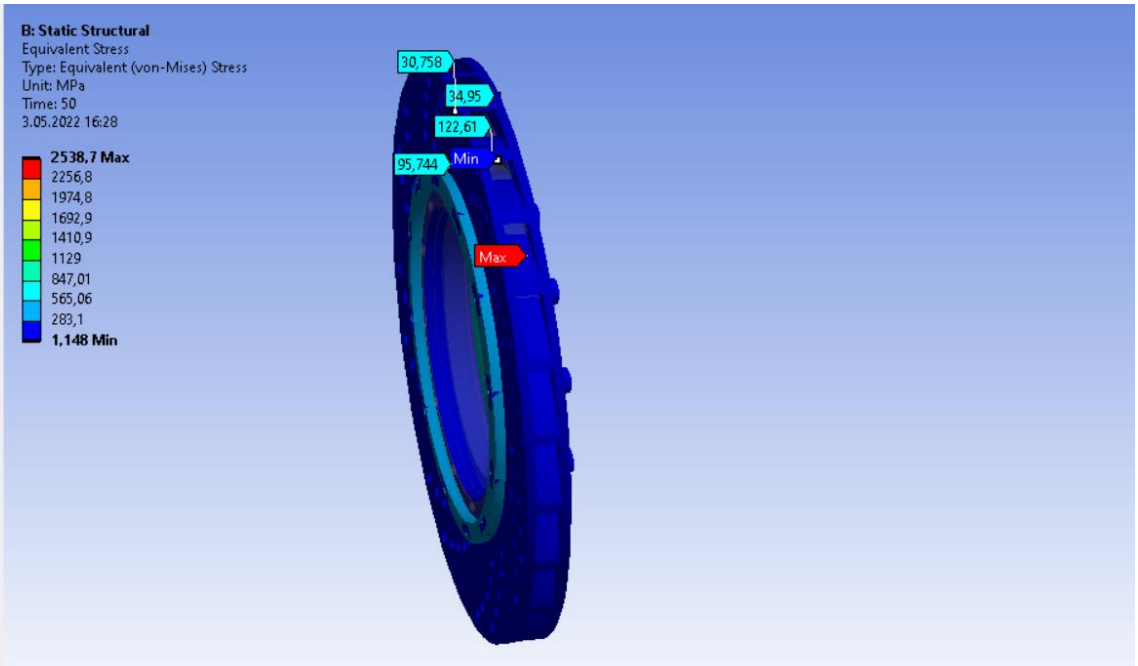


Figure 4-9 Side View of Disc

When we look at elastic tension, we see that we have a similar appearance to stress analysis. The disc surface is less valuable, which means that it can only return to the shape of its original piece with less force.

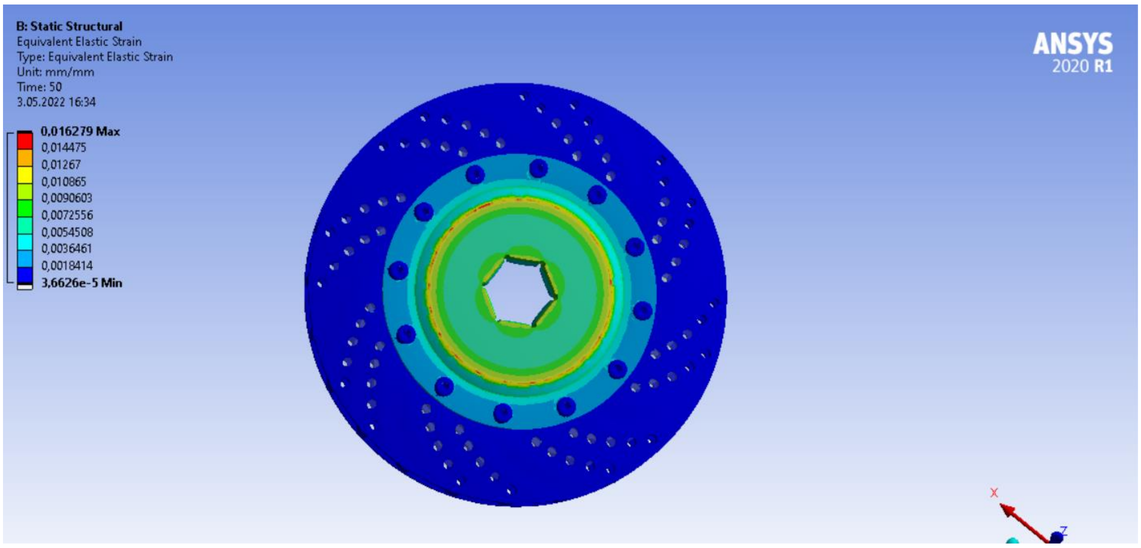


Figure 4-10 Elastic Strain of Nissan Disc

4.2 First Design of Brake Disc

4.2.1 Steady State

When we look at the results, we see that the maximum temperature is 300 degrees, and the min temperature is 284.04 degrees. Our average temperature value is 296.23 degrees.

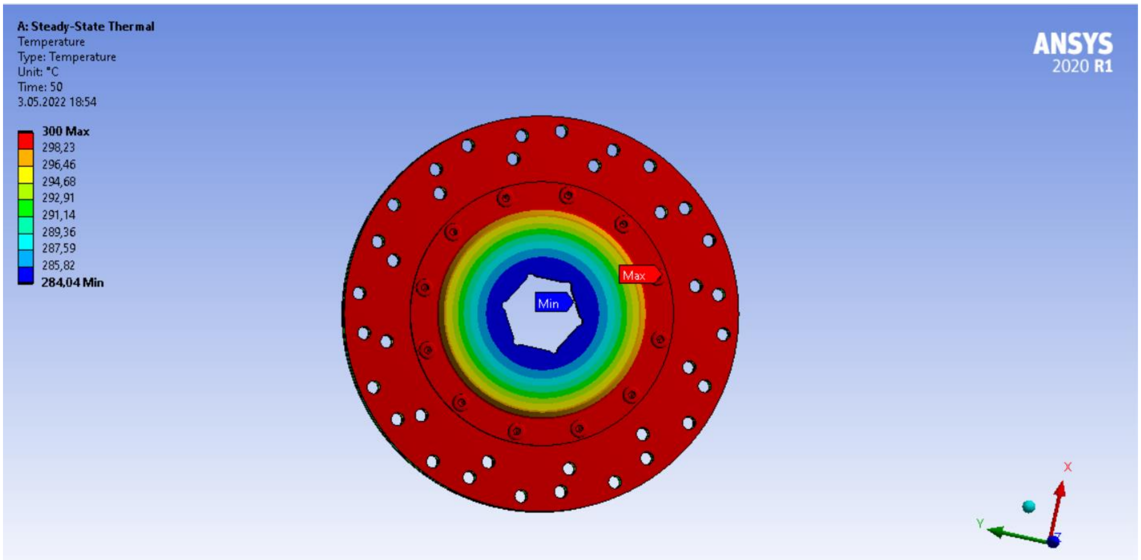


Figure 4-11 Temperature at Design #1

When we examine the new design disc, we see that the distribution of heat has changed, and the average temperature value has changed. This is due to both the new design and the material change. If we examine the back of the disc, we can see that it is more colourful and cooler in temperature than the previous disc.

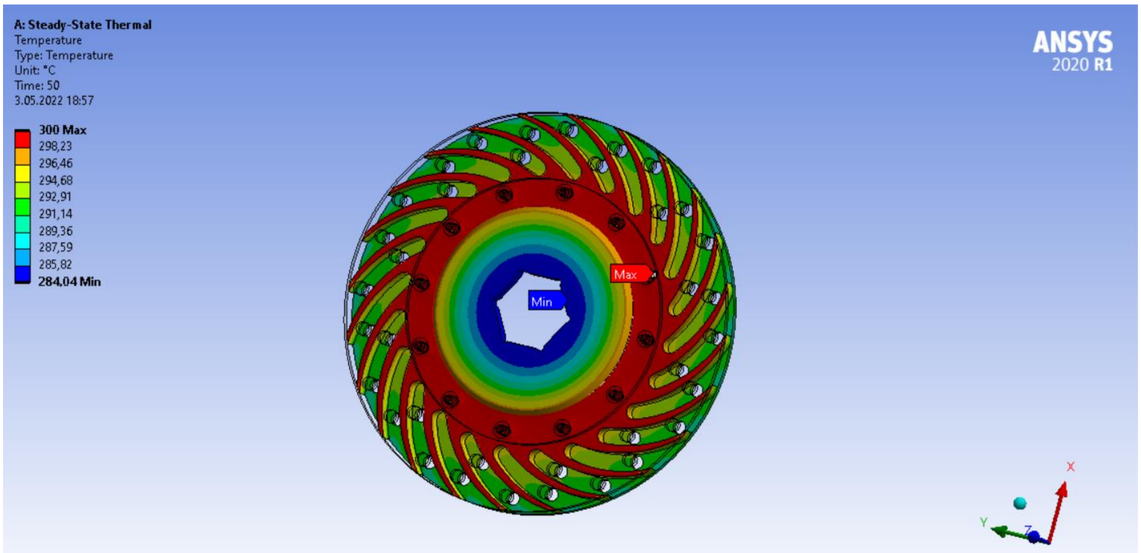


Figure 4-12 Transparent view of Design #1

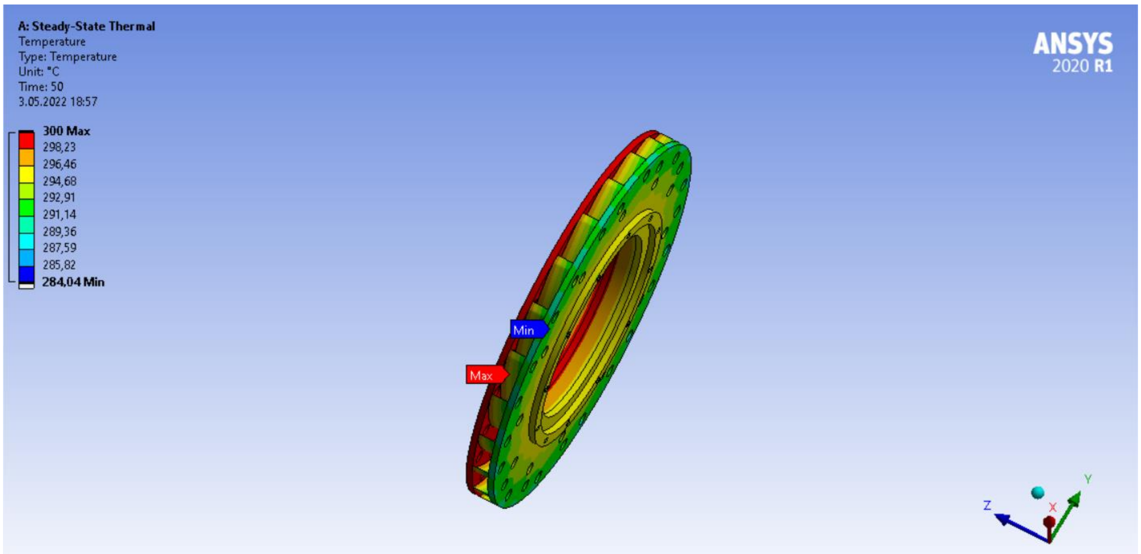


Figure 4-13 Top View of Temperature Distribution of Design #1

When we examine the heat flux, we observe that the minimum value increases. In the analysis, the minimum regions increase in width in direct proportion to the increase in the diameter of the holes. We can see the maximum, minimum and average value in the figure below.

