STRUCTURAL ANALYSIS OF A TWO-WHEELER DISC BRAKE

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Abstract: Automotive brakes have come a long way, from drum brakes being widely used for a long time until disc brakes came along and began slowly wiping out the usage of drum brakes. This is primarily due to the number of advantages that the disc-pad setup brings - better stopping distance being one of the most important aspects of any braking system. Apart from this, key advantages of disc brakes over drum brakes include better heat dissipation, fade resistance, self-adjusting ability, compact packaging and so on. Although drum brakes too have certain advantages over disc brakes with lesser cost of manufacturing being one of them, the pure superiority of disc brakes outweighs the few benefits of the drum brakes and this has also reflected in the market. However, there is always scope for improvement when it comes to the structural and thermal characteristics of the brake disc. Researches have been carried out to discover better suited materials and brake disc designs to improve the overall structural and thermal characteristics and reduce uneven wear, squealing etc. The aim of this research is to analyze a new design and material combination based on earlier researches to decrease the deformation and provide a base for improving thermal characteristics.

Keywords: Disc brake, brake pads, silicon carbide single crystal, Solidworks, ANSYS, static structural analysis.

1. Introduction

A brake is a device which makes use of frictional resistance to stop the motion of any machine or vehicle. It absorbs the kinetic energy and dissipates it in the form of heat. Brake systems must be able to fulfill certain key requirements such as:

- Minimum stopping distance - Vehicle must be able to come to a complete halt within a regulated distance in case of emergency braking.
- Prolonged application of the brake should not lead to brake fade.
- Must have anti-wear properties [1].

A disc brake assembly, be it in the case of any vehicle, consists mainly of calipers which house the brake pads and the disc/rotor as shown in fig. 1.

![Figure 1. Motorcycle Disc Brake (Duke 200)](image1)

![Figure 2. Disc Brake Assembly](image2)
Brakes are important components of any vehicle's retardation system. The disc brake uses a metallic rotating disc which is sandwiched between two pads that are activated by a cylinder backed in a caliper mounted on the stud shaft. When the brake pedal is depressed, the brake pads are pressed either mechanically or pneumatically on to the rotating disc. The kinetic energy of the vehicle is converted into heat due to the friction between the disc-pad interface and is absorbed mainly by the rotor and pads in the form of heat [2][3]. This heat is then dissipated into the surrounding atmosphere. As there is generation of frictional heat on the disc-pad interface, there is a rise in temperature. If this temperature exceeds the critical value of the given material it leads to disastrous events such as brake failure, premature wear, failure of bearing and thermal cracks or vaporization of brake fluid [4]. In addition, due to the heat generation at the disc-pad interface, global deformation occurs in the disc and pad. Some of the usual deformations are coning and buckling [5-7]. Apart from this, macro cracks could appear on the disc brake in radial direction after a number of braking cycles in turn affecting the life and performance of the disc brake [8-9]. Lee and Yee [4] found out that the unequal distribution of temperature on the surface of frictional pad causes thermal distortion popularly known as coning and this is responsible for judder effect and variation in the thickness of the rotor.

Researches have been carried out to analyze various designs of the rotor by including different types of ventilations such as circular, oval, square holes and so on. On the other hand, different metals and composites have also been analyzed over the years to find structurally and thermally superior solutions especially for higher end vehicles such as sports cars and bikes which require high performance brakes. This paper focuses on improving the structural behavior of the disc brake by designing and analyzing a new design keeping in mind the need for better thermal characteristics as both the parameters are closely linked.

2. Literature Review

Belhocine studied the thermo-mechanical behaviour between brake disc and pad to identify the factors affecting the design of ventilated disc based on transient temperature conditions. He used grey cast iron due to its good thermo-physical properties and concluded that the variations in temperature observed were less compared to solid conventional disc. Further, his work proves that ventilation plays a key role in the disc as it provides good high temperature thermal resistance. He carried out static structural analysis on a composite disc and analysed its performance by comparing it with that of a standard steel disc. The deformation of composite structure was found to be considerably less than steel [10]. C. Radhakrishnan, Yokeswaran, Naveen Kumar, et al. focused on use of Titanium alloy 550 for the brake disc due to its thermal stability, high strength and forgeable qualities. They concluded that the deformation of Titanium alloy 550 was very less compared to cast iron and stresses induced in Titanium alloy 550 were six times less than that of grey cast iron [11]. Shinde, Sagar, & Baskar worked on enhancing the cooling performance of disc brake by varying the cut patterns on the disc. They concluded that elliptical type disc has better heat transfer than circular ones. However, the strength to withstand the braking force was more in case of circular type [12]. Huang & Chen calculated heat transfer coefficient of disc brake surface and its effect on design parameters. Using Reynold's equation, they calculated heat transfer coefficient and amount of flux generated. After tabulating the results of heat transfer coefficients depending on operating speeds and temperature, it was observed that temperature distribution patterns were different for different models. They concluded that the model can be used as a design tool for designing brake discs [13].

