Design and Analysis of a Disc Brake Rotor for Optimal Performance in Racing

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ABSTRACT

The braking system is an important and indispensable part of an automotive. The brake disc rotor forms part of the braking system and plays a significant role to effectively stop the vehicle. Therefore, the investigation of rotor design and analysis is important towards attaining optimal braking performance. In this research, three designs of vented rotor geometry were tested, namely normal vented, vented and cross-drilled and vented and slotted, and subjected to coupled thermal-structural analyses using ANSYS Workbench. For material selection for these designs, the CES EduPack software was applied and Carbon/Carbon (C/C) composite was identified as the best material for use as a rotor material for racing application. The results showed that the vented and cross-drilled design is the most appropriate design for the vehicle applications since it records lowest maximum temperature, stress, strain and total deformation compared to the other two design. This design also helps to enhance brake performance by allowing for faster heat dissipation and hence reducing thermal stresses on the rotor.

Keywords: Brake disc rotor, vented and cross-drilled design, Carbon/Carbon (C/C) composite

INTRODUCTION

Automotive braking system commands great importance in vehicles design and operation [1]. It comes with the safety aspect which is considered as a key priority in new vehicle development. One of the key parts in automotive braking system is the rotating brake disc rotor. This part in combination with the stationary brake shoe/pad is fundamentally important in attaining optimal braking performance. A vehicle brake disc rotor plays a major role in achieving vehicle braking capacity. During braking, a retarding torque is generated through the conversion of the mechanical energy to thermal energy. This is because of frictional work done at the rotor-pad interface as a result of relative sliding, that occurs during braking [2]. In the recent past, there have been considerable applications of brake rotors in light weight vehicles necessitating the need to develop lightweight brake disk rotors [3,4]. A vehicle's strength and merit can be gauged based on the performance of its braking system. With long repetitive braking, a number of vehicles' braking components experience significant rise in temperature and this may result in a reduction of the vehicle braking performance. High temperature may result in brake fade, brake fluid vaporization, bearing failure, premature wear, thermally excited vibration and thermal cracks [5]. In this regard, it has been found to be very crucial to predict the rise in temperature and assess the thermal performance of a given brake system at the early stages of the design.

Brake discs are generally exposed to significant thermal stresses during regular braking and very high thermal stresses at the time of hard braking [6]. High decelerations during racing can generate high temperatures within a fraction of a second. In effect, the temperature variations tend to cause a thermal shock that causes surface cracks. The temperature excursion also tends to cause high level of plastic deformation of the rotor. In case there is no thermal shock, high braking cycles can result in the generation of macroscopic cracks in the direction of the disk brake radius through the rotor thickness. Since the brake lining materials are poor conductors of heat, the brake disc bears the burden of the heat resulting into high temperatures [7,8]. At these high temperatures, the coefficient of friction between the contacting surfaces of the disc and the lining is greatly reduced and this necessitates extra pedal pressure for braking to be achieved. When this occurs frequently, brake fade sets in which is characterized by extremely low friction coefficient. The implication is the vehicle’s inability to attain any significant braking effect.

Therefore, it is absolutely necessary to have the brake discs designed in a way to reduce brake fade by quickly dissipating heat during braking cycle. This also plays a major role in reducing thermally induced stresses and deformations [9,10]. The choice of materials is also important in achieving quick heat dissipation and lightweight considerations.

Theory of Disc Brakes

The first disc brake was designed in 1902 by Fredrick William. The first and original design comprised of two discs that pressed against each other to generate friction to slow and stop the car [11]. Disc brakes are generally composed of a discs/rotor and the brake caliper assembly. The later comprise of hydraulic action pistons that push the brake pads against the rotating disc, forcing the pads to be clamped on the rotating disc/rotor and creates a clamping force. This clamping force contributes to produce a frictional force, friction generation, heat generation and kinetic energy transfer. In this respect, the discs are generally designed guided by these crucial factors relating to heat generation and dissipation and the force applied [12]. Figure 1 shows a typical arrangement of a disc brake and its components:

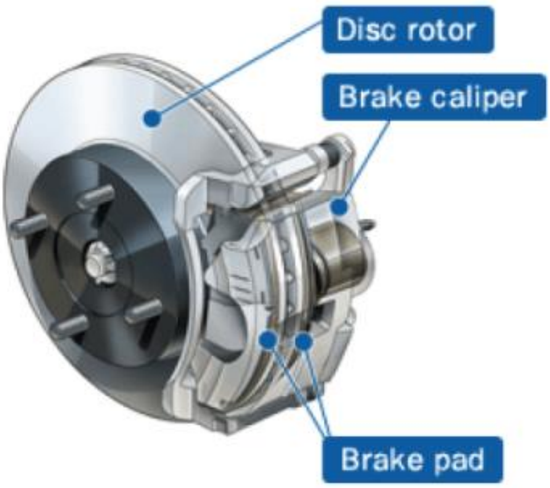


Figure 1: A typical arrangement of a disc brake and its components [11]

Brake discs are very important in stopping the vehicle. Heat generation during braking and the dissipation of such heat is very important factors in disc brake performance. When the vehicle is in motion, it possesses kinetic energy. To stop the vehicle, the kinetic energy is transferred to the discs in the form of heat energy. The discs have to be designed in a way that removes or dissipates the heat in faster way to avoid heat-related deformation and cracks and deterioration of brake pads performance. Cars moving at very high speeds like racing such as racing vehicles have higher kinetic energy than the others and hence require proper and effective heat dissipation at the time of braking [13]. To ensure the required heat dissipation is attained, the rotors are generally altered and adjusted with innovations being incorporated [14].