Results	
Minimum	1,5212e-005 W/mm²
Maximum	8,4641e-002 W/mm²
Average	1,0309e-002 W/mm²

Figure 4-14 Table of Heat Flux Values

Again, considering that the maximum value in the results is at the spikes within the channels, the average value is closer to the minimum value.

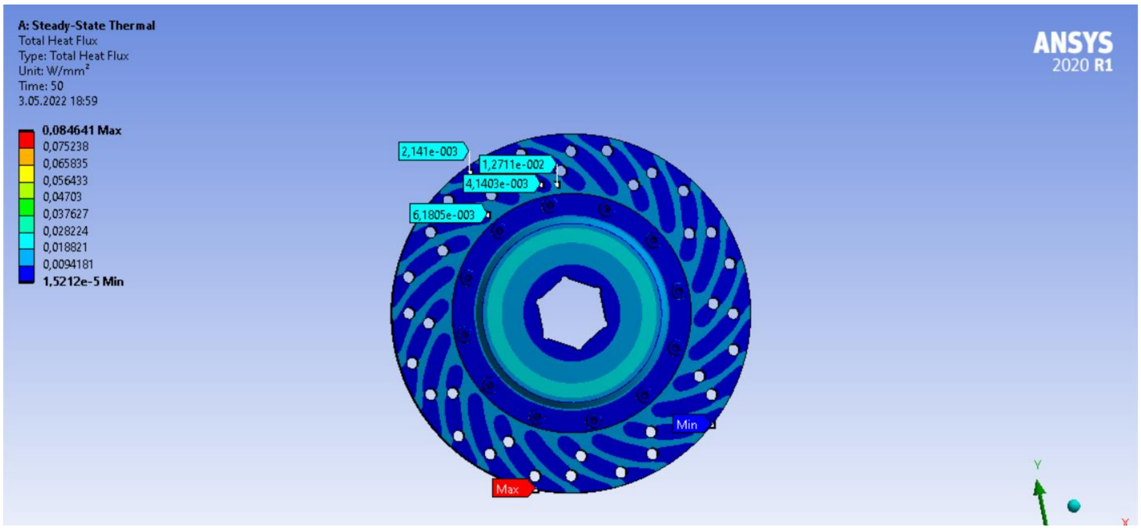


Figure 4-15 Heat Flux Distribution of Design #1

4.2.2 Static Structural

When we look at the deformation of our new design, we see that the colour lines on the piece look the same as in the previous analysis. In addition, the increase in deformation catches our eye, and we observe that there is an increase in maximum values.

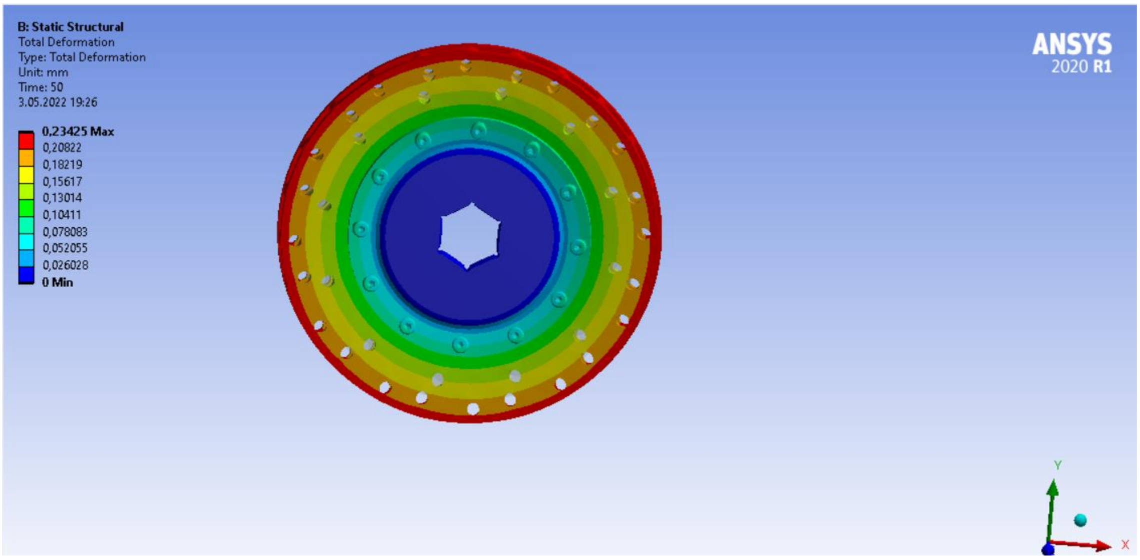


Figure 4-16 Total Deformation of Design #1

Although the deformation seems to be 0 in the disc drum, this value is valid only for the front surface, there is deformation on the rear surface and in the middle.

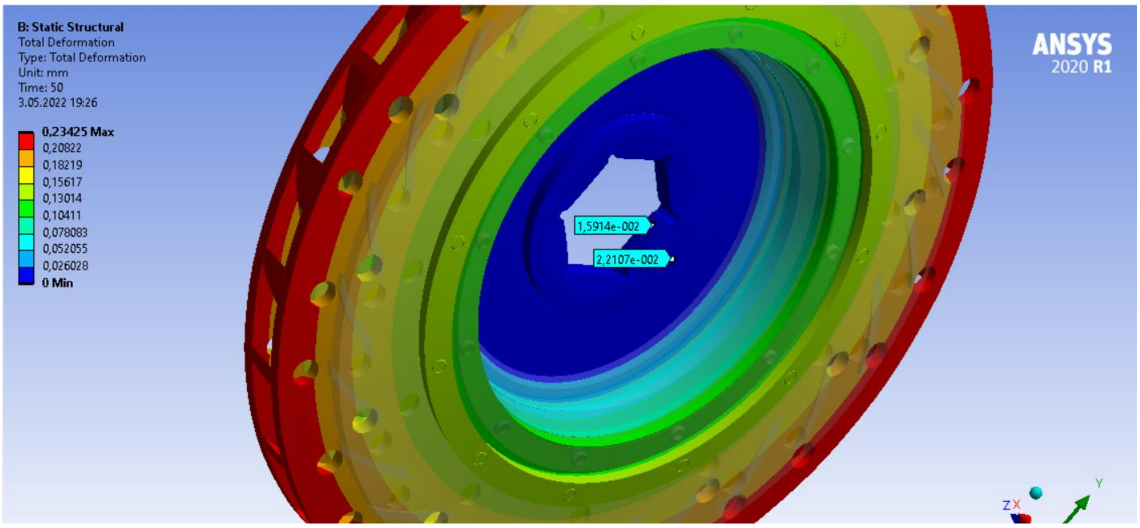


Figure 4-17 Deformation on Disc Drum

When we come to the stress analysis, we encounter a different result than the previous analysis. Changes in both the distribution of the results and their values are striking. This may be due to the change of material. Average stress 269.74 MPa.

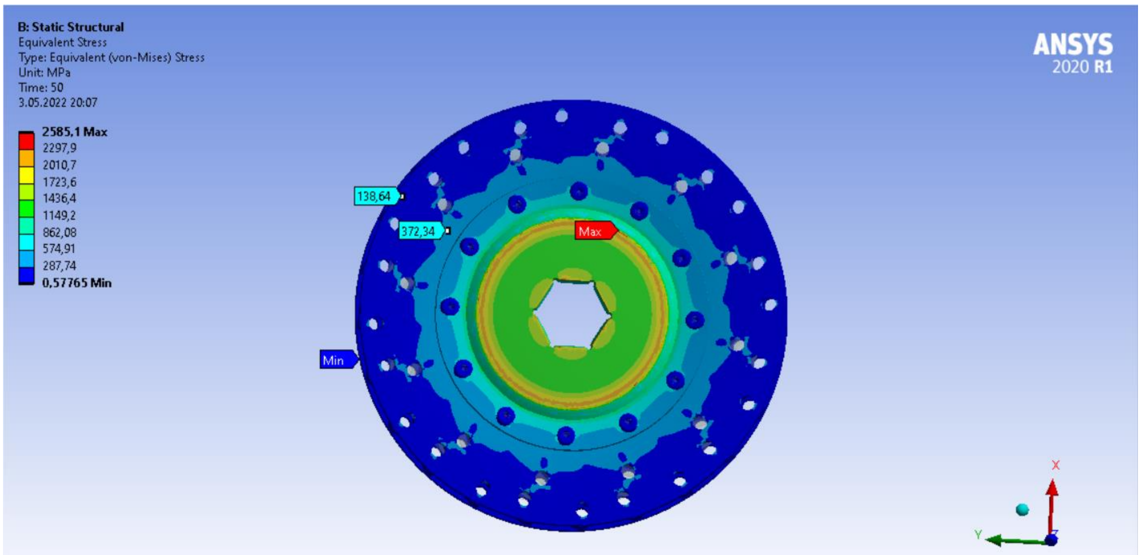


Figure 4-18 Equivalent Stress of Design#1

When we examine the analysis, we observe that the stress increases as we get closer to the brake drum.

When we examine the elastic tension, we observe that the maximum value increases but decreases from the minimum value.

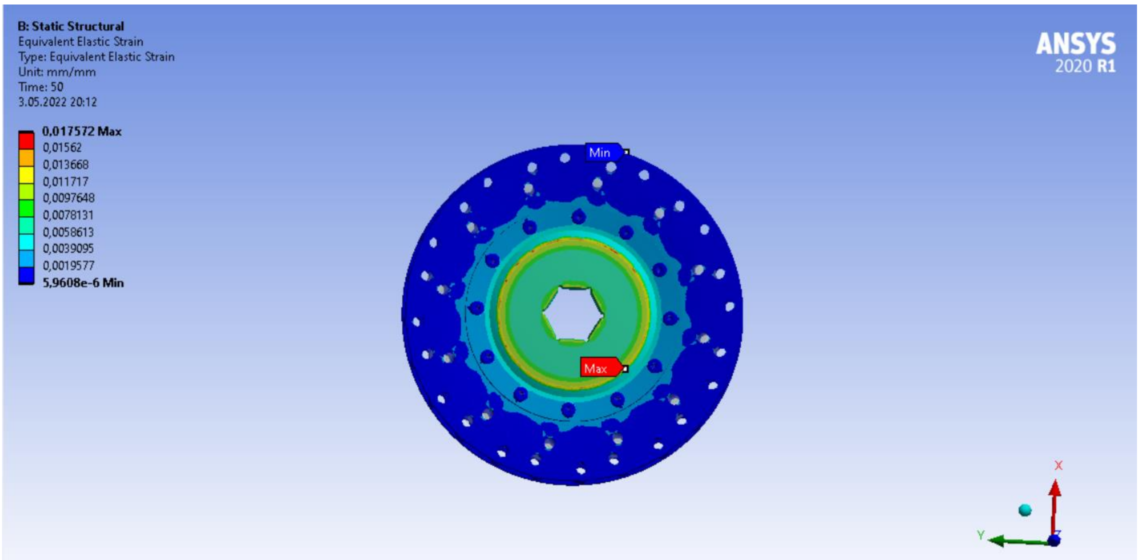


Figure 4-19 Elastic Strain of Design #1

Results	
Minimum	5,9608e-006 mm/mm
Maximum	1,7572e-002 mm/mm
Average	1,4317e-003 mm/mm

Figure 4-20 Values of Elastic Strain for Design #1

4.3 First Design of Brake Disc Version #2

4.3.1 Steady State

When we look at the results, the change catches our eye. The maximum temperature is measured as 300.08, while the minimum temperature is 284.5 degrees and the average temperature is measured as 298.21 degrees.

