Design Analysis and Optimisation of Brake Disc Made of Carbon Fiber Composite

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Abstract - *The research mainly concentrates on brief comparison on current automotive brake disc and carbon fiber brake discs and by varying the plate thickness. The research of brake disc performance mainly includes thermal conductivity, thermal fatigue resistance, wear resistance. Stress and strain the ceramic and resin were used as the matrix, carbon fiber materials were used as reinforcements to prepare brake discs. SOLID WORKS is used to design the disc plate and ANSYS is used to analyze the compositions and properties of disc plate. The performance and life of carbon fiber discs are better than gray cast iron discs and cast iron with graphite nodules disc.*

Key Words: Brake disc, Solid Works, Thermal Properties, Wear Properties, Carbon fibre disc.

1.INTRODUCTION

A composite is combination of two materials in which one of the materials, called the reinforcing phase, is in the form of fibres, sheets, or particles, and is embedded in the other materials called the matrix phase. The reinforcing material and the matrix material can be metal, ceramic, or polymer. Composites typically have a fibre or particle phase that is stiffer and stronger than the continuous matrix phase and serve as the principal load carrying members. The matrix acts as a load transfer medium between fibres, and in less ideal cases where the loads are complex, the matrix may even have to bear loads transverse to the fibre axis. The matrix is more ductile than the fibre and thus acts as a source of composite toughness. When designed properly, the new combined material exhibits better strength than would each individual material. Since many years ago, the combination of different materials has been used to achieve better performance requirements. As an example of that the Sumerians in 4000 B.C. used to add straw to the mud to increase the resistance of the bricks. Although the benefits brought by the composite materials are known for thousands of years, only a few years ago the right understanding of their behaviour as well as the technology for designing composites started to be developed. The airplane F111 was one of the first models to incorporate composite technology. The possibility to combine high strength and stiffness with low weight has also got the attention of the automobile industry: the Ford Motor Company developed in 1979 a car with some components made from composite materials. The prototype was directly 570 kg lighter than the same version in steel, the transmission shaft had a huge reduction of 57% of its original weight. More recently, Chrysler developed a car completely based on composite materials, known as CCV (Composite Concept Vehicle). Besides these examples in the automobile and aeronautical industry, the applications of composite materials have been enlarged, including now areas as the sporting goods, civil and aerospace construction and in medical field. In order to have the right combination of material properties and in service performance, the static and dynamic behaviour is one of the main points to be considered. Composites are used not only for their structural properties, but also for electrical, thermal, tribological, and environmental applications. "Composites are multifunctional material systems that provide characteristics not obtainable from any discrete material. They are cohesive structures made by physically combining two or more compatible materials, different in composition and characteristics and sometimes in form". The composites should not be regarded simple as a combination of two materials. In the broader significance; the combination has its own distinctive properties. In terms of strength to resistance to heat or some other desirable quality, it is better than either of the components alone or radically different from either of them. "The composites are compound materials which differ from alloys by the fact that the individual components retain their characteristics but are so incorporated into the composite as to take advantage only of their attributes and not of their short comings", in order to obtain improved materials. Composite materials as heterogeneous materials consisting of two or more solid phases which are in intimate contact with each other on a microscopic scale. They can be also considered as homogeneous materials on a microscopic scale in the sense that any portion of it will have the same physical property.

1.1 CHARACTERISTICS OF SiC MATRIX

Silicon carbide (SiC) is one of the hardest technical ceramics available. For many years it was second only to diamond on the Mohr's scale, and to date, sintered silicon carbide remains both a competitive and supplementary material for abrasive synthetic diamonds. Combined with its high thermal conductivity and superb corrosion resistant properties, silicon carbide ceramics are workhorse materials for challenging application areas. Silicon carbide is a popular abrasive in modern lapidary due to the durability and low cost of the material. In manufacturing, it is used for its hardness in abrasive machining processes such as grinding, honing, water-jet cutting and sandblasting.

The advantages of this include:

- ➢ Unmatched hardness (2600 Kg/mm2)
- ➢ Superior thermal conductivity (150 W/(mK))
- ➢ Moderate thermal shock resistance (ΔT = 400°C)
- ➢ Good flexural strength at high temperatures
- ➢ High wear resistance and low density
- ➢ Good high temperature strength (reaction bonded)
- ➢ Oxidation resistance (reaction bonded)
- ➢ Excellent chemical resistance.