Types of Brake Disc Rotors

Disc brakes can be categorized as vented and non-vented (solid). The vented brake discs comprise of two discs of metal with ribs in-between, that connect these two discs and ensure larger surface area [15]. Figure 2Figure 2 illustrates vented and non-vented brake discs. Whether, a brake disc is vented or non-vented, it can fall into any of the following types depending on the features on its geometry.

Figure 2: Vented and non-vented (Solid) disc brake rotor [15]

Normal Disc Rotors

These types of discs are considered as the standard design and they are found in many commercial vehicles. They are solid, with flat faces and no modifications which allows them to provide maximum surface area for brake pads action. They offer good braking power. However, they are prone to brake pad glazing and fade due to build-up of gas during braking. Brakes fade results in partial or total loss of braking power. Brake pad glazing refers to oxides formation on the brake pad material [16]. Solid discs are also prone of excessive heat generation and the absence of modifications to dissipate the heat much faster leads to wearing of the disc resulting into loss of braking performance [2]. Figure 3a shows a solid (non-vented) disc type.

Drilled Disc Rotors

Drilled rotors are characterized by holes drilled through their thickness. The essence of drilling holes through the discs is to provide path for faster heat dissipation. Thus, this kind of rotor allows for the heat to be dissipated faster from the surface during braking cycle. The gas built up during braking is also able to escape through the drilled holes and is never trapped between the discs surface and brake pad material. Due to these crucial roles played by the holes, brake fading, and brake pad glazing are reduced significantly. This helps in enhancing brake performance [2]. Despite providing braking performance improvement, the drilled holes tend to weaken the rotor. Due to repeated applications of braking, fatigue may set in resulting in cracks development in the weakened rotor. Thus, the durability of drilled rotors is reduced. Drilled disc brake rotors can either be normal drilled and cross drilled (as shown in Figure 3 b and c). Cross drilled rotors have the holes drilled at an angle and this differentiates them from normal drilled rotors which have the holes drilled normal or perpendicular to the surface of the disc. Cross-drilled rotors offer more surface area for heat dissipation than normal drilled and they are therefore considered to have better heat dissipation capability [11].

Slotted/ grooved disc brake rotors

Slotted/grooved disc brake rotors apply slots carved into their surface. The slots are meant to evacuate the built-up gas, the heat and any water that may come into contact with the disc. These types of rotors are common in performance car applications since for such applications a lot of stress is imparted on the disc. Slotted discs eject brake pad dusts easily and averts pad glazing that allows it to remain fresh and provides better braking. However, slotted discs are known to be noisy during braking due to the pads scrubbing. The brake pads also wear out quickly. Figure 3d illustrates typical slotted/grooved disc brake rotors.

Combined Rotors

Disc rotors can be a combination of the basic types described above. The most common combination is drilled and slotted rotors. Combination seeks to leverage on the strengths of the two types while minimizing the weaknesses. For instance combining slotting and drilling helps a rotor have increased surface area, avoid dust debris and dust accumulation and prevent brake fading. However, the strength is reduced due to the existence of slots and drilled holes. Figure 3e shows a typical drilled and slotted rotor.

High performance disc brake rotors are of slotted type and these are the kind of rotors applied in racing cars. A glance at the practical application of disc brake for high performance vehicles reveals that drilled rotors are also used for racing applications. This shows a lack of consensus on the best type of disc brake rotor to apply and this call for more investigation.

Normal Disc Rotor	Drilled disc brake rotor (Normal drilled)	Cross-drilled brake disc rotor	Slotted disc brake rotor	Cross drilled and Slotted disc brake rotor
				
(a)	(b)	(c)	(d)	(e)

Figure 3: Types of disc brake rotor

Thermal characteristics of a Brake disc

A brake disc must have adequate thermal stability to be able to perform effectively. For any disc shape and configuration, thermal stability depends on the thermal properties of the material, heat treatment prior to machining and the rotor design. The most important thermal properties of a brake disc rotor are thermal capacitance, thermal conductivity, heat dissipation and thermal expansion coefficient [17] .Thermal capacitance refers to the ability of the disc to store heat. At the start of the braking process, a lot of frictional heat gets stored. In the cases of involving short braking, thermal capacitance becomes dominant. Thermal conductivity refers to the ability to redistribute thermal energy. In the cases of low as well as long intensity braking action, peak temperature is largely dependent on the material's thermal conductivity. This property has small effect when it comes to short braking. The heat that develops while braking has to be taken away/dissipated to keep the brakes effectively functioning. Heat dissipation becomes extremely important for long braking times such as two to three minutes. Thermal expansion coefficient controls the phenomenon such as DTV (disc thickness variation) and hot spotting [18]. The expansion coefficient must be suitable to avoid temperature gradients that are likely to trigger temporary DTV resulting from uneven material thermal expansion.

Materials used for disc brake

Different studies reported the used of different materials such as cast iron, cast steel, stainless steel, Aluminium alloy, Al 7075, Al-MMC and Carbon Fibre reinforced Polymer (CFRP) for brake disc analysis [19–22]. The material use for the brake disc rotor at the commercial front has also been well recorded and various car manufacturers and models are known to apply certain materials for their different applications. For ordinary cars, cast iron is the most common materials used on account of better metallurgical stability, better ease of manufacture, and lower cost. Racing car manufacturers such as Ferrari and McLaren are known to use Carbon-Ceramic and composite based discs due to their excellent heat performance characteristics. In addition to this, a carbon fibre reinforced carbon matrix has excellent material properties such as high thermal shock resistance, high modulus of elasticity, low thermal expansion coefficient, high thermal conductivity, high abrasion resistance, excellent heat resistance properties, low density and high strength [23]. These properties make the material suitable for the application disk brake rotor for racing application. The material can be applied in high performance braking applications. The mechanical properties of carbon-carbon (C/C) composites are varied in nature due to the various methods applied to manufacture the material and the filler arrangement. C/C composites maintain higher mechanical properties at higher temperatures in contrast to other materials that properties deteriorate with at higher temperatures [24, 25]. The greater strength to weight ratio and the specific stiffness of C/C composite are also very important for racing applications.