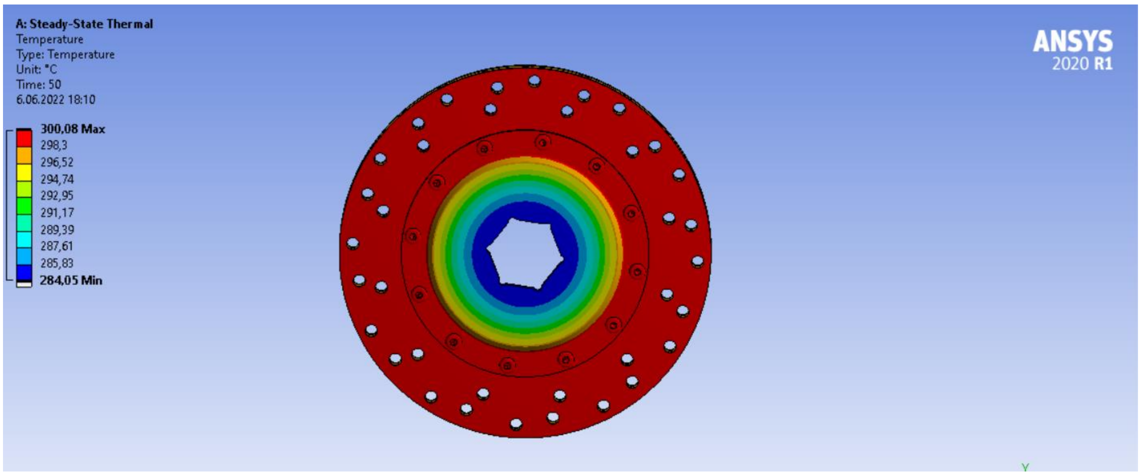


Figure 4-21 Temperature Distribution of Design #1 Version #2

At the same time, when we examine the temperature distribution, we see that there is a change. We understand from here that the temperature distribution is related to the material itself and the distribution of the temperature on the disc greatly affects.

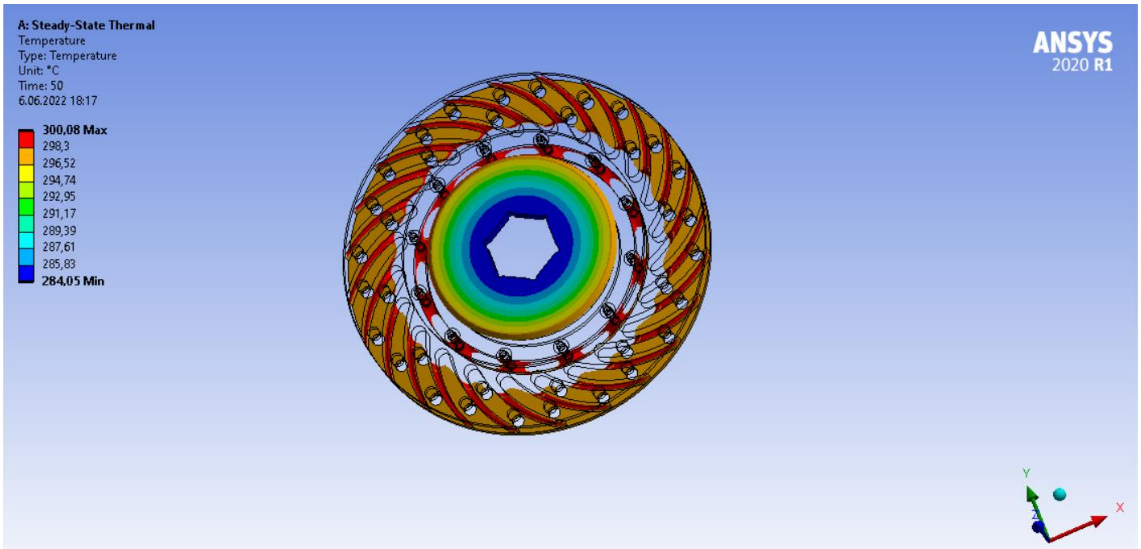


Figure 4-22 Transparent View of Temperature Distribution of Design #1 Version #2

When we examine the heat flux, we see that both the maximum and minimum values are very close to each other on average. Here we understand that the heat flux is more related to the design of the disc than the structure of the material.

Results	
Minimum	1,5537e-005 W/mm²
Maximum	8,6347e-002 W/mm²
Average	1,0427e-002 W/mm²

Figure 4-23 Table of Heat Flux Values of Version #2

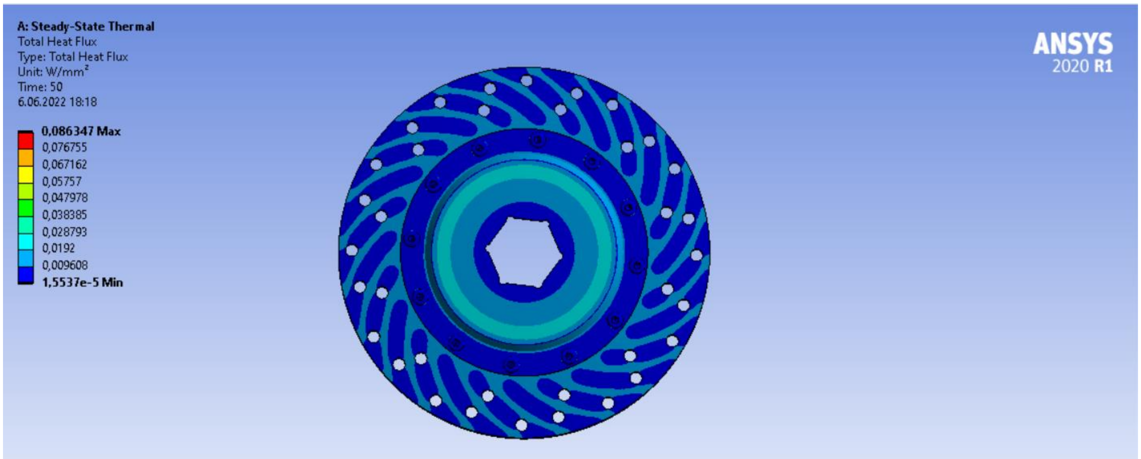


Figure 4-24 Heat Flux Distribution of Design #1 Version #2

4.3.2 Static Structural

When we look at the deformation, the changes in the values catch our eye. While the maximum deformation was 0.23 in the previous version, this value decreases to 0.13 in the second version. This shows us the effect of material strength on deformation.

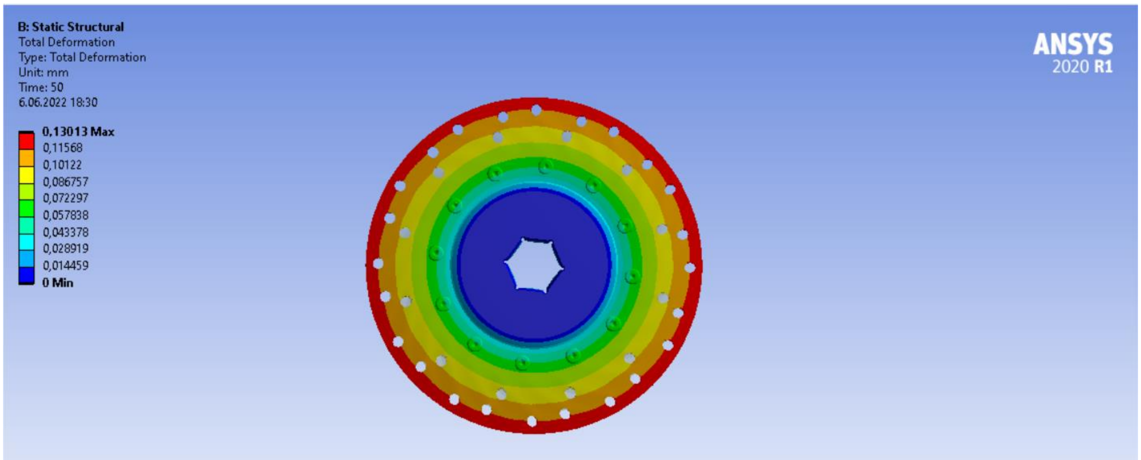


Figure 4-25 Total Deformation of Design #1 Version #2

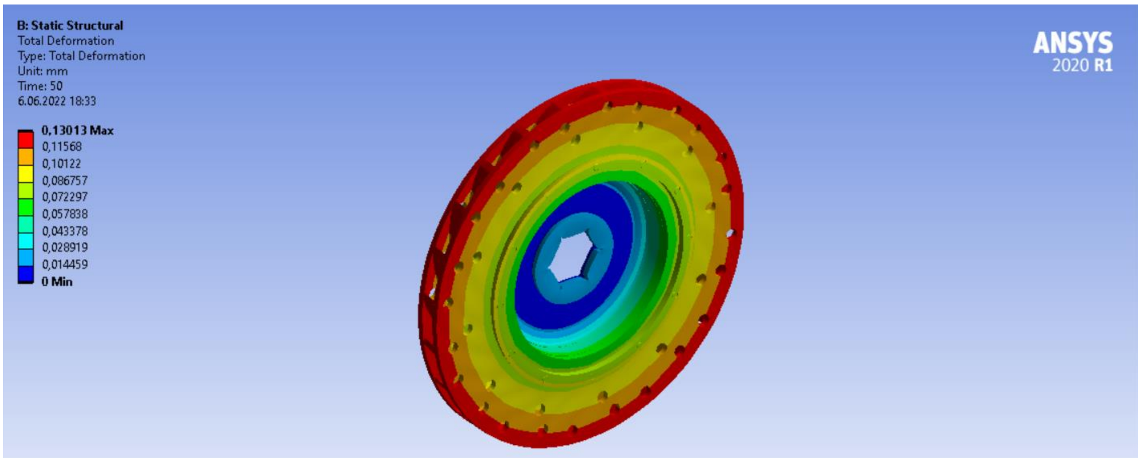


Figure 4-26 Back Side of Deformation View of Version #2

When we come to the stress analysis, we see that the situation has changed, and the average pressure value of 269.74 MPa in the first version drops to 227.38 MPa. This can be explained by the change of material. At the same time, while the maximum stress value is decreasing, the minimum pressure value is slightly increasing.

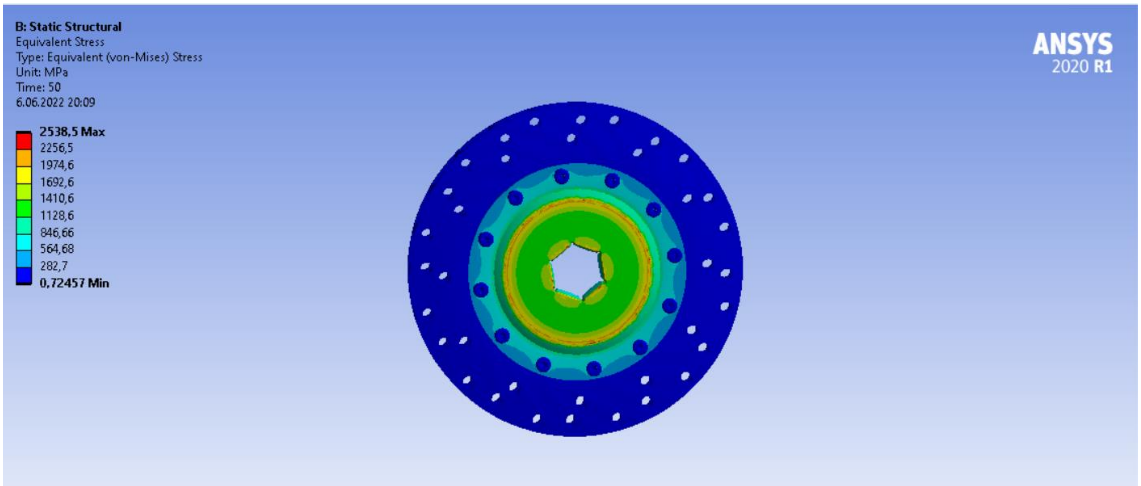


Figure 4-27 Equivalent Stress of Design#1 Version #2

At the same time, as we will see in both stress and strain analyses, the distribution pattern on the disc changes. This information shows us that gray cast iron is more homogeneous in transmitting stress and strain.