1.2 CHARACTERISTICS OF CARBON FIBER

Carbon fibre is composed of carbon atoms bonded together to form a long chain. The fibres are extremely stiff, strong, and light, and are used in many processes to create excellent building materials. Carbon fibre material comes in a variety of "raw" building-blocks, including yarns, unidirectional, weaves, braids, and several others, which are in turn used to create composite parts. The properties of a carbon fibre part are close to that of steel and the weight is close to that of plastic. Thus the strength to weight ratio (as well as stiffness to weight ratio) of a carbon fibre part is much higher than either steel or plastic. Carbon fibres are about 5–10 micrometres in diameter and composed mostly of carbon atoms. Carbon fibre is very popular in aerospace, civil engineering, military, and motorsports, along with other competition sports. The properties of carbon fibre includes

- ➢ High specific strength (strength to weight ratio)
- ➢ Very rigid
- ➢ High corrosion resistant and chemically stable
- ➢ Electrical and thermal conductivity
- ➢ Good fatigue resistance
- ➢ Good tensile strength
- ➢ Fire resistance
- ➢ Low coefficient of thermal expansion
- ➢ Non poisonous, biologically inert, X-ray permeable

2. MATERIAL SELECTION

Brakes are of utmost importance in an automobile and safety of the operator and passengers depend directly on the braking system, the material for the disc rotors must be chosen appropriately. Many materials are widely available in the market like ceramic components, carbon-carbon composites, stainless steels and cast iron components; grey cast iron is apt for rotors because of its strength and thermal properties, high temperature resistance and availability. Properties of grey cast iron, properties of cast iron with graphite nodules and properties of carbon fibre reinforced SiC are listed below

2.1 PROPERTIES OF GRAY CAST IRON

Chemical composition: C=2.7-4%, Mn=0.8%, Si=1.8-3%, S=0.07% max, P=0.2% max
Density: 7.06 $*10^3$-7.34 $*10^3$kg/m^3
Modulus of elasticity: 124GPa
Thermal expansion (20 ºC): 9.0*10-6ºC^{-1}
Specific heat capacity (25 ºC): 490J/(kg*K)
Thermal conductivity: 53.3W/(m*K)
Electric resistivity: 1.1*10-7Ohm*m
Tensile strength: 276MPa
Elongation: 1%
Shear strength: 400MPa
Compressive yield strength: 827MPa
Fatigue strength: 138MPa
Hardness (Brinell): 180-302HB

This material data has been provided by Subs Tech. All metrics apply to room temperature unless otherwise stated. SI units used unless otherwise stated. Equivalent standards are similar to one or more standards provided by the supplier. Some equivalent standards may be stricter whereas others may be outside the bounds of the original standard.

2.2 PROPERTIES OF CAST IRON WITH GRAPHITE NODULES

Malleable iron is a cast iron in which the graphite is present as temper carbon nodules, instead of flakes as gray iron or spherulites as in ductile iron. M4505 is used where slightly higher strength and hardness than M3210 is needed.
Related Standards SAE J158

Equivalent Materials AISI M4504

- ➢ Density ρ 7.2 - 7.34 g/cm^3 at 20 °C
- ➢ Elastic modulus E 172 GPa at 20 °C
- ➢ Elongation A 4 % at 20 °C
- ➢ Hardness, Brinell HB 163 - 217 [-] at 20 °C
- ➢ Poisson's ratio ν 0.27 [-] at 20 °C
- ➢ Shear modulus G 64 GPa at 20 °C
- ➢ Tensile strength Rm 448 MPa at 20 °C
- ➢ Yield strength YS 310 MPa at 20 °C
- ➢ Coefficient of thermal expansion α 1E-5 - 1.4E-5 1/K at 20 °C
- ➢ Specific heat capacity cp 460 - 527 J/(kg·K) at 20 °C
- ➢ Thermal conductivity λ 51 W/(m·K) at 20 °C

This material data has been provided by SAE. All metrics apply to room temperature unless otherwise stated. SI units used unless otherwise stated. Equivalent standards are similar to one or more standards provided by the supplier. Some equivalent standards may be stricter whereas others may be outside the bounds of the original standard.

2.3 PROPERTIES OF CARBON FIBER REINFORCED SiC

Properties from carbon fibre-reinforced silicon carbide(C/SiC) - a composite material that combines carbon fibres within a ceramic matrix to maximize the properties of both materials.