The literature survey conducted in the preceding section has highlighted different configurations, materials and properties of disc brake rotors. The literature has that revealed that finite element analysis of brake disc rotor has been studied widely with the main focus on the different configurations of the disc. In most of the studies reported, cast iron featured prominently as the mostly used material in FEM analysis [26, 27]. There is need to carry out numerical analysis while applying other advanced materials like composites while still evaluating the different configurations of the disc. During this study, the material selection was carried out for the brake disc rotor with the help of CES

EduPack software. Three designs of the rotor were studied, and these designs were modelled using SolidWorks and their coupled thermo-structural finite element analyses were performed using ANSYS.

MATERIAL SELECTION FOR THE BRAKE DISC

Material selection is an important aspect for product design and manufacturing process. The selection of suitable materials must satisfy technical/functional, safety and legal requirements. To maintain the competitive edge of the product, its economic viability as defined by the materials used and the manufacturing process must be observed. Another aspect needs to be considered in material selection is material disposal after the expiry of the useful time. This helps in selecting materials that are environmentally friendly. Recyclable and biodegradable materials are usually recommended to reduce wastes. Thus, proper material selection can ensure that the selected material fulfils the required function, minimizes waste, reduces weight and reduces carbon footprint thereby advancing the aspect of environmental friendliness.

Due to the many materials available for consideration for a given task, there is a risk of neglecting the best material for any given application. For this study, it is important to consider a systematic way for material selection for the given application. The CES EduPack is applied for material selection methodology that has been well documented by Professor Ashby in his numerous work on material and process selection [28].

The first step and the starting point of a material selection is design translation which refers to the examination of the design requirements of the brake disc rotor with an aim of identifying the constraints, these needs and requirements impose on material choice. A broad choice of materials that are available can be narrowed down first by screening out all materials that cannot satisfy the set constraints. This is followed by further narrowing the obtained candidate materials through the use of ranking of the materials based on how best they can maximize performance. After ranking, a shortlist of materials that can be used for brake disc materials can be obtained and the final process is selecting the best material from the shortlist. This is done by seeking documentation of the top-ranked materials, a process that considers the strengths and weaknesses of the ranked shortlist materials, to arrive at the final material choice. The strategy for selecting materials is illustrated in Figure 4. The materials selection of the rotor is based on the thermal and structural characteristics as discussed above. From these, the constraints for the brake disc can be identified as follows:

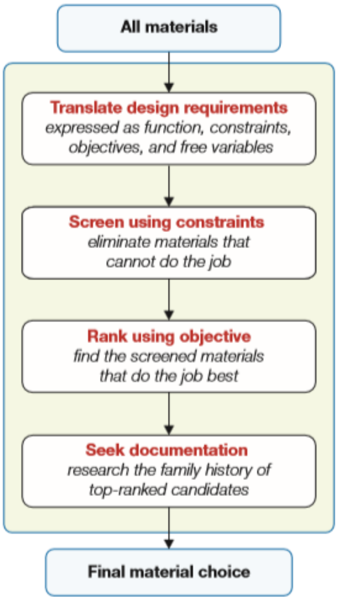


Figure 4: The strategy for selecting materials involving four key steps [28]

- *The brake disc should have high thermal capacitance. This can be defined by the specific heat capacity and the density of the material.*
- *The brake disc should have good thermal conductivity. Thermal conductivity ensures faster heat dissipation and helps avoid thermal distortion of the disc brake rotor.*
- *The brake disc should have excellent heat dissipation properties. This may not be related to material but largely depends on the disc geometry.*
- *The material should have a low thermal expansion coefficient. This will go a long way in averting rotor thermal distortion*
- *Due to repeated braking cycles, the rotor should have excellent fatigue strength*
- *The rotor should also exhibit excellent wear characteristics due to interaction with the brake pad friction material. This can be satisfied by selecting materials with good material hardness.*
- *Since racing cars need to be light to maximize performance, it follows that the brake disc has to be as light as possible. Thus, the key objective that will be coupled with the constraints to generate the performance indices is to minimize the mass of the brake disc. Price is also included in some indices but in this case the need for a lightweight design outweighs cost considerations.*
- *Another consideration is the rigidity of the brake disc. It has to be rigid enough and have enough compressive strength to support the prevailing forces.*

The following performance indices were used in the materials selection charts:

$$M_1 = \frac{E^{\frac{1}{2}}}{\rho C}, M_2 = \frac{\sigma_c S_e}{\rho C}, M_3 = \frac{\lambda}{\rho \alpha}, M_4 = \frac{H_v}{\rho C}, M_5 = \frac{K_{IC}}{\rho}$$

Where,

$E = Young's modulus$
$\rho = Density$
$C = Price$
$\sigma_c = Compressive\ strength$
$S_e = Fatigue\ strength$
$\lambda = Thermal\ conductivity$
$\alpha = Thermal\ expansion\ coefficient$
$H_v = Hardness$
$K_{IC} = Fracture\ toughness$
$\lambda = Thermal\ conductivity$