When we look at the elastic stress values, although the change in the maximum value does not change much, we see an increase in the minimum value. This causes an increase in the average stress value.

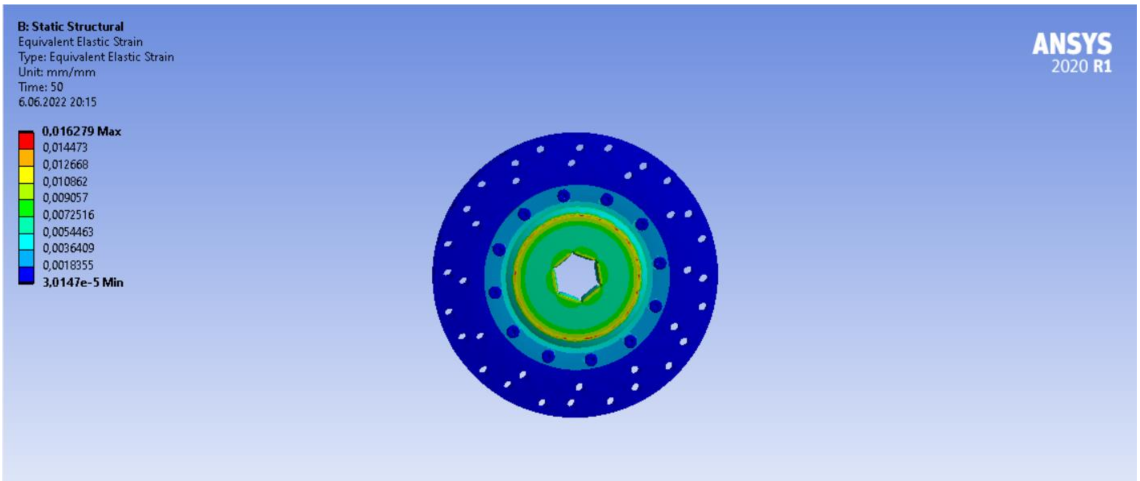


Figure 4-28 Elastic Strain of Design #1 Version #2

4.4 Second Design of Brake Disc

4.4.1 Steady State

In the second design, we used the materials in the original part, so when we examine the results, the maximum temperature is 300.08 degrees, the minimum temperature is 284.05 degrees, and the average temperature is 298.2 degrees.

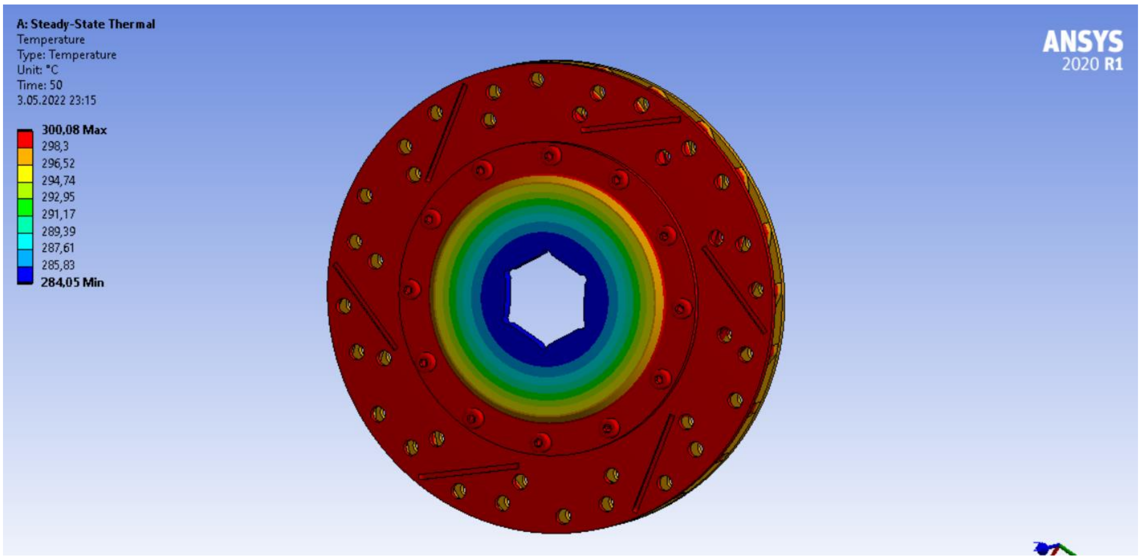


Figure 4-29 Temperature Distribution of Design #2

When we examine the heat flux, we see a different result than what we have seen before. As a result of the channels in our design, we see that the heat flux is in dark blue at the point where the channels pass on the front disc surface.

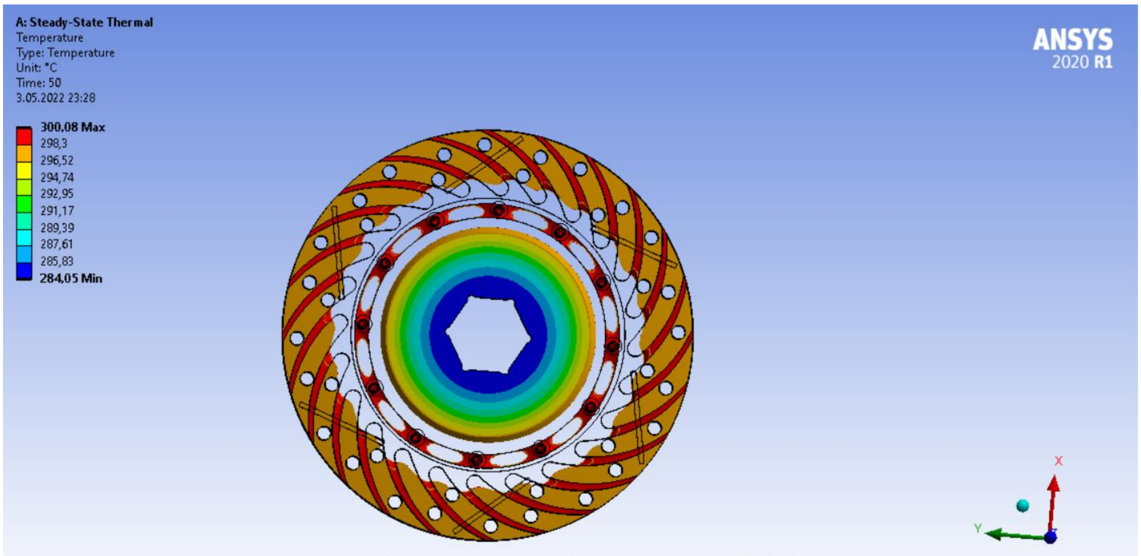


Figure 4-30 Transparent View of Temperature Distribution of Design #2

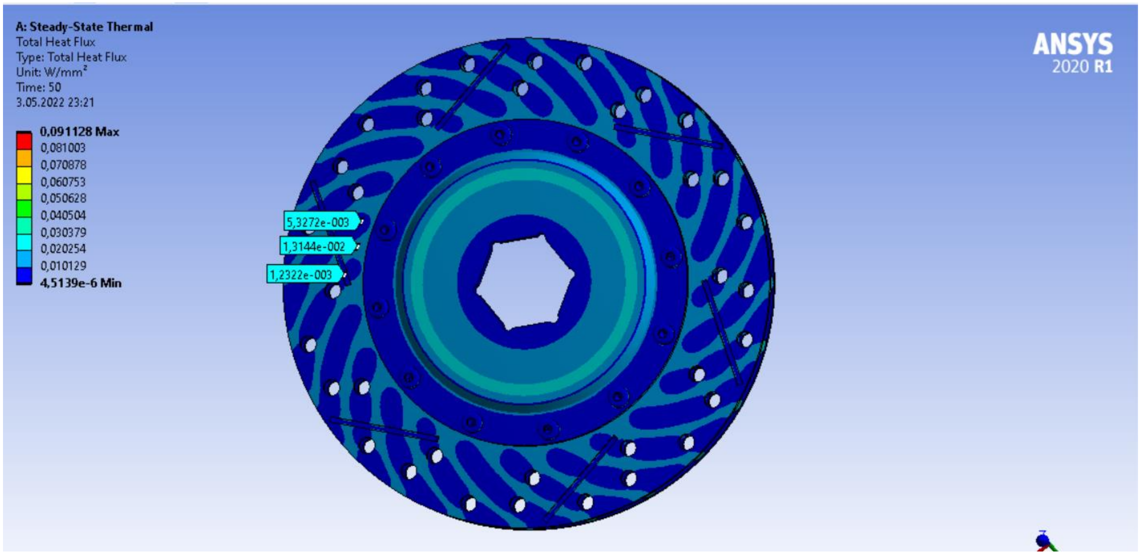


Figure 4-31 Heat Flux for Design #2

At the points where the channels pass, we see that there is a 2-3 times difference compared to the light blue section. At the same time, we can see the maximum, minimum and average heat flux values in the figure below.

Results	
Minimum	4,5139e-006 W/mm²
Maximum	9,1128e-002 W/mm²
Average	1,0536e-002 W/mm²

Figure 4-32 Properties of Heat Flux for Design #2

4.4.2 Static Structural

When we examine the deformation results of the new design, we can see that it does not make much difference compared to the original design. The reason for this is that the effect of the material used on the deformation is much more than the surface design.

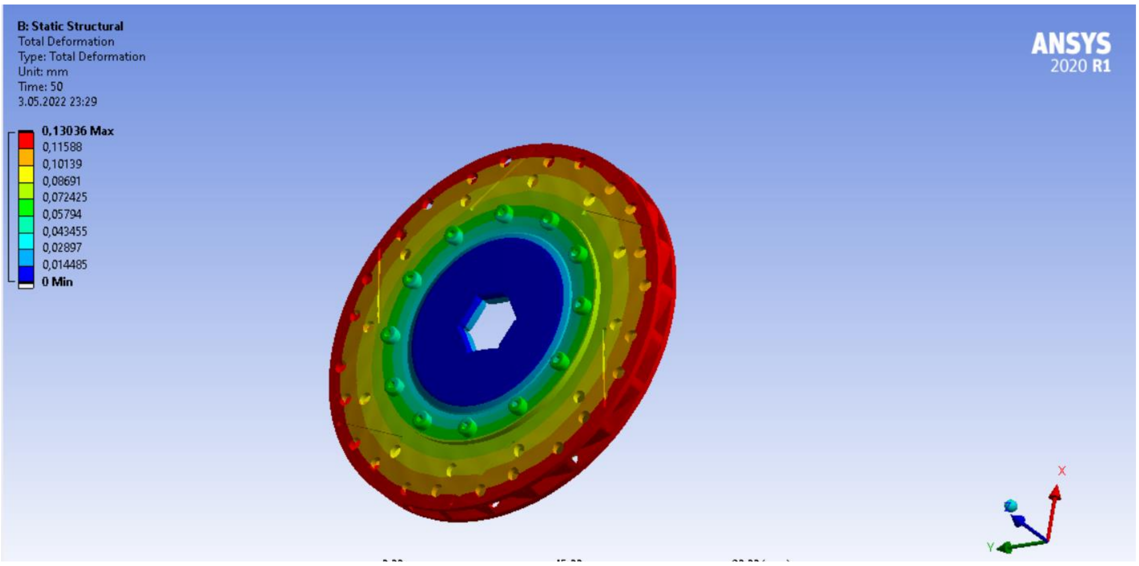


Figure 4-33 Total Deformation of Design #2

Values related to total deformation are shown in the figure below.