➢ Hard and ductile instead of being brittle
➢ High resistance to most corrosive and abrasive media
➢ Near net shape processing by in situ joining
➢ Adjustable properties to meet specific customer requirements
➢ High thermal-mechanical fatigue and high thermal shock resistance
➢ High heat resistance – up to 1200 °C
➢ Technology established within automotive serial production of brake disks.

Density ρ 2.1 - 3 g/cm^3 at 20 °C
Elastic modulus E 30 - 60 GPa at 20 °C
Elongation A 0.3 - 0.5 % at 20 °C
Flexural strength σ bend 50 - 90 MPa at 20 °C
Coefficient of thermal expansion α 1.8E-6 - 2.3E-6 1/K 200°C
Max service temperature, Tmax, inert 1400 °C in non-oxidizing environments
Thermal conductivity λ 20 - 60 W/(m·K) at 20 °C

2.4 DESIGN PHASE

The design of Disc brakes is varied depending on the application, amount of exposure, thermal properties of the material and the amount of heat dissipation required when brakes are applied and the total mass to be stopped. Following procedures are taken to design a disc.

Step 1: Outer radius and thickness of disc is given and revolved along the thickness of disc.
Step 2: Inner disc is drawn and extruded.
Step 3: A vented structure is drawn and the structure is repeated along the outer disc.
Step 4: Internal hole are drilled along the inner disc.

DESIGN SPECIFICATIONS

Diameter of outer disc – 345mm
Diameter of inner disc – 198mm
Thickness of outer disc – 28mm
Thickness of inner disc – 54.7mm
Diameter of inner hole – 15mm

DESIGN CALCULATIONS

Braking Capacity for an commercial car – 360Nm
Radius of outer disc (r1) – 172.5mm
Radius of inner disc (r2) – 99mm
Contact between pad and rotor - 20º
Effective radius(Re) – $r1+r22$
Effective radius (Re) – 136mm
Contact length (L) - $Ø360∗2\pi r2$
Contact Length(L) – 350mm
Torque in calliper (T) – $Braking\ capacity2$
Torque on calliper (T) – 160N
Co efficient of friction (μ) – 0.35
Force (F) - $T\mu∗Re$
Force (F) - 4410N

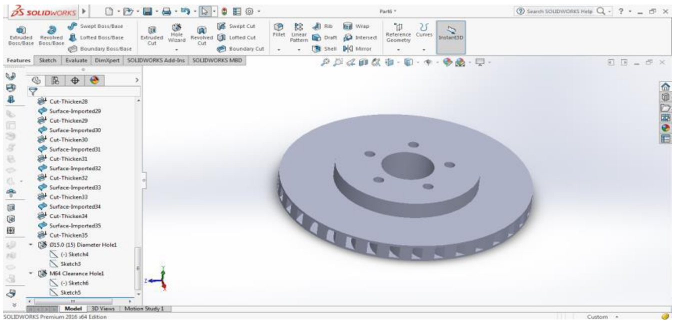

Fig -1: Design Phase

2.5 FINITE ELEMENT ANALYSIS

Generation of mesh: Creating a mesh in the imported geometry is an important step in ANSYS analysis as the size of the finite element is decided by the mesh properties. Finer the mesh is, more accurate are the results. Equal mesh are provided for both Gray cast iron disc rotor and Carbon fiber disc rotor
Total number of nodes – 34401
Total number of elements – 19506

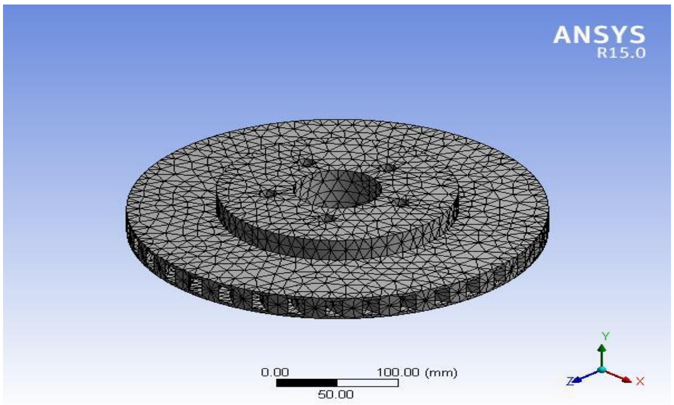

Fig -2: Meshing

Applying boundary conditions: The next step in the static structural ANSYS analysis is to apply the boundary conditions. Since the analysis is performed for deformation, displacement, stress and strain, the boundary conditions of force and rotational velocity is applied. Frictional force of 4410N Newton is applied on both the faces of the rotor where the pads would attach and clamp themselves. Also since the disc has to be fixed at its centers, fixed supports are given to the hub bolts and the inner portion of the entire inner circle. Thus, overall there are 4 initial boundary

conditions given to the disc rotors model or geometry before proceeding to the solution.
Solving the model: Once the conditions are applied, the model is solved for three factors:

➢ Total deformation
➢ Equivalent stress
➢ Equivalent elastic strain

2.6 TOTAL DEFORMATION

GREY CAST IRON ROTORS

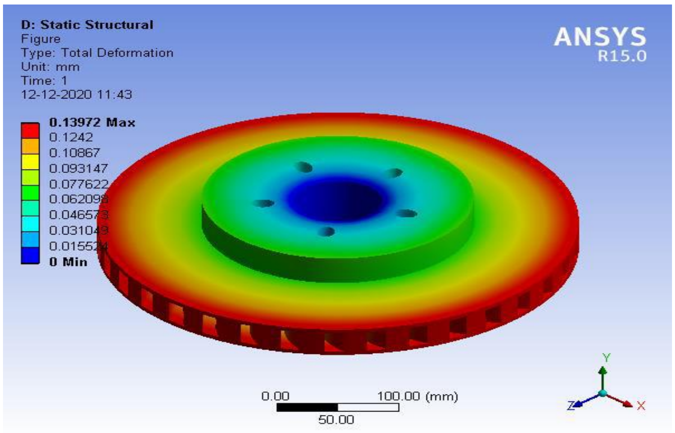

Fig -3: Total deformation in grey cast iron

CAST IRON WITH GRAPHITE NODULES ROTORS

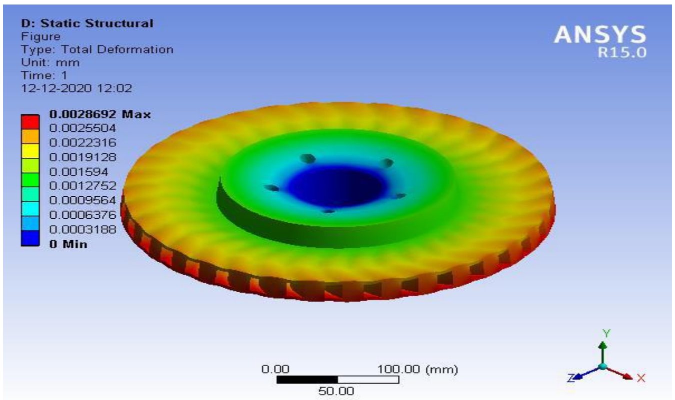

Fig -4: Total deformation in cast iron with graphite nodules

CARBON FIBER REINFORCED SiC ROTORS

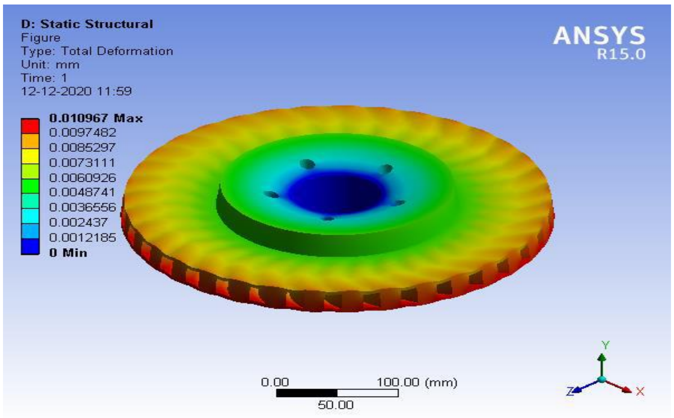

Fig -5: Total deformation in Carbon fiber reinforced SiC rotors

2.7 EQUIVALENT STRESS

GREY CAST IRON ROTORS

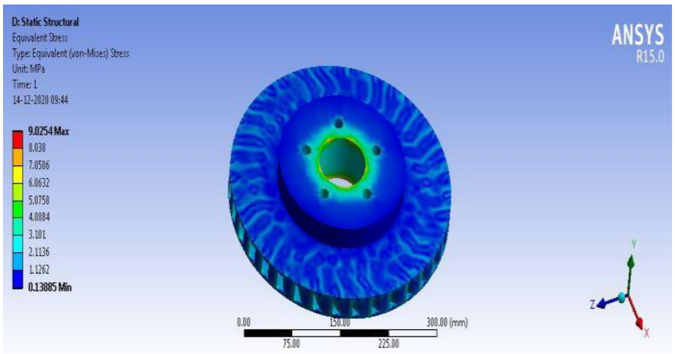

Fig -6: Stress in Grey cast iron rotors

CAST IRON WITH GRAPHITE NODULES ROTORS

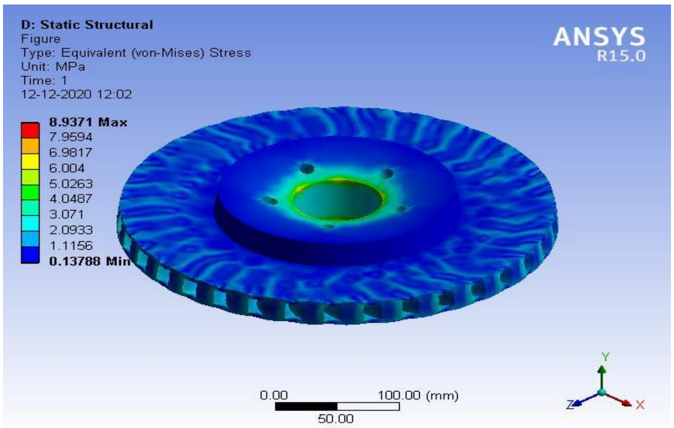

Fig -7: Stress in cast iron with graphite nodules rotors

CARBON FIBER REINFORCED SiC ROTORS

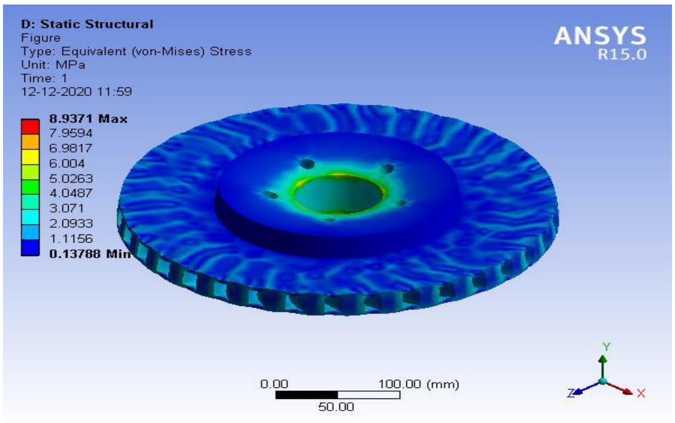

Fig -8: Stress in carbon fiber reinforced sic rotors

2.10 EQUIVALENT ELASTIC STRAIN

GREY CAST IRON ROTORS

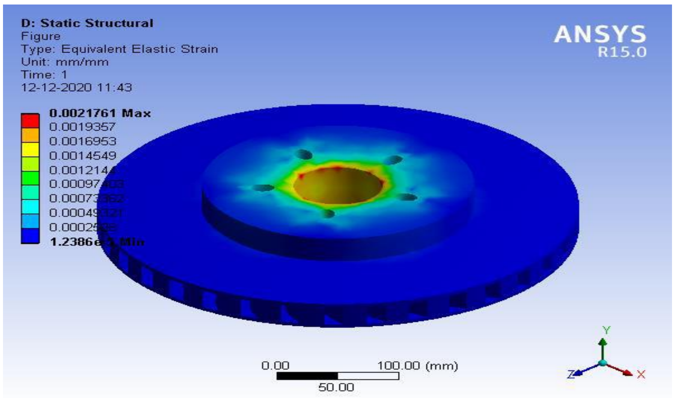