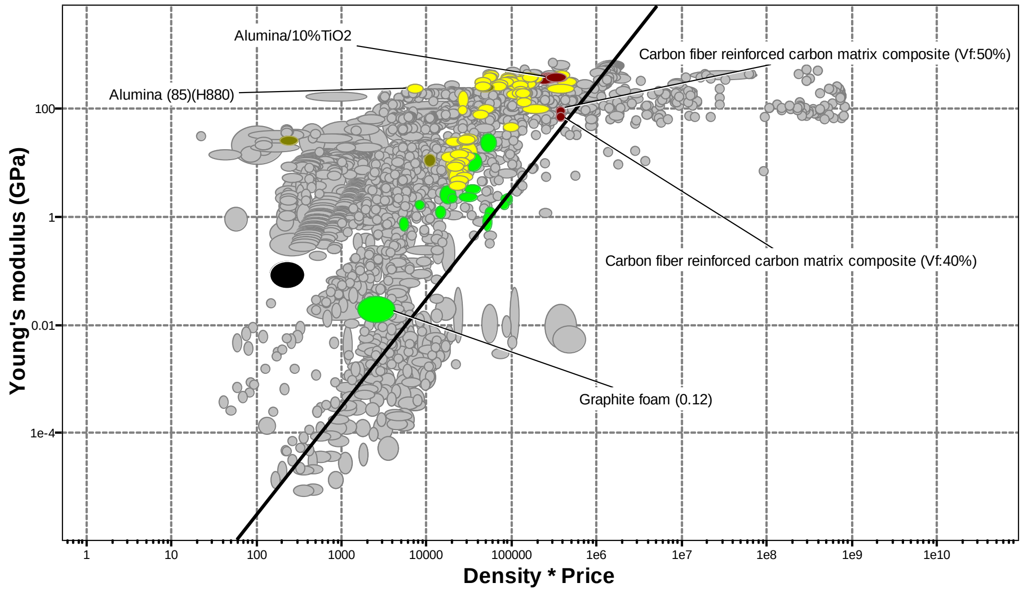


Figure 5: Young’s modulus vs density* price

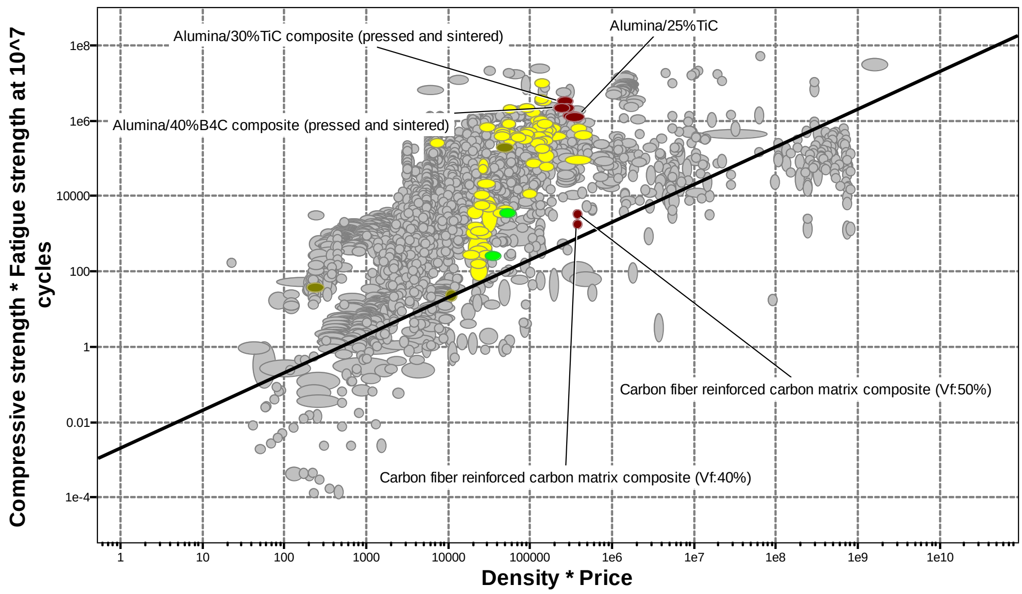


Figure 6: Compressive strength*fatigue strength vs density* price

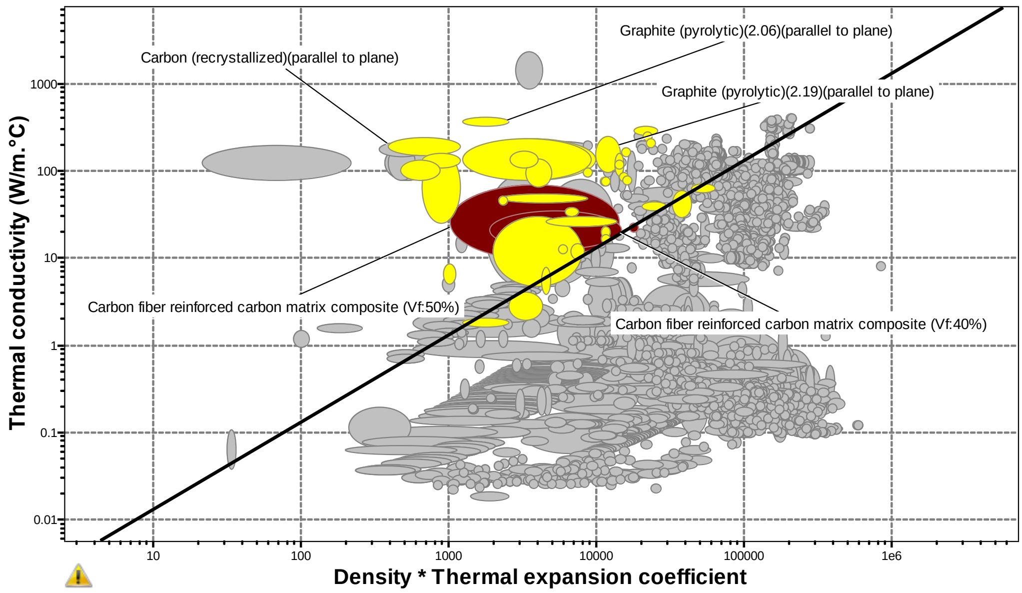


Figure 7: Thermal conductivity vs density* thermal expansion

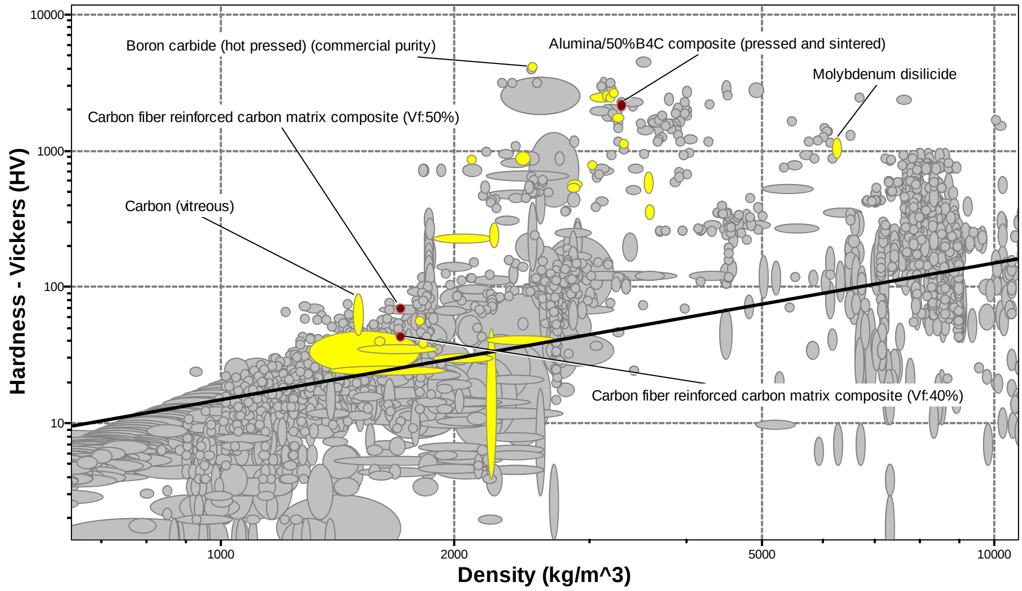


Figure 8: Hardness vs density

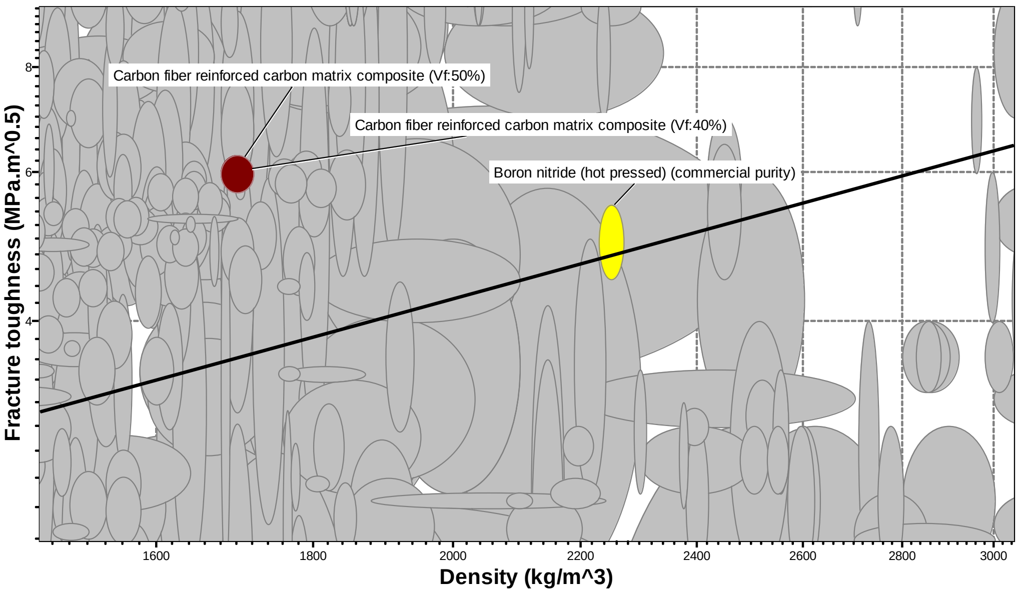


Figure 9: Fracture toughness vs density

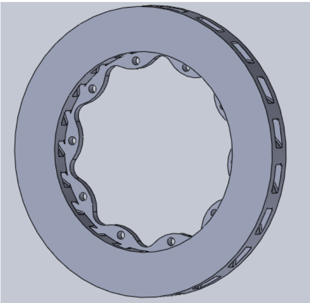
Before the application of these performance indices, the 1500^0C surface temperature was defined to ensure the disc material can withstand in high temperature. Figure 5 to Figure 9 were obtained from each selection stage. On the basis of these results, the three materials were shortlisted, Boron Nitride (hot pressed) (commercial purity), Carbon fibre reinforced carbon matrix composite (Vf: 40%), Carbon fibre reinforced carbon matrix composite (Vf: 50%). Boron Nitride material is a technical ceramic material and it is typical used for insulation applications. Since its application is mostly as a refractory material, it does not qualify for the application of as a disc brake material. Carbon fibre reinforced carbon matrix composite (Vf: 40%) material is typically used as aircraft and high speed train brakes and can withstand high temperatures. Carbon fibre reinforced carbon matrix composite (Vf: 50%) material is also typically used as aircraft and high speed train brakes and can withstand high temperatures. The material with Vf (volume ratio of the carbon fiber) of 50% exhibits a high thermal conductivity than the one with Vf of 40% [29]. Therefore, carbon fibre reinforced carbon matrix composite (Vf: 50%) was selected as the final material best suited for brake disc application.