Results	
Minimum	0, mm
Maximum	0,13036 mm
Average	8,2379e-002 mm

Figure 4-34 Values of Total Deformation Design #2

When we look at the result of our stress analysis, we observe that the maximum stress value does not change, while the minimum stress value decreases compared to the original part.

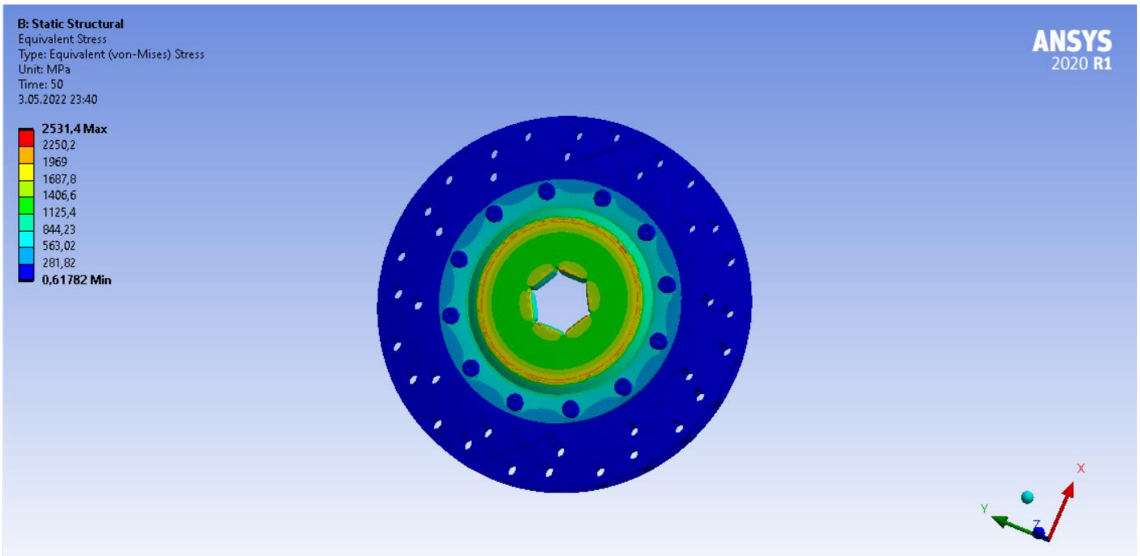


Figure 4-35 Stress Results for Design #2

As a result, our average stress value decreases compared to the original part. In addition, as we can see in the images, the distribution of stress is similar to the original piece.

Results	
Minimum	0,61782 MPa
Maximum	2531,4 MPa
Average	225,32 MPa

Figure 4-36 Values of Stress for Design #2

When we examine the elastic tension, we get results similar to the original design in this result. Although there are differences, its closeness to the original part. We observe that the material used in the structural analysis is more important than the design. The difference in stress analysis is due to the design.

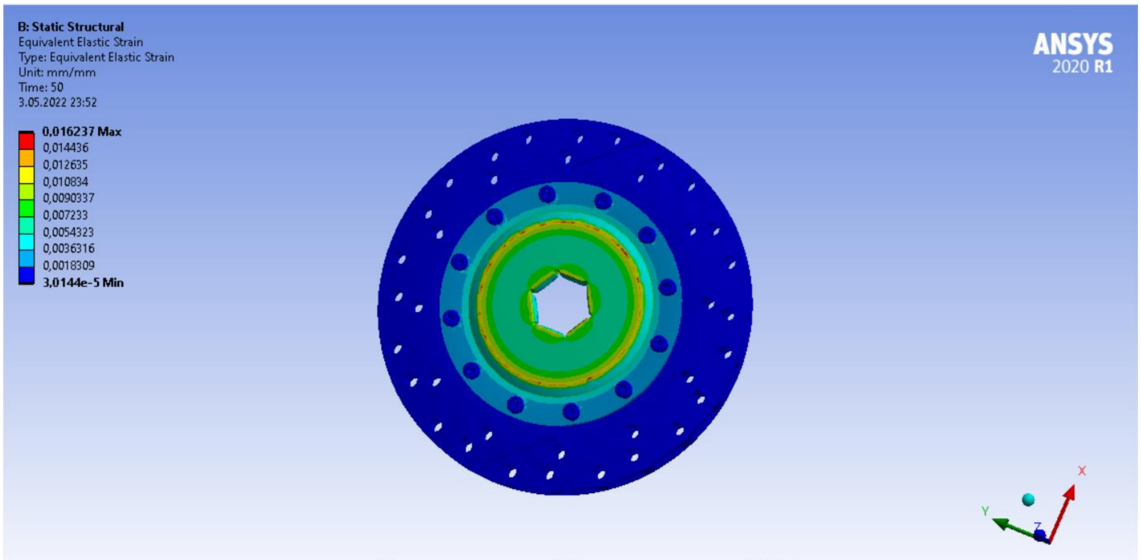


Figure 4-37 Elastic Strain for Design #2

We observe that the average elastic stress in the second design is slightly lower than that of the original part.

Results	
Minimum	3,0144e-005 mm/mm
Maximum	1,6237e-002 mm/mm
Average	1,4169e-003 mm/mm

Figure 4-38 Values of Elastic Strain for Design #2

4.5 Structural Optimization of Brake Disc

4.5.1 Steady-State Thermal

Materials in the original part were defined for temperature analysis. The materials used are suitable for general use and special vehicles. The result of the analysis was defined as 284.18 C as the minimum value. Our maximum value is 300.16 C. You can see our results in different regions through the probes.

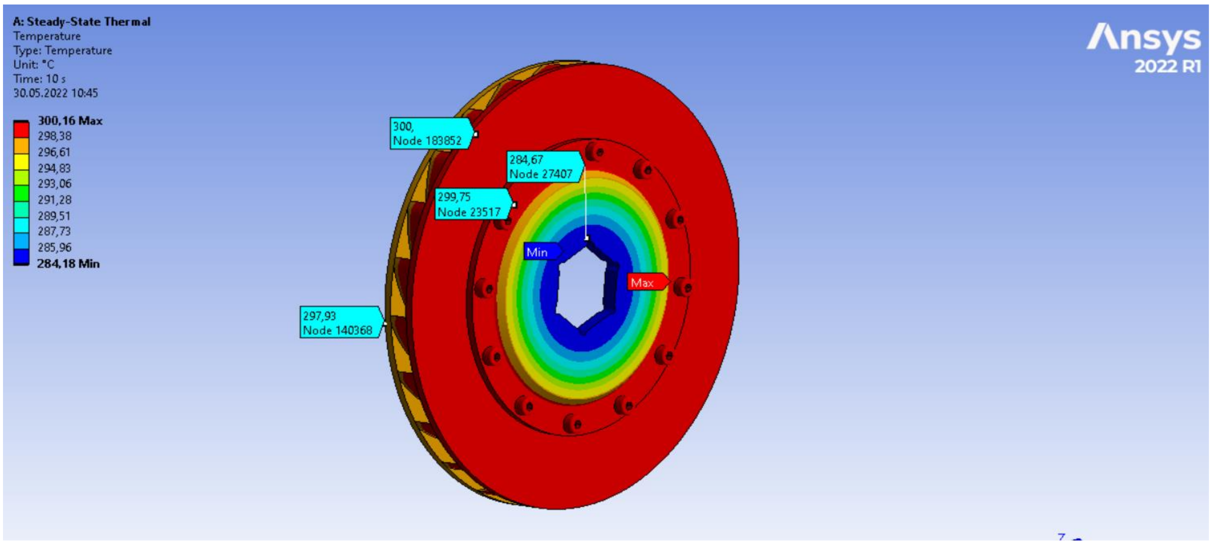


Figure 4-39 Temperature Distribution

As seen in the temperature analysis, the air holes on the brake discs are important for cooling and distributing the heat in a healthy way.

When we examine the heat flux values, it is observed that since the flow density is in the cold regions, it concentrates on the clamp, which is part of the brake system, and on the air ducts. The temperature drop on the brake disc without air vents was less. For this reason, a heat flux is formed towards the clamp at the midpoint.

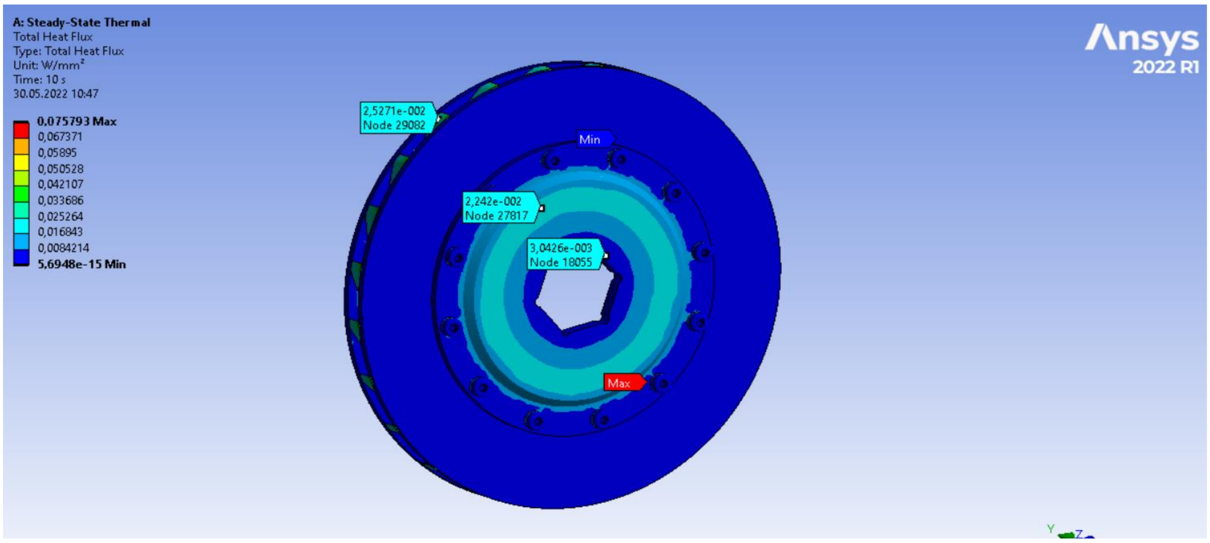


Figure 4-40 Total Heat Flux

4.5.2 Structural Analysis

Structural analysis section, which is the step before structural optimization, presented an analysis in which we can see the deformation in line with the results of the temperature analysis. When we look at the deformation analysis and other designs and analyzes, we see that the maximum deformation is towards the ends of the brake disc, but this value is smaller than other designs. This is because there are no cooling holes on the brake disc.