Fig -9: Elastic strain in grey cast iron rotors

CAST IRON WITH GRAPHITE NODULES ROTORS

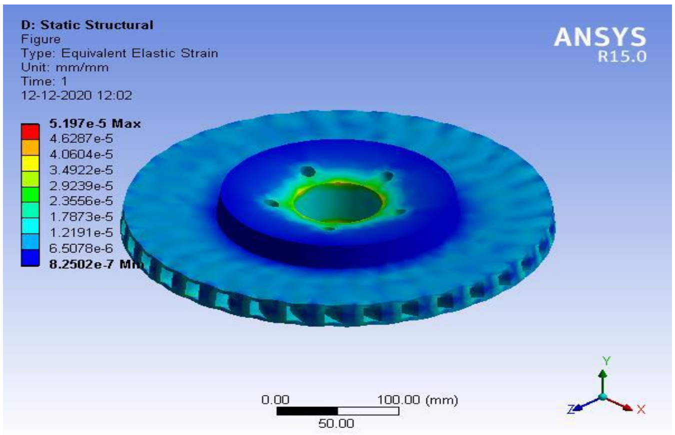

Fig -10: Elastic strain in cast iron with graphite nodules

CARBON FIBER REINFORCED SiC ROTORS

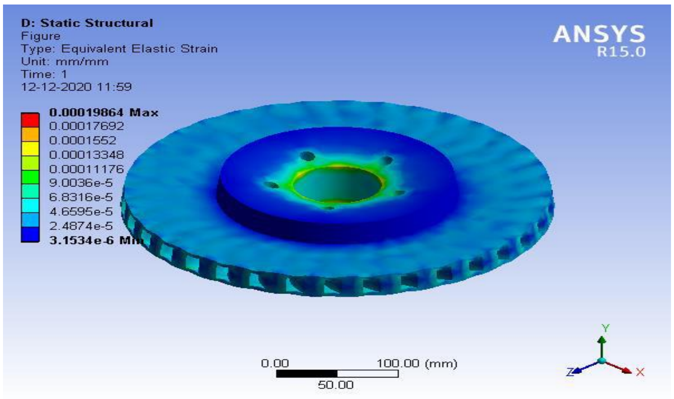

Fig -11: Elastic strain in carbon fiber reinforced SiC rotors

2.12 STEADY STATE THERMAL ANALYSIS

Temperature variation and heat flux throughout the geometry of the rotor are calculated and analyzed here. Due to the application of brakes on the car disc brake rotor, heat generation takes place due to friction and this temperature so generated has to be conducted and dispersed across the disc rotor cross section. The condition of braking is very much severe and thus the thermal analysis has to be carried out. A steady state thermal analysis determines the temperature distribution and other thermal quantities under steady state loading conditions. A steady state loading condition is a situation where heat storage effects varying over a period of time can be ignored.

