Review on Thermal Analysis of Disc Brake

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Abstract

An automotive disc brake is a device which creates resistance to the motion of wheel under running conditions. The basic function of disc brake is to stop or slow down the motion of wheel by applying frictional force through calliper assembly. During this process kinetic energy converts in heat energy and dissipate into surrounding atmosphere. The conversion of energy results in speed retardation, and brings the vehicle in steady state. The heat dissipation properties during actuation have significant impact on the brake performance. During operation the high stresses are built up, results in wear and fading. The performance parameters can be improved by considering thermal characteristics of disc brake materials. The objective of this study is to investigate, under extreme working conditions, the thermochemical behaviour of different brake rotors in order to evaluate their efficiency and stability, also to identify any compromising weakness on them. In this paper the investigation is done by considering different material used for brake disc manufacturing and the thermal behaviour of the same in loading condition analysis of different shapes with different material of disc rotor.

Keywords: Analysis, brake, disc, heat, thermal

I. INTRODUCTION

The disc brake is a wheel brake which slows rotation of the wheel by the friction caused by pushing brake pads against a brake disc with a set of calliper. The brake disc is usually made of cast iron, but may in same cases made of composites such as reinforced carbon-carbon or ceramic matrix composites. This is connected to the wheel and/or the axle. To stop the wheel, friction material in the form of brake pads, mounted on a device called a brake a calliper, is forced mechanically, hydraulically, pneumatically or electromagnetically against both sides of disc. Friction causes the disc attached to the wheel to stop or slow down.

Disc-style brakes development and use begin in England in 1890. The first calliper type automobile disc brake was patented by Frederick William Lanchester in his Birmingham, U.K factory in 1902 and used successfully on Lancheester cars. A disc brake consists of cast iron disc bolted to the wheel hub and the stationary housing called calliper [1].

Generally, the amount of heat is a time related function depending on thermal characteristics of the parts enabling friction contact, as well as their size, shape, activation pressure and sliding speed. The temperature on friction surface of automotive brake can reach very high value. High temperature during braking moreover could cause the brake fade, which means losing both efficiency and safety during stopping process. High thermal loads, in fact, can determine considerable distortion of the brake rotor. The brake factor values differ significantly depending on the variation of brake interface temperature, which is quiet uniform under the same initial brake temperature. This means that, depending on initial brake temperature deceleration and braking time significantly differ from one braking application to another [7]. Taking into consideration that initial brake rotational speed and control line pressure take predetermined and well-known values of the contact surface enables estimating the coefficient of friction in automotive brake. Having the knowledge of the main influencing factors at the initiation of braking process and also during braking process, enables the prediction of output brake parameters. Consequently it is vital to have knowledge about the temperature on the contact surface of the disc and the brake pad throughout the braking application [7].

The disc brake is usually made of cast iron. To reduce automobile weight and improve fuel efficiency and also reduce the heat dissipation rate of brake disc, the automotive industry has dramatically increased the use of aluminium in light vehicles in recent years. Aluminium alloy based metal matrix composites (MMC’s) with ceramic particulate reinforcement have shown great
promise for such applications. These materials having lower density and higher thermal conductivity as compared to the conventionally used cast iron [6].

For all these reasons, increasing the thermal efficiency and the integrity of brake component has become an essential objective in modern automotive engineering field. With this aim innovative rotors must be designed to improve the convection mechanism of disc brake.

In present work the aim is to take the review of temperature distribution phenomena of disc rotor under baking condition, also the solution which should be efficient than the existing model of brake disc rotor. The structural optimization technique will be used to optimize the disc brake rotor and then validate it in thermal analysis. The outer diameter and inner mounting position of holes on wheel hub is considered as constraint for design. The effect of increasing surface area on the heat dissipation will be analysed [8].

The objective is to design a disc brake using Solidworks 15.0 and carry out the finite element analysis (FEA) on the prepared model using ANSYS 14.5. Thus we obtained the value of heat generated, total heat flux, convective heat transfer coefficient and the temperature distribution on disc brake.

II. BRAKING SYSTEM

A brake is a device by means of which artificial frictional resistance is applied to moving machine member, in order to stop the motion of a machine. In the process of performing this function, the brakes absorb either kinetic energy of the moving member or the potential energy given up by objects being lowered by hoists, elevators etc. The energy absorbed by brakes is dissipated in the form of heat. This heat is dissipated in to the surrounding atmosphere to stop the vehicle, so the brake system should have the following requirements:
- The brakes must be strong enough to stop the vehicle with in a minimum Distance in an emergency.
- The driver must have proper control over the vehicle during braking and the vehicle must not skid.
- The brakes must have good anti fade characteristics i.e. their effectiveness should not decrease with constant prolonged application
- The brakes should have good anti-wear properties.

Based on mode of operation brakes are classified as follows:
1) Hydraulic brakes.
2) Electric brakes.
3) Mechanical brakes.