Radhika worked on circular and oval hole profiles and proved that oval/elliptical holes not only provide better heat transfer but also lesser deformation as significantly lesser stresses are induced [14]. Amit and Sachin further worked with similar hole profiles and showed the effect of spacing between the cut patterns on thermal characteristics of the rotor. They were also able to show that oval cut patterns perform better [15].
3. Experimental Details

3.1 Material Selection
Based on literature review, it was decided that three models would be prepared based on a single design. The following are the materials selected:

- Model 1 – Magnesium Alloy
- Model 2 – Aluminum Alloy
- Model 3 – Cast Iron + Aluminum Alloy + Silicon Carbide Single Crystal

Carbon Ceramic was selected for brake pads, which was common across all the three models. Aluminum alloy has been widely used due to its less affinity towards galling, lower production costs and superior thermal characteristics compared to conventional materials. Magnesium alloy is commonly used in the casting of automotive parts. These are among the lightest alloys and aluminum alloy also happens to have a significantly better performance index when compared to titanium alloy at a relatively lower cost. Further, to try to improve structural characteristics, a combination of cast iron at the center of the disc due to less stresses induced in the region, aluminum for majority of the contact patch with the brake pads and silicon carbide tips with high strength and thermal conductivity was considered.

3.2 Material Properties

| Property                        | Units | Carbon Ceramics |
|--------------------------------|-------|----------------|
| Density                        | Kg/m³ | 1600           |
| Elastic Modulus                | Pa    | 7e+10          |
| Poisson’s Ratio                |       | 0.1            |
| Ultimate Compressive Strength  | Pa    | 1.9e+8         |
| Maximum Temperature Use        | °C    | 1750           |
| Thermal Conductivity           | W/mK  | 8              |
| Specific Heat                  | J/gK  | 1.123          |

| Property                        | Units | Al Alloy | Mg Alloy | Cast Iron | SiC |
|--------------------------------|-------|----------|----------|-----------|-----|
| Density                        | Kg/m³ | 2770     | 1800     | 7200      | 3200|
| Elastic Modulus                | Pa    | 7.1e+10  | 4.5e+10  | 1.1e+11   | 7e+11|
| Yield Strength                 | Pa    | 2.8e+8   | 1.93e+8  | --        | 2.1e+10|
| Poisson’s Ratio                |       | 0.33     | 0.35     | 0.28      | 0.192|
| Thermal Conductivity           | W/mK  | 171      | 156      | 52        | 350 |
| Specific Heat (Cp)             | J/KgK | 875      | 1024     | 447       | 1090|

Carbon ceramics possess high thermal resistance as well as strength-weight ratio. They produce significantly less noise during braking and due to their composition wear rate is lower than that of conventional pad materials. One of the most important reasons behind this is the ideal operating temperature of the carbon ceramics, which is much higher compared to the that of conventional brake pad materials. The ability to maintain their functionality at high temperatures is their biggest advantage. In high-performance vehicles, as much as six tons of actuating force is generally required to stop the vehicles which produces a lot of heat, over 800°C, whereas the boiling point for brake fluid is between 600 to 750°F. However, the carbon ceramic brakes can diffuse the heat before it affects the brake fluid. Repeated heavy braking at high speeds is easily achieved for longer. On the other hand, there is also
less brake dust accumulation from carbon ceramic brakes. Carbon ceramic brake pads are durable and do not wear out as fast as the regular brake pads in comparable driving conditions.

3.3 Calculations

Given: Based on a standard 200-250cc motorcycle
Mass of the vehicle (M): 230 kg
Speed of the vehicle (u): 27.77 m/s
Pad Area (A): 5021.16 mm²
Radius of the disc (R): 140 mm
Braking Time (T): 5 sec

Now, let us consider the extreme condition of hard braking, wherein the vehicle is supposed to be stopped within a distance of 22m from a speed of 100km/hr to 0 km/hr.