Temperature and heat flux applied are equal for all the rotors

- Cast iron rotor
- Cast iron with graphite nodules rotor
- Carbon fiber reinforced rotor

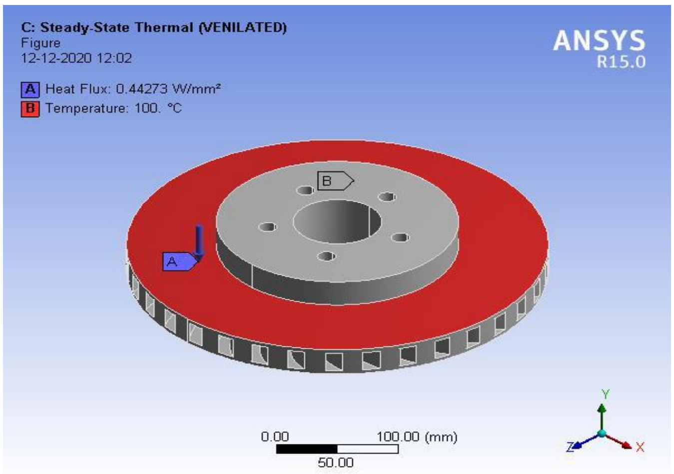

Fig -12: Steady state thermal analysis

Table -1: THERMAL ANALYSIS IN GREY CAST IRON ROTORS

Model (C4, D4) > Steady-State Thermal (C5) > Solution (C6) > Results

Object Name	*Temperature*	*Total Heat Flux*
State	Solved	
Scope		
Scoping Method	Geometry Selection	
Geometry	All Bodies	
Definition		
Type	Temperature	Total Heat Flux
By	Time	
Display Time	Last	
Calculate Time History	Yes	
Identifier		
Suppressed	No	
Results		
Minimum	100. °C	1.9013e-016 W/mm²
Maximum	100. °C	2.2617e-013 W/mm²
Minimum Value Over Time		
Minimum	100. °C	1.9013e-016 W/mm²
Maximum	100. °C	1.9013e-016 W/mm²
Maximum Value Over Time		
Minimum	100. °C	2.2617e-013 W/mm²
Maximum	100. °C	2.2617e-013 W/mm²
Information		
Time	1. s	
Load Step	1	