3D MODELLING AND FINITE ELEMENT ANALYSIS FOR THE DISC BRAKE ROTOR

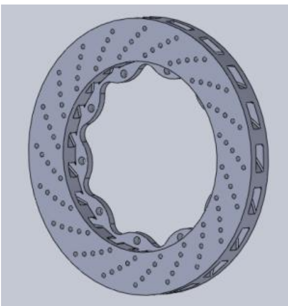
The three rotor designs vented, vented and drilled and vented and slotted were selected, and modelled using SolidWorks with the rotor diameter of 355 mm and rotor thickness of 36mm as shown in Figure 10. The generated three-dimensional (3D) models were then exported to ANSYS Workbench in which a coupled finite element (FE) thermo-structural analyses were carried out. The rotor material was selected as Carbon-Carbon Composite material and its material properties (CES EduPack, 2017) are shown in Table1.

Table 1: The material properties for Carbon-Carbon Composite material

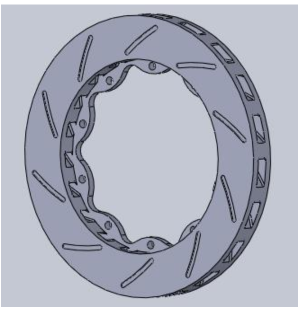
The material properties for Carbon-Carbon Composite material	
Density	1700 kg/m^3
Poisson's Ratio	0.32
Young's modulus	95 GPa
Shear modulus	36 GPa
Compressive strength	235 MPa
Thermal conductivity	40 W/M-K
Coefficient of thermal expansion	0.7E-6 K^{-1}



Normal Vented Disc Brake Rotor



Vented and Drilled Disc Brake Rotor



Vented and Slotted Disc Brake Rotor

Figure 10: The three geometries for the disc brake rotor.

The finite element analysis approach:

To performed couple thermo-structural analysis, the thermal analyses were carried out first and then the structural analyses were performed.

Thermal boundary conditions

In carrying out the thermal analysis, some assumptions were made such as the analysis is based on thermal loading only, the braking action is applied on the rear brakes only, the material of the brake disc is homogeneous and isotropic, thermal conductivity of the material is uniform during the analysis, specific heat of the material remains constant during the analysis, only ambient air cooling is taken into consideration. Based on these assumptions, the value of heat flux is 738184.3 W/m^2, heat transfer coefficient by convection is 230 W/m^2 ^{0}C and the ambient temperature is 22 ^{0}C were selected as boundary conditions as shown in Figure 11.

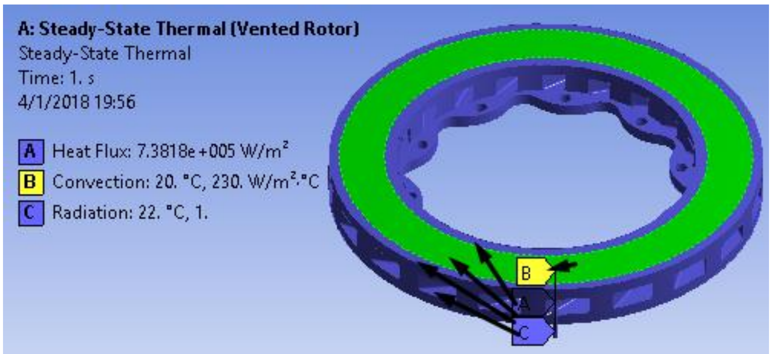


Figure 11: Thermal boundary conditions for the vented disc rotor design.

Structural Boundary Conditions

The structural conditions used for the finite element model was comprised of fixed support. This boundary condition was applied on holes of the bolt on the disc to simulate the actual condition where the bolts are used to fix the rotor to the wheel assembly [29] as shown in Figure 12.

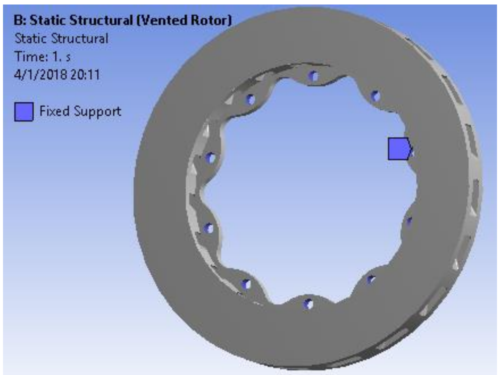


Figure 12: Structural boundary conditions for the vented disc rotor design

Couple thermo-structural analysis

The couple thermo-structural analysis approach was adopted as illustrated in Figure 13.