According to Newton’s law of motion,

\[ v^2 = u^2 + 2as \]

Therefore, we get,

\[ a = 17.526 \text{ m/s}^2 \]

Calculation of Braking force,
In two wheelers, 70% of the weight acts on the front-end during braking, hence we have,

\[ F_b = 0.7 \times M \times a \]
\[ F_b = 2821.79 \text{ N} \]

Calculation of Brake Torque,
\[ T_b = F_b \times R \]
\[ T_b = 397.31 \text{ N-m} \]

Calculation of Pad Pressure,
\[ P_b = \frac{Brake \ force}{Pad \ Area} \]
\[ P_b = 0.5619 \text{ Mpa} \]

| Specifications                  | Units | Values  |
|--------------------------------|-------|---------|
| Outer diameter of disc         | mm    | 280     |
| Inner diameter of disc         | mm    | 100     |
| Thickness of disc              | mm    | 3       |
| Thickness of pad               | mm    | 6       |
| No. of clamp holes             | –     | 6       |
| Pad area                       | mm²   | 5021.16 |
| Weight of the vehicle          | kg    | 230     |
| Speed of the vehicle           | km/h  | 100     |
| Stopping distance              | m     | 22      |

The dimensions in the table above are similar to those found on 200-250cc bikes in the market.

3.4 Finite Element Analysis
The steps followed to conduct the finite element analysis of the disc brake were:
- Modelling the geometry
- Meshing
- Applying the boundary conditions
- Evaluating results
Geometry
As mentioned earlier, Solidworks was used to design the disc brake setup as per dimensions in table 3. Three different models were considered with different materials but the same design. As oval cut patterns have been proven to be better than circular, a disc was designed with oval cuts of gradually increasing area in the contact region of the disc and pads. The disc and two pads were assembled and saved as three separate models in iges format, namely model 1, model 2 and model 3.

![Figure 3. Disc Brake CAD model (Solidworks)](image)

![Figure 4. Model 1 CAD](image)

![Figure 4. Model 2 CAD](image)

![Figure 3. Model 3 CAD](image)

The three models were imported to ANSYS 19.2 and material properties were assigned as shown above.

Meshing
Meshing is the most important step in FEA as it decides numerical convergence to the solution. Finer meshing offers more accurate results. In this research, fine meshing was done using triangulated surface mesher with a minimum element size of 4 mm.

| Table 4. Mesh Details |
|-------------------------------------------------|
| Model 1 | Model 2 | Model 3 |
| No. of elements | 73703 | 72481 | 87189 |
| No. of nodes | 141730 | 139655 | 229368 |

Boundary Conditions
To conduct the structural analysis, disc was fixed at the six hub mounting points and at calliper. Moment was then applied on the disc about the axis in a plane perpendicular to the plane of disc. Calculated pad pressure was applied on both the brake disc pads. Geometry for the structural analysis with boundary conditions is as shown in figure.
This simulates the real-world scenario wherein the brake disc is rotating with the wheel it is connected to at the wheel hub and the callipers being actuated as the driver slams the brakes, resulting in pad pressure being applied on the spinning disc.

**Structural Analysis**

As moment is provided about the hub mounting points of the brake disc and clamping forces are generated at the contact patch between the disc and the pads, the region in contact is held firmly by pads whereas the outer region i.e. the region diametrically opposite to that of contact tends to follow the rotation of disc thereby resulting in greater deformation at the periphery, whatever be the material selected, as shown below. The results in case of aluminium alloy as well as magnesium show minimal deformation for a large chunk of the disc around its centre. Based on this understanding, model 3 has been conceptualized. Cast iron has been used at the central region where stresses are minimal to help cut costs. Aluminium alloy was retained for majority of the contact region. Silicon carbide single crystal was chosen for the tips at the periphery to enhance both structural and thermal characteristics which is

**Figure 6. Model 1 Mesh**

**Figure 8. Model 2 Mesh**

**Figure 5 Model 3 Mesh**

**Figure 10. Model 1 Boundary Conditions**

**Figure 11. Model 2 Boundary Conditions**

**Figure 12. Model 3 Boundary Conditions**
undoubted due to its high thermal conductivity, while balancing the possible increase in cost by using cast iron around the hub region. Fig. 15 shows the deformation of model 3.