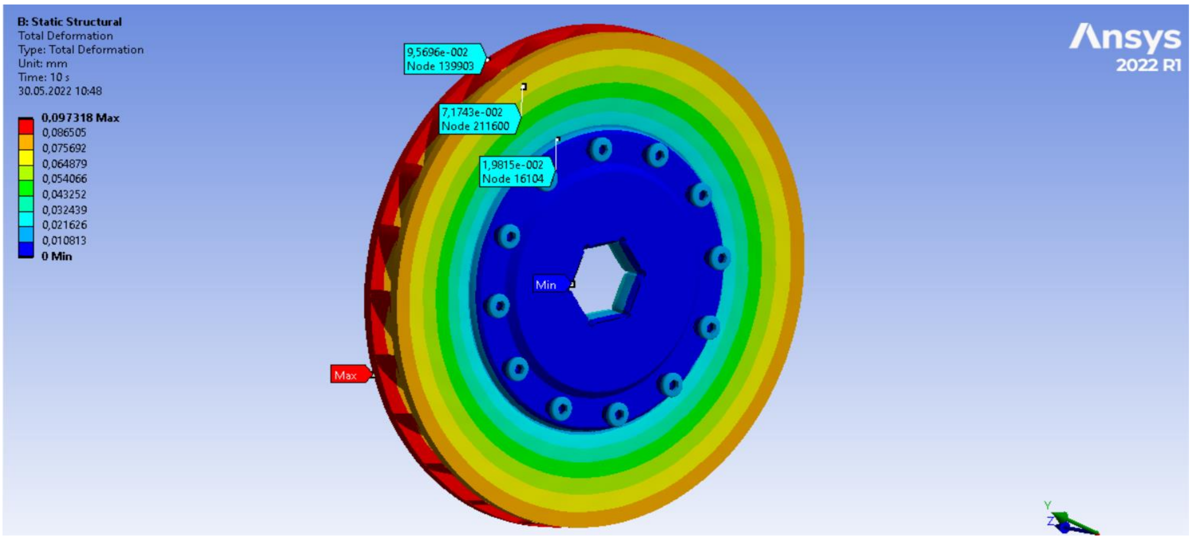


Figure 4-41 Total Deformation

When we examine the stress level, maximum and minimum values are observed at the connection point based on the contact relations of the brake clamp. This is because the heat cannot be fully dissipated and therefore stress accumulates at the junction points.

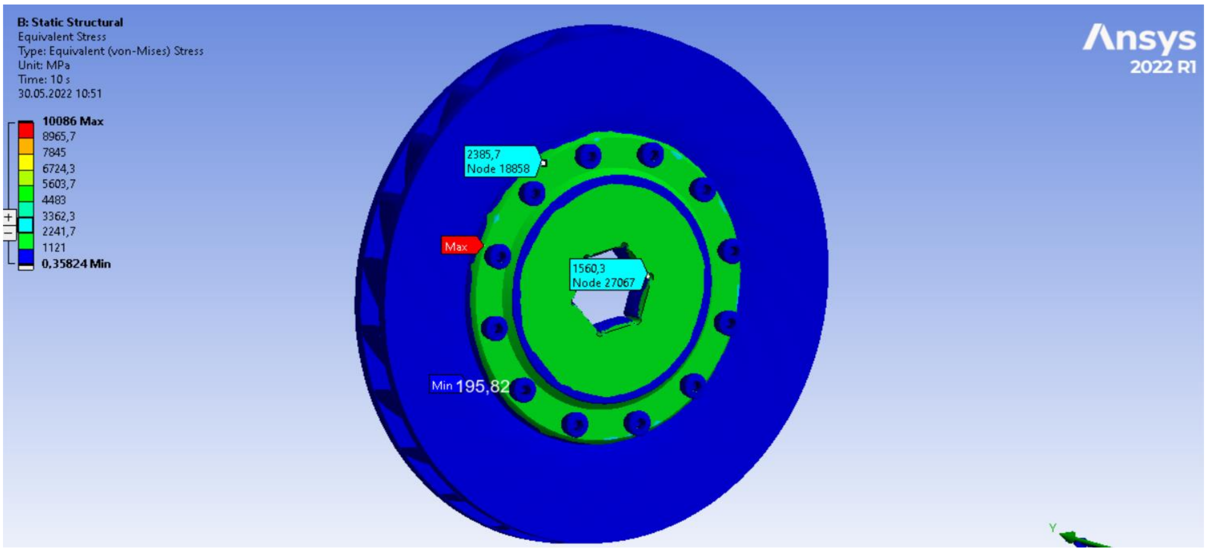


Figure 4-42 Stress

The tension level is also seen over the connection element. Minimum and maximum values are striking at the contact points.

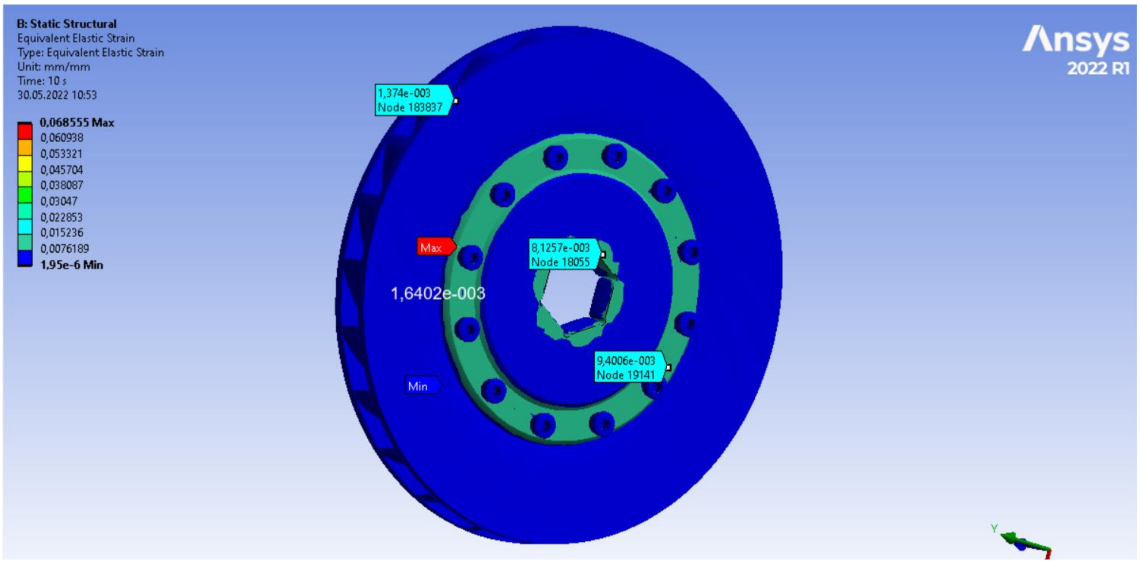


Figure 4-43 Elastic Strain

4.5.3 Structural Optimization

For structural optimization, we start by connecting the results of our two analyses to the structural optimization tree. The number of iterations should be kept at the maximum level. ANSYS software can finish the process before it reaches the last iteration. In our analysis, the weight was optimized according to the stretching point. At this point, optimization results have emerged from the end parts of the part where there is no braking force and the air channels in between. Based on this result, it has emerged because of structural optimization that there is no need for support due to the amount of deformation caused by the braking force of the pressed area and air ducts brought by air cooling up to a certain section.

4.5.3.1 Structural Optimization Result for 50%

Details of "Topology Density"

Calculate Time History	Yes
Suppressed	No
Results	
Minimum	1,e-003
Maximum	1,
Average	0,55603
Original Volume	29502 mm³
Final Volume	18420 mm³
Percent Volume of Original	62,437
Original Mass	0,21564 kg
Final Mass	0,13576 kg
Percent Mass of Original	62,96
Visibility	

Ready

Figure 4-44 Results for %50

As a result of the structural optimization made for 50%, it is observed that the original volume has decreased by 38% because of the analysis, and the desired parameters have been reduced by gradually eating from the non-contact disc part and air ducts.

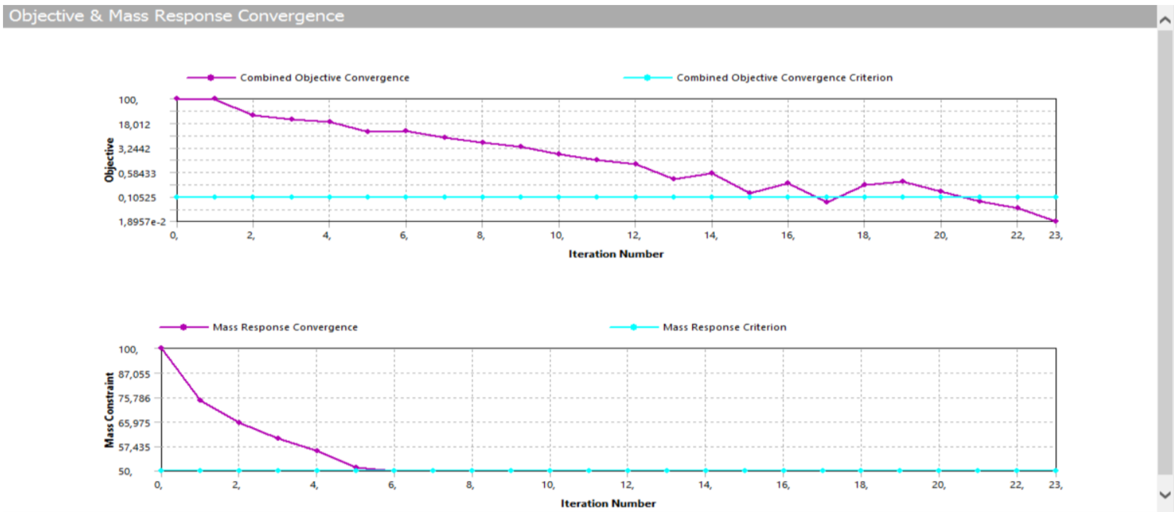


Figure 4-45 Objective & Mass Response Converge

Convergence is very important for structural optimization and the program iterates to ensure convergence. As seen in the graph, the result of 23 iterations converged to the desired result.