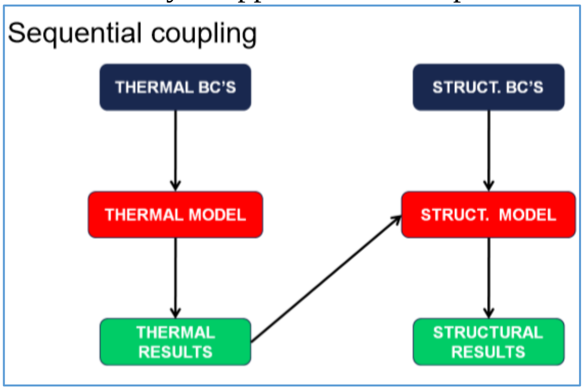


Figure 13: The couple thermo-structural analysis approach

The above coupling is a sequential coupling technique that requires the undertaking of thermal analysis followed by structural analysis. The analysis process can be classified as pre-processing, solver or solution and post-processing. The pre-processing entailed the selection of the analysis type, the specification of the material properties, the modelling or the importation of the rotor geometry, meshing the geometry and specification of the boundary conditions. The analysis type for this study was selected as steady state thermal analysis since steady flow conditions were assumed for the determination of maximum temperature on the disc. The material properties were specified by editing the engineering data and creating a custom material of carbon-carbon composite with the required material properties. The rotor geometry generated in SolidWorks was imported into the Workbench interface. The Design Modeller was applied to do any modification such as face split to define the regions for heat flux application. The rotor model was meshed using adaptive meshing type having a relevance to mechanical of one. The relevance centre and the span angle centre were set to medium. All other settings were maintained as default. After meshing of the model, the boundary conditions were applied. The pre-processing stage is followed by the analysis stage in which the solver was engaged to obtain the solution. For the thermal analysis, the temperature distribution, the maximum and the minimum temperature were computed. The post-processing stage entails the presentation of the analysis results and based on the sequential coupling adopted, the thermal analysis results were adopted first. These results were then fed to the pre-processing stage (model set up) of the structural analysis to allow for the computation of the thermal stress of the rotor.

RESULTS

The following results were obtained after carrying out the thermo-structural analyses for the three selected disc brake rotor designs.

Thermal analysis results

For the thermal analysis, the temperature distribution and total heat flux were computed. The Figure 14 shows the contour plots for these results.

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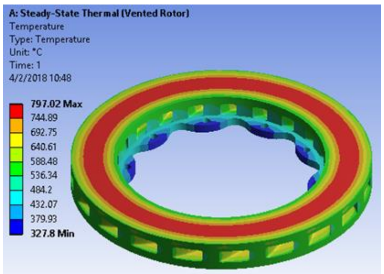
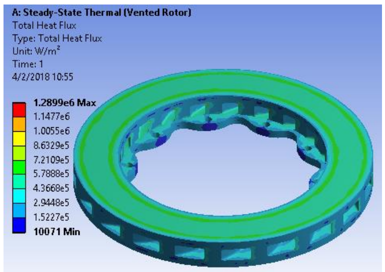
<tr><td>Normal Vented Disc Brake Rotor</td><td>
</td><td>
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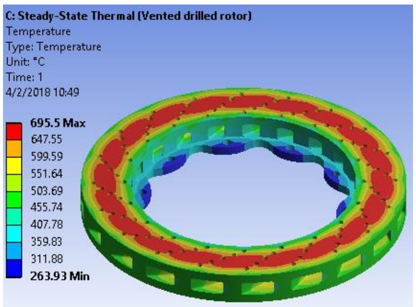
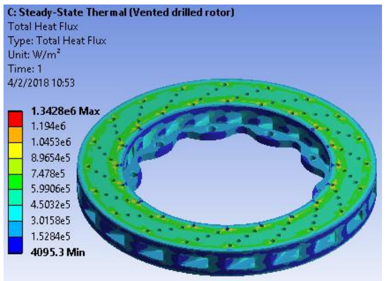
<tr><td>Vented and Drilled Disc Brake Rotor</td><td>
</td><td>
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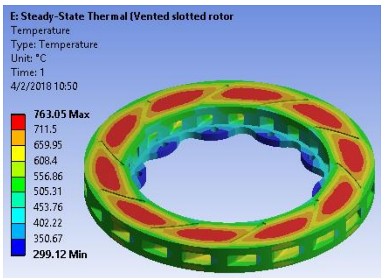
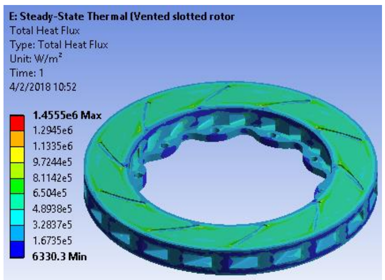
<tr><td>Vented and Slotted Disc Brake Rotor</td><td>
</td><td>
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<tr><td></td><td>Temperature Distribution</td><td>Total Heat Flux</td></tr>
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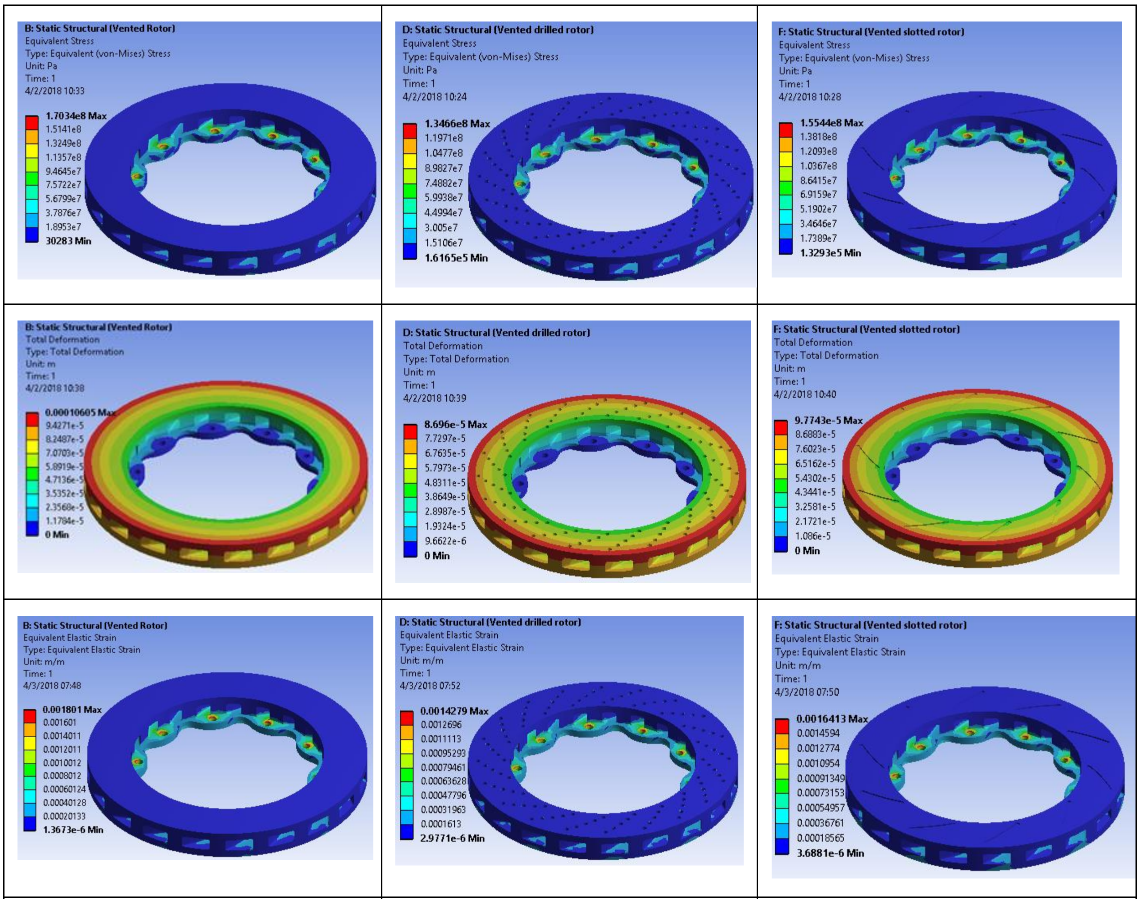
Figure 14: Thermal analyses results for three selected disc brake rotor designs