4. Results and Discussions

|                   | Unit | Model 1     | Model 2     | Model 3     |
|-------------------|------|-------------|-------------|-------------|
| Maximum Deformation | mm   | 0.040908    | 0.063906    | 0.030057    |
| Minimum Deformation | mm   | 0           | 0           | 0           |
| Average Deformation | mm   | 0.014645    | 0.023531    | 0.0095401   |

As earlier researches have shown, aluminium alloy undergoes lesser deformation than magnesium alloy. The newly conceptualized model 3 performs even better as it has the least deformation compared to the other two models. When compared to [16] from which the disc and pad parameters as well as material properties have been obtained, the design approach of using gradually increasing area of oval holes seems to have paid off well.

5. Conclusions

Model 1 and 2 that have been replicated in terms of materials previously worked with have shown results that are in line with the researches carried out earlier. In terms of cut patterns, the oval hole approach also performs similar to what has been shown earlier. The gradually increasing area of the slots on the contact region could aid heat dissipation. Model 3 which consists of a combination of three materials and performed better than model 1 and 2 structurally, appears to a very promising concept.
that could perform better than the other 2 thermally. This will be explored next in an extensive thermal analysis carried out using the same parameters.

References

[1] V. Chengal Reddy, M. Gunasekhar Reddy, Dr. G. Harinath Gowd, Modeling and Analysis of FSAE Car Disc Brake Using FEM, ISSN 2250-2459, 3(9), September 2013.
[2] Praveena S, Lava Kumar M, Sreekanth Reddy S, Modeling and Structural Analysis of Disc Brake, ISSN: 2319-8753, 3(10) October 2014.
[3] Jung, S. P., Park, T. W., Kim, Y. G., A study on thermal analysis and shape optimization of a ventilated disc, International Journal of Precision Engineering and Manufacturing 13 (1), 57-63, 2012
[4] S. Lee and T. Yeo, Temperature and coning analysis of brake rotor using an axisymmetric finite element technique, Proc. 4th Korea-Russia Int. Symp. on Science & Technology, Vol.3, pp.17-22, 2000.
[5] G. Ranjith Kumar, S. Thriveni, M. Rajasekhar Reddy, Dr. G. Harinath Gowd, Design Analysis & Optimization of an Automotive Disc Brake, International Journal of Advanced Engineering Research and Science.
[6] Haider Hussain and Dr. A.I. Khandawawala. Application of Transient Thermal Analysis For Three Feeder Design Optimization For Sand Casting, International Journal of Mechanical Engineering and Technology, 4(6), 2013, pp. 241-248.
[7] P. Dufr´enoy and D. Weichert. A thermomechanical model for the analysis of disc brake fracture mechanisms. Journal of Thermal Stresses, 26(8):815–828, 2003.
[8] S. Panier, P. Dufr´enoy, and D. Weichert. An experimental investigation of hot spots in railway disc brakes. Wear, 256(7-8):764–773, 2004.
[9] T.K. Kao, J. W. Richmond, and A. Douarre. Brake disc hot spotting and thermal judder: an experimental and finite element study. International Journal of Vehicle Design, 23(3):276–296, 2000.
[10] Belhocine, A., & Bouchetara, M. (2012). Thermal analysis of a solid brake disc. Applied Thermal Engineering, 32, 59-67.
[11] Radhakrishnan, C, Yokeswaran, K., Vengadeshprasadh, M., Vishnuhasan, A., Vimalraj, T., & Velusamy, M. (2015). Design and analysis of disc brake with titanium alloy. International Journal of Innovative Science, Engineering & Technology, 2(5), 1044-1050.
[12] Shinde, V. V., Sagar, C. D., & Baskar, P. (2014). Thermal and structural analysis of disc brake for different cut patterns. International Journal of Engineering Trends and Technology, 11(2), 84-87.
[13] Huang, Y. M., & Chen, S. H. (2006). Analytical study of design parameters on cooling performance of a brake disk (No. 2006-01-0692). SAE Technical Paper.
[14] Radhika S, Sathiyamurthy S (2017) Analysis of structural and thermal characteristics of disc brake with circular/oval shaped holes for two wheeler. IEI 6:20–27
[15] Amit M. Patil, Sachin S. Kudte Springer Nature Switzerland AG 2020 P. M. Pawar et al. (eds.), Techno-Societial 2018.
[16] Chetan Babasaheb et al. Static structural and thermal analysis of brake disc with different cut patterns. J. appl. res. technol, México, v. 16, n. 1, p. 41-52, 2018.