Table -2: THERMAL ANALYSIS IN CAST IRON WITH GRAPHITE NODULES ROTORS

Model (C4, D4) > Steady-State Thermal (C5) > Solution (C6) > Resu

Object Name	*Temperature*	*Total Heat Flux*
State	Solved	
Scope		
Scoping Method	Geometry Selection	
Geometry	All Bodies	
Definition		
Type	Temperature	Total Heat Flux
By	Time	
Display Time	Last	
Calculate Time History	Yes	
Identifier		
Suppressed	No	
Results		
Minimum	100. °C	1.1592e-016 W/mm²
Maximum	100. °C	2.2938e-013 W/mm²
Minimum Value Over Time		
Minimum	100. °C	1.1592e-016 W/mm²
Maximum	100. °C	1.1592e-016 W/mm²
Maximum Value Over Time		
Minimum	100. °C	2.2938e-013 W/mm²
Maximum	100. °C	2.2938e-013 W/mm²
Information		
Time	1. s	
Load Step	1	

Table -3: THERMAL ANALYSIS IN CARBON FIBER REINFORCED SIC ROTORS

Model (C4, D4) > Steady-State Thermal (C5) > Solution (C6) > Results

Object Name	*Temperature*	*Total Heat Flux*
State	Solved	
Scope		
Scoping Method	Geometry Selection	
Geometry	All Bodies	
Definition		
Type	Temperature	Total Heat Flux
By	Time	
Display Time	Last	
Calculate Time History	Yes	
Identifier		
Suppressed	No	
Results		
Minimum	100. °C	8.4578e-017 W/mm²
Maximum	100. °C	1.9874e-013 W/mm²
Minimum Value Over Time		
Minimum	100. °C	8.4578e-017 W/mm²
Maximum	100. °C	8.4578e-017 W/mm²
Maximum Value Over Time		
Minimum	100. °C	1.9874e-013 W/mm²
Maximum	100. °C	1.9874e-013 W/mm²
Information		
Time	1. s	
Load Step	1	

3. RESULTS AND DISCUSSION

Disc Brakes are the most popular brakes among all brake types and have a wide range of application. Various types of Disc brakes and Brake Disc Rotors are studied and the design is understood

Disc Rotors of 345 mm outer diameter, 198 mm inner diameter and 28 mm flange thickness are modeled Solid works and analyzed using ANSYS. Due to limitations in time and software knowledge and resource, analysis is performed only for static structure and steady state thermal toolbox in ANSYS. The table below summarizes the results observed for three different materials such as

- Grey Cast Iron
- Cast Iron with Graphite nodules
- Carbon fiber reinforced SiC

Table -4: RESULTS

	Grey Cast Iron		Cast Iron with Graphite nodules		Carbon fiber reinforced SiC	
	Max	Min	Max	Min	Max	Min
Total Deformation (mm)	0.134	0	$2.8*10^{-3}$	0	0.011	0
Equivalent Stress (Mpa)	9.025	0.1388	8.9371	0.1378	8.9371	0.1378

Equivalent Strain	2.176* 10^{-3}	1.238* 10^{-5}	5.197* 10^{-5}	8.2502* 10^{-7}	1.98* 10^{-4}	3.1534* 10^{-6}
Heat Flux (W/mm²)	2.2617* 10^{-13}	1.9013* 10^{-16}	2.2938* 10^{-13}	1.1592* 10^{-16}	1.9874* 10^{-13}	8.4578* 10^{-17}

4. CONCLUSION

It is observed that the carbon fibre reinforced SiC disc rotor have a better performance when compared to both cast iron with graphite nodules rotors and grey cast iron rotors due to reduced stress, strain, overall deformation and thermal stability. Hence, Carbon fibre reinforced SiC rotors are generally used in performance cars like sports cars, ATV's and UTV's. However, cast iron with graphite nodules rotors and grey cast iron rotors are generally weak, usual commercial vehicles on roads prefer these disc rotors.

In this study design analysis and optimization of brake disc made of carbon fibre composite was carried out. Disc Rotors of 345 mm outer diameter, 198 mm inner diameter and 28 mm flange thickness are modelled Solid works and analysed using ANSYS. The table 4 summarizes the results observed for three different materials

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