Static Structural Analysis

For the static structural analysis, equivalent von Mises stress and elastic strain, and total deformation distribution were computed during the analysis. Figure 15 shows the contour plots for these results. The resulted presented can be summarized in a comparison Table 2 below.



Normal Vented Disc Brake Rotor	Vented and Drilled Disc Brake Rotor	Vented and Slotted Disc Brake Rotor

Figure 15: The static structural analysis results for three selected disc brake rotor designs

Table 2: Comparison table for the results

Parameter	Normal vented rotor	Vented and Cross-drilled rotor	Vented and slotted rotor
Temperature (°C)	797.02	695.5	763.05
Heat Flux (W/m^2 x10^6)	1.2899	1.3428	1.4555
Stress (MPa)	170.34	134.66	155.44
Strain	0.001801	0.0014279	0.0016413
Deformation (mm)	0.10605	0.08696	0.097743

DISCUSSION ON RESULTS

The results of temperature distribution after the braking action are shown in Figure 14. The contour plots show that temperature is highest at the region of brake pad-rotor interface. This is the region where the frictional heat flux is applied during the braking action and it is therefore in principle expected to exhibit high temperatures. As the brakes are applied, the rubbing action of the brake pads results in heat generation after the vehicle's kinetic energy is converted to heat and absorbed by the disc. For the normal vented rotor, the highest temperature is 797.02 ℃ and the minimum temperature is 327.8℃. The temperature distribution in this case can be seen to be highest at a ring region where the brake pad contacts the rotor. The temperature is lowest at the inner section of the rotor adjacent to the regions where the rotor is bolted to the wheel. For the vented and cross-drilled rotor design, the highest temperature is 695.5 ℃ while the lowest temperature is 263.93℃. For the slotted vented rotor, the highest temperature is 763.05 ℃ while the lowest is 299.12 ℃. Comparing the three designs with regard to temperature distribution, it can be seen that the cross-drilled vented rotor is able to dissipate heat much more effectively than the other two designs since it recorded the lowest temperature value after the application of the brakes. The slotted vented rotor also records better performance than the normal vented rotor. These findings show that the geometry modifications such as cross drilling and slotting are effective in enhancing heat dissipation capabilities [21,30,31]. The difference in temperature distribution affects the thermal stress, strains and deformation since the thermal loading is the only loading applied in the static structural analysis. In this regard, the stress, the strain and the deformation distributions are consistent with temperature distribution with the cross-drilled rotor recording lowest values while the normal vented rotor recorded the highest levels as shown in Figure 15. As observed that the thermal-induced stress, strain and deformation are highest on the disc with the highest temperature distribution. This can also be observed in the three designs with the normal vented rotor recording highest stress, strains and deformation levels and the cross-drilled vented rotor recording the lowest values. In this respect, the most suitable disc brake rotor geometry is the vented, cross drilled type.

CONCLUSION

The braking system is an important and indispensable part of an automotive. The brake disc rotor forms part of the braking system and plays a major role in effectively stopping the vehicle. Therefore, the rotor design and its analyses are important towards attaining optimal braking performance. In this research, a study was undertaken to evaluate the performance of the normal vented, vented and cross-drilled and vented and slotted geometries of vented rotors. The rotor material was selected as Carbon/Carbon composite which can withstand high temperatures than other materials and has good material properties. The above study leads to the following conclusions:

- Maximum temperature on the rotor was noted to be lowest in vented and cross-drilled rotor. This was followed by the slotted rotor and the normal vented rotor recorded the highest maximum temperature.
- It was noted that the stress, strain and total deformation are all correlated to the temperature distribution and as such their distribution in the three rotor designs is consistent with thermal distribution with lower values being recorded in the vented and cross-drilled rotor.

- The results clearly showed that surface modifications of the geometry by way of drilling and slotting offers more surface area for heat dissipation, which subsequently helps in reducing thermal stress and strains.
- From the above results it can also be concluded that the Carbon/Carbon composite is the optimum material for brake disc because it can withstand to thermal and static loads coming on brake disc.

ACKNOWLEDGE

The authors would like to thank University of Sunderland to provide its support for this research work.

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