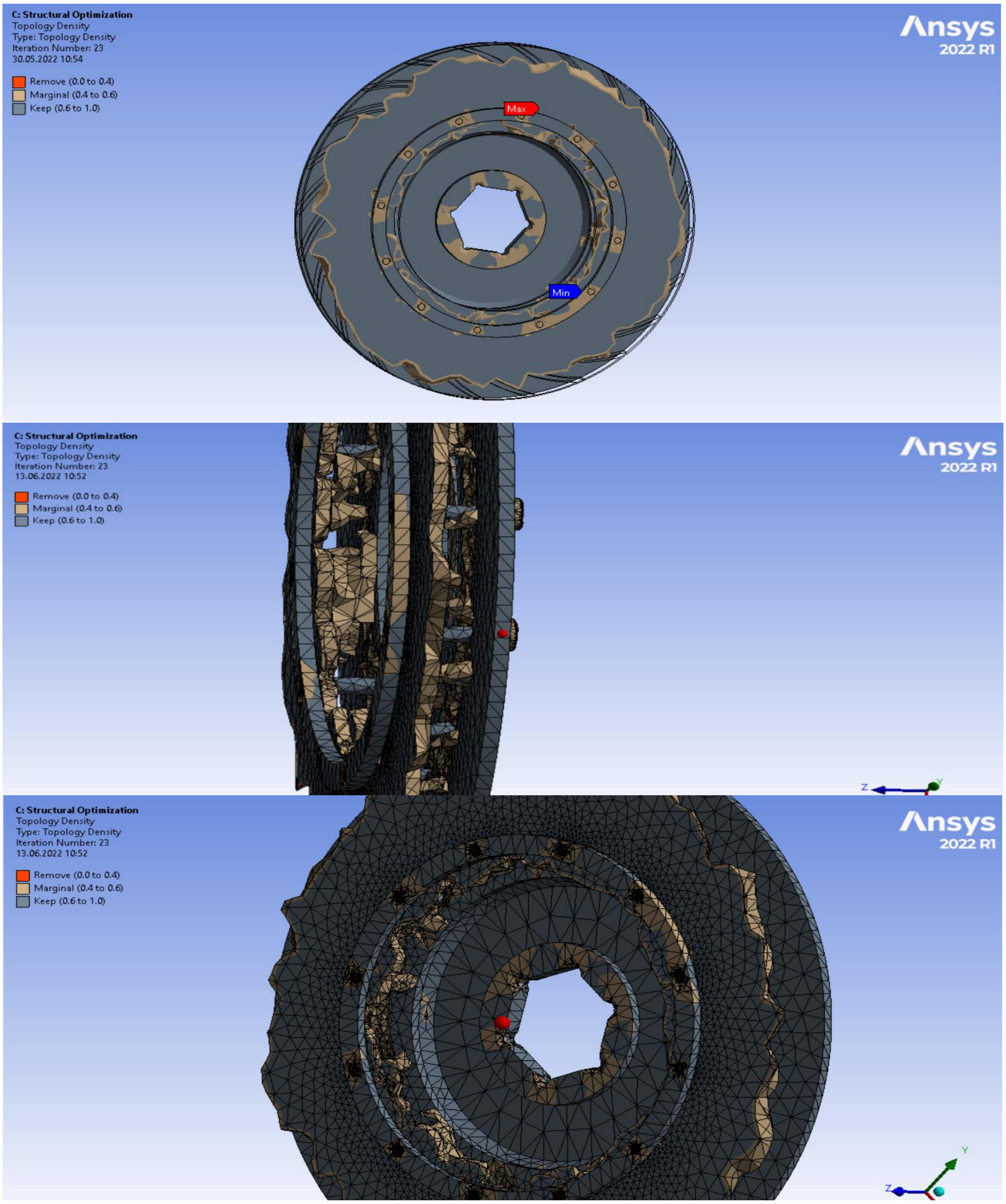
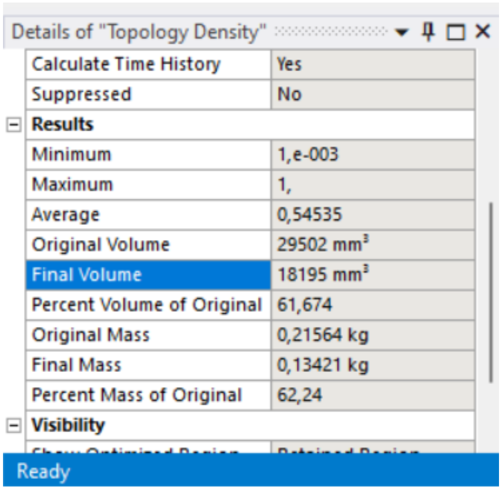


Figure 4-46 Topology Density (different looks)

As a result of 23 iterations, there are points where we can optimize our design. As can be seen in the figures, the volume of the non-pressurized areas is gone and at some points the design should be improved.

4.5.3.2 Structural Optimization Result for 67%


Details of "Topology Density"

Calculate Time History	Yes
Suppressed	No
Results	
Minimum	1,e-003
Maximum	1,
Average	0,54535
Original Volume	29502 mm³
Final Volume	18195 mm³
Percent Volume of Original	61,674
Original Mass	0,21564 kg
Final Mass	0,13421 kg
Percent Mass of Original	62,24
Visibility	

Ready

Figure 4-47 Results for %67

Structural optimization for 67% was completed with 32 iterations. In the results, there was a loss of volume in the region where the volume was largely unpressurized and in the regions between the two discs. The volume change rate is around 39%. Our weight change was around 37.76%.

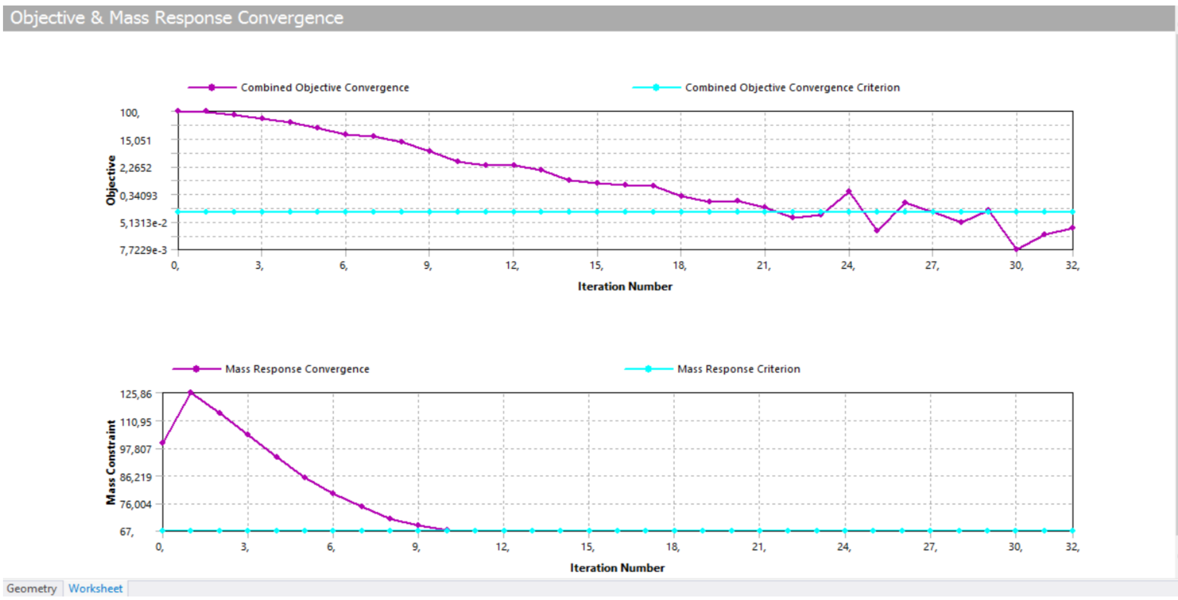


Figure 4-48 Objective & Mass Response Converge

When the convergence values for 67% were examined, it was found to converge after 32 iterations. In the analysis, which shows a more linear convergence, there is fluctuation in some regions. The reason for this may be hardware and may be due to the structure of the part.

The figures below show the weight reduction in the pressure-free disc and the middle part.

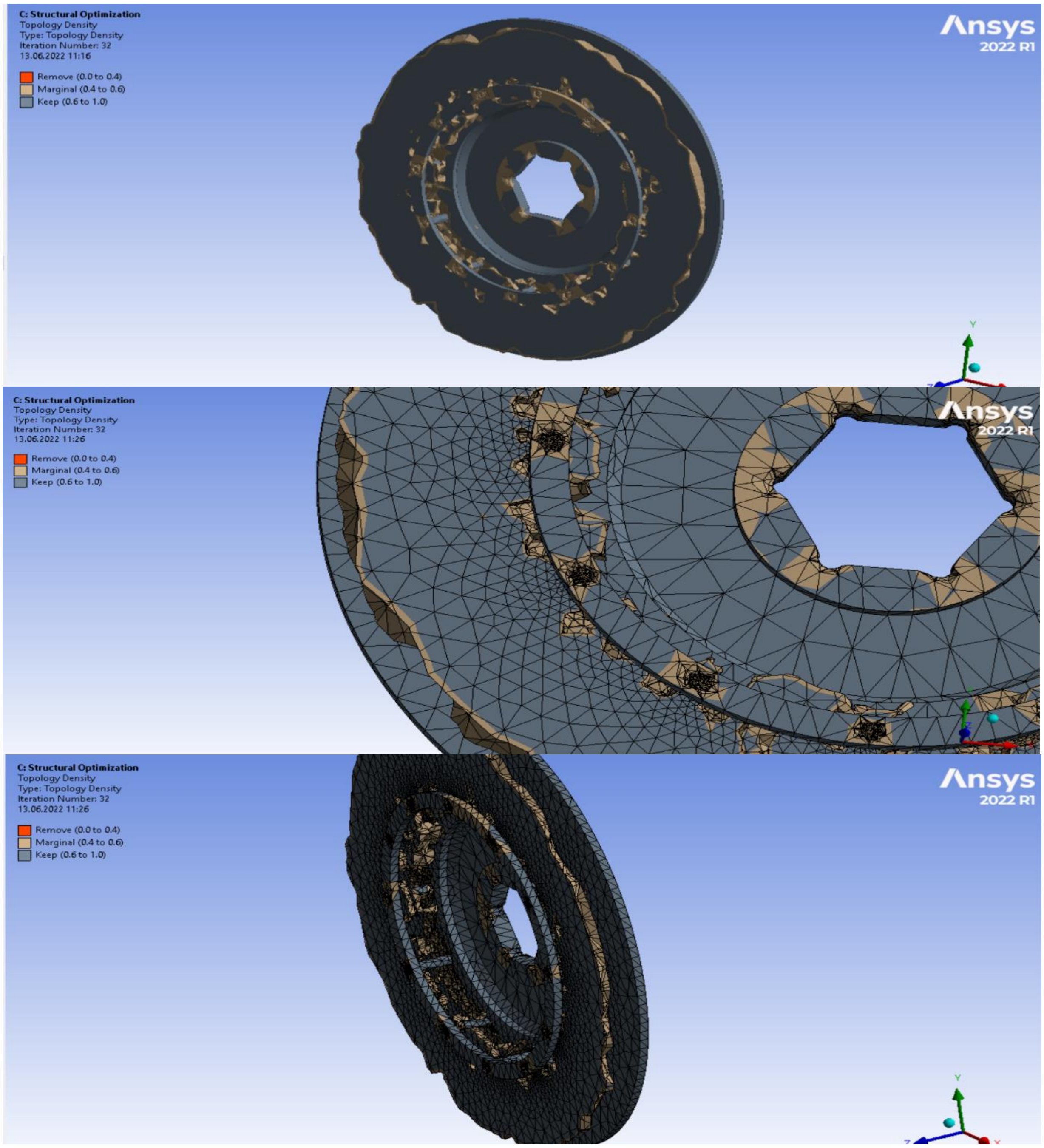


Figure 4-49 Topology Density (different looks)

4.5.3.3 Structural Optimization Result for 82%

Results	
Minimum	1,e-003
Maximum	1,
Average	0,68261
Original Volume	29502 mm³
Final Volume	24151 mm³
Percent Volume of Original	81,862
Original Mass	0,21564 kg
Final Mass	0,1771 kg
Percent Mass of Original	82,129
Visibility	

Ready

Figure 4-50 Results for %82

When the results for 82% are examined, it is seen that the volume reduction is at the two-disc connection points, and it is revealed that optimization work can be done on the air ducts at the centre of gravity. There was an approximate 18.8% reduction in volume. There is a 17.9% change in weight values.

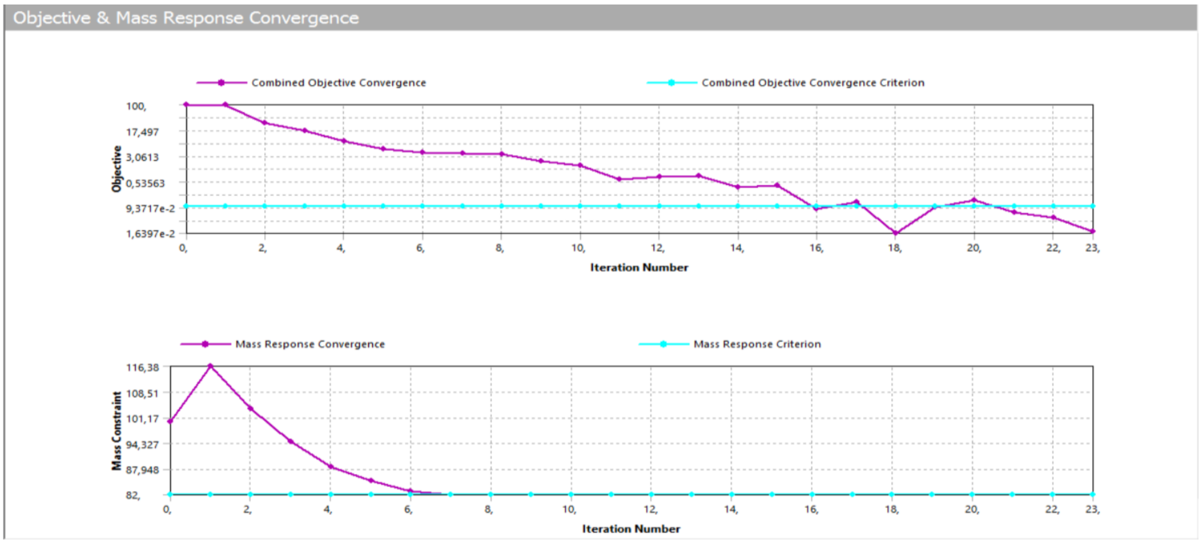


Figure 4-51 Objective & Mass Response Converge

The convergence values were completed after 23 iterations. In general, although convergence occurred at some points, the program continued to converge for the right result.

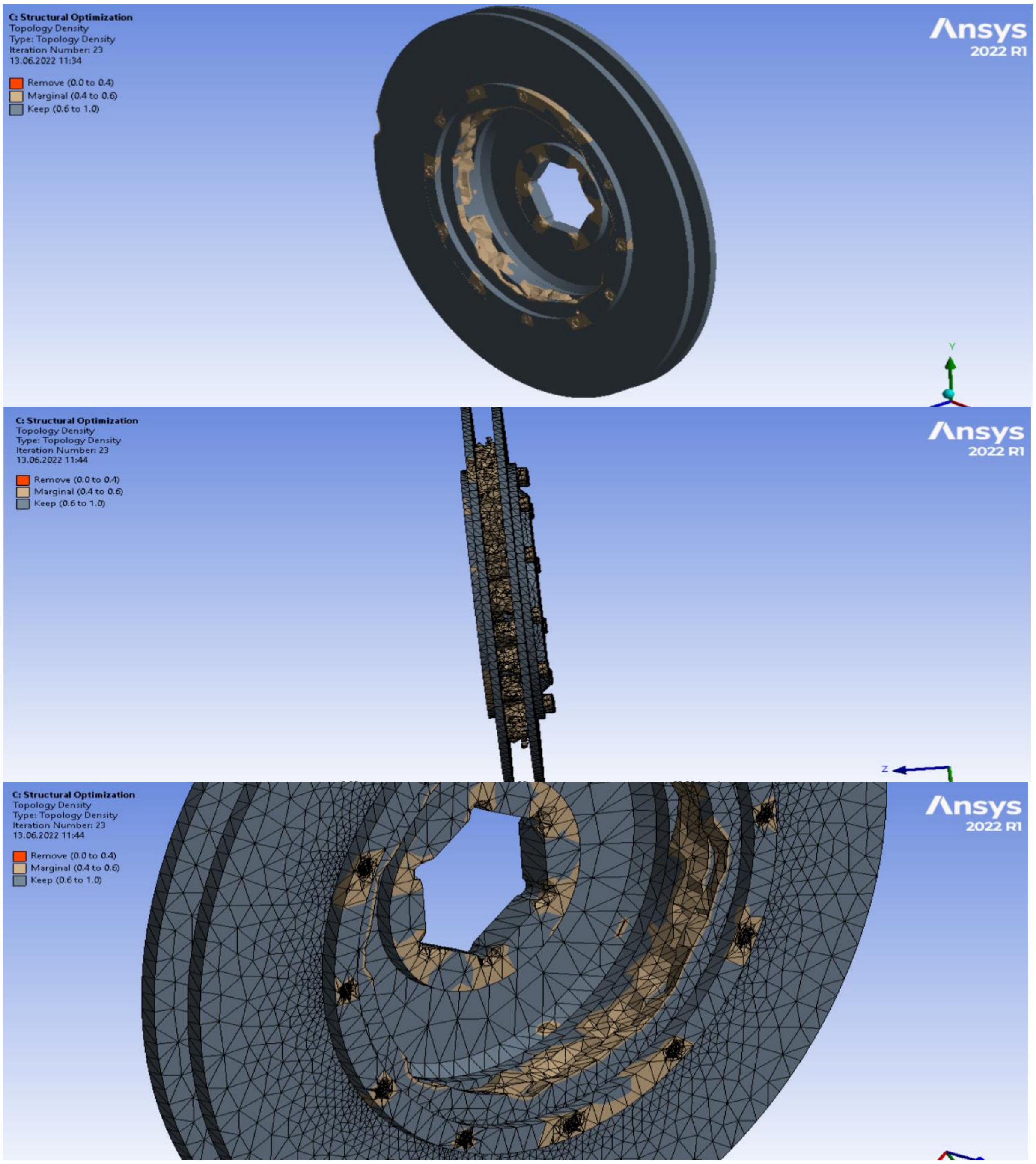


Figure 4-52 Topology Density (different looks)

When the results are examined, a large change is observed on the air ducts and the clamp.

5. COST ANALYSIS AND FEASIBILITY

5.1 Cost Analysis

All production points should be considered when performing cost analysis. In general, hourly wages are calculated for CNC required works. At this point, the simpler the material to be processed, the less costly a product can be produced. Before starting a design, a designer or engineer should first consider the cost and reveal the product accordingly. At the point of manufacture of the brake disc, the quality of materials for structural durability and these must be completed in accordance with each vehicle category in accordance with the vehicles to be sold. Air ducts/air vents, one of the most important points for the brake disc and extending the usage time, come out at a reasonable cost for medium and high-end vehicles, even if CNC costs arise. The cost analysis of our brake discs is given in the table below.

Gray Cast Iron Price: USD/KG=2.20 to TL/KG=35.64

Stainless Steel Price: USD/KG=2.02 to TL/KG= 32.72

CNC Vertical Machining Center: 525 TL/Hour

Bold price= 1,78 TL (one)

Table 1 5.1 Cost Analysis of Disk Brake All Parts (TL)

Name of Part	**Material**	**Machining**	**LABOR**	**Total Cost**
Perforated and Air Duct Disk	Gray Cast İron (6,75 Kg)	CNC (20 minute) =525/3=175 TL + Casting Machine (35,64*6,75) =240,57 TL = **415,57 TL**	60 TL	475,57
Without Holes and Air Ducts Disk	Gray Cast İron (7,5 Kg)	Casting Machine (35,64*7,5) = **267,3 TL**	25 TL	292,3
Brake Drum for Brake Disc	Stainless Steel (2,2 Kg)	CNC (35 minute) = 525/(60/35) =306,25 TL + Casting Machine (35,64*2,2) = 78,41 Tl = **384,66 TL**	45 TL	429,66
Nut and Bolt	Stainless Steel (0.3 Kg) Piece=12	A couple of Nut and Bolt= 1,78 Tl*12= **21,36 TL**	-	21,36

	Cost (All Part)
All Brake Disc with Air Hole	**926,59 TL**
All Brake Disc without Air Hole	**743,32 TL**

5.2 Feasibility

The purpose of the feasibility report is to determine whether the designed product is suitable for production. As a result of our analysis, we see that there is no obstacle in the manufacturability of our new designs. Especially when we compare our second design with the original Nissan disc, we see obvious similarities and improvements, which shows that we have a better version of a normally manufacturable disc. Also, as we mentioned, the brake discs are made of ceramic, gray cast iron and stainless steel. Efficient discs can be produced with all of these, but the main purpose of their production is what kind of car these cars are. This is also the design purpose of perforated and slotted discs. As the complexity in the production of the disc increases and the material gets quality, it can be said that this disc will be installed in a car that will operate under more difficult conditions. Considering all these situations, our discs are producible.

6. DISCUSSION

When we handled the analyses in the 3 designs, we obtained results that were sometimes close to each other and sometimes far from each other. There was a certain similarity between the Nissan disc and the latter design. Now let's compare what happened step by step.

When we look at the temperature analysis, we see that the distribution is like the Nissan disk, the second design is similar and the average temperature value is 298.2 degrees on average, while this value is 296.23 degrees in the first design. The main factor here was the choice of material, stainless steel emerged in a more advantageous situation in temperature transitions than grey cast iron. The temperature was delivered colder on the way to the rear disc.

When we examined the heat flux analysis, we obtained different results in all three designs. In this case, we saw that the second design gave a better result than the other two designs. The minimum value was lower than the others, which shows that the slotted and perforated structure is much more useful. In the first design, although the hole diameters increased, the region where the heat flux was minimum increased, it had a higher level of minimum heat flux compared to the original Nissan disc. The most interesting part was the second design, with the Nissan disc. The same materials were used in these two products, but the second design gave a better heat flux result and distribution than the original Nissan disc.

When we compare the deformation results, we see that the effect of material selection on the result is more effective than the change in design. The average deformation value of the first design made of stainless steel was higher than the other two products whose main material was grey wrought iron. The second design with the Nissan disc, produced from the same material but with different designs, had approximately similar average deformation values, despite minor differences. From this, we conclude that as we mentioned above, the main effect on deformation is the choice of material.

When we come to the stress analysis, the obvious difference emerges in the first disc design. The stress distribution on the disc surface is different compared to the other two designs. The average stress value in the first design gives a higher result than the other two designs. Here, too, we see the effect of both design and material on stress. When we examine the Nissan disc and the second design, we see that the stress values are lower than the first design. In addition, the average stress value is lower in the second design compared to the Nissan disc. As a reminder, we should note that the surface area of the disc is less than the original Nissan disc, thanks to the slotted structure in the second design.

When we examine the results of the elastic stress analysis, we see that the minimum value is lower in the second design. In this design, we observe that the effect of material selection is greater as the results of the Nissan disc and the second design are close to each other. Considering the minimum value, we observe that the minimum value of the Nissan disc and the second design is 5 times greater than the minimum value of the first design. When we consider the Nissan disc and the secondary disc, we see that the elastic stress is lower in the second design.

There are some differences in the three structural optimization analyzes we have done. These may be hardware related. In order to converge to the best results in terms of hardware, the need for high-end hardware stands out.

50% Response Constraint value was the analysis that reduced the volume and weight the most. A volume value of 62.437% was maintained at this point. The closest value, 67% Response Constraint value, yielded values close to the results made and obtained with 50%. The most striking point as the difference between the two is the number of iterations. It maintained its volume at a rate of 61,674% with a 67% Response Constraint value. The last analysis, the Response Constraint value of 82%, is similar to the convergence values of the analysis performed with the value of 50% with 23 iterations. Response Constraint value of 82% preserved its volume with a rate of 81,862

When we examine the results of all the structural optimizations, it has been revealed that improvements should be made on the parts between the 2 discs and the disc part for which the pressure value is not entered. All values were compared, and the best analysis results were evaluated.

7. CONCLUSION

As a result, if we make a general assessment, we analysed 3 different discs during this project. These designs, which were meshed at similar intervals while meshing, had similar values as the total number of meshes. At the same time, we measured the stability of the results we obtained by performing the analyses more than once. We obtained mesh-independent results. Other than that, we kept it the same for all designs while adjusting the ambient conditions. In addition, we made the same number of iterations, which brings the accuracy of the analyses closer to each other. As a result of each analysis, we obtained different results and interpreted these differences because of our observations. Each design had advantages and disadvantages in different departments. In addition to all these, if we examine the designs in general, the thing that catches my eye is that the second design is more advantageous than the other designs. Considering the stress distribution and heat flux from the deformation distribution, it turned out to be much more advantageous than other designs. Since I took today's sports cars as an example while making this design, we also saw why sports cars have brake discs in such designs.

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