The mechanical brakes according to the direction of acting force may be sub divided into the following two groups:
1) Radial brakes:
In these brakes the force acting on the brake drum is in radial direction. The radial brake may be subdivided into external brakes and internal brakes.
2) Axial brakes:
In these brakes the force acting on the brake drum is only in the axial direction. E.g. Disc brakes, Cone brakes.

A. Disc brake

A disc brake consists of a cast iron disc bolted to the wheel hub and a stationary housing called calliper. The calliper is connected to some stationary part of the vehicle, like the axle casing or the stub axle and is cast in two parts, each part containing a piston. In between each piston and the disc, there is a friction pad held in position by retaining pins, spring plates etc. passages are drilled in the calliper for the fluid to enter in housing.

To stop the rotation of wheel, friction material in the form of brake pad, mounted inside the calliper is forced mechanically, hydraulically, pneumatically or electromagnetically. Friction between the brake pads and disc causes the attached wheel to slowdown or stop. Compared to drum brake, more stopping performance is achieved by the disc brake, as discs are more prone to the brake fade and disc brake recover more quickly from immersion. Most drum brake design have at least one leading shoe, which gives a servo effect. By contrast the disc brake has no self-servo effect and its braking force is always proportional to the pressure placed on the brake pad by the braking system via any brake servo, braking pedal or lever, this tends to give the driver better “feel” to avoid impending lockup.

III. MATERIALS OF DISC ROTOR

The authors M. A. Maleque, S Dyuti and M.M. Rahman has worked on collecting data which of different materials which can be used in manufacturing of disc rotor. While finding these materials they came across two methods for selection of materials which are cost per unit method and digital logic method [6].

In automobiles, nowadays most of the disc brakes are made of grey cast iron and steel combined with composite brake pads, which are sufficient for use in braking system which doesn’t require that much braking torque. But currently the industry is solely focused on improvising braking power with increase in competition for high-end vehicles. In addition, by considering history and current scenario of on-highway vehicles and aircraft have motivated designers for weight reduction, long lasting...
service and better efficiency of braking system. By taking the above discussed factors in consideration the implementation of lightweight materials with high friction coefficient (i.e. aluminium and carbon composites) will be innovation factor in braking system, which are used in aircraft and formula one racing cars. These materials should have properties like abrasion resistance, corrosion resistance, light in weight and enough strength. Above mentioned properties can be fulfilled by composite materials [2].

Cast Iron: Traditional material for automotive brake rotor is the cast iron. The specific gravity or density of cast iron is higher which consumes much fuel due to high inertia. Metallic iron containing more than 2% dissolved carbon within its matrix but less than 4.5% is referred to as grey cast iron because of its characteristic colour. Considering its cost, relative ease of manufacture and thermal stability, this cast iron is actually a more specialized material for brake applications [6].

Titanium alloys: Titanium alloy and their composites have the potential to reduce weight of the brake rotor disc component which is about 37% less than a conventional cast iron with the same dimensions and offering good high temperature strength and better resistance to corrosion [6].

Aluminium-Metal Matrix Composite (AMC): Aluminium alloy based metal matrix composites (MMCs) with ceramics particulate reinforcement have shown great promise for brake rotor applications. These materials having a lower density and higher thermal conductivity as compared to conventionally used grey cast irons are expected to result in weight reduction of about 50-60% in brake system. The friction properties of AMC brake disc are thus remarkable poorer than those of conventional brake disc. After increasing hard particles content the result showed that the repeated braking operation did not lower the friction coefficient. Three major problems exist with this aluminium matrix rotor. First, because of density difference between aluminium and SiC, segregation or inhomogeneous distribution of SiC particles during solidification cannot be avoided. This ultimately effects on the convective heat transfer coefficient of material. Also, adding SiC particles in aluminium matrix dramatically reduces the ductility of material, resulting in low product liabilities.

Based on properties, potential candidate materials for automotive brake disc were selected as:
1) Grey cast iron (GCI)
2) Ti-Alloy
3) Ti composite (TMC)
4) 20% SiC reinforced Al-Composites (AMC 1)
5) 20% SiC reinforced Al-Cu alloy (AMC 2)

<table>
<thead>
<tr>
<th>Properties</th>
<th>Compressive Strength (Mpa)</th>
<th>Friction Coefficient µ</th>
<th>Wear rate ((\times 10^{-6} \text{ mm}/\text{N/m}))</th>
<th>Specific heat (C_p) (KJ/Kg.k)</th>
<th>Specific gravity ((Mg/m^3))</th>
</tr>
</thead>
<tbody>
<tr>
<td>GCI</td>
<td>1293</td>
<td>0.41</td>
<td>2.36</td>
<td>0.46</td>
<td>7.2</td>
</tr>
<tr>
<td>Ti-6AI-4V</td>
<td>1070</td>
<td>0.34</td>
<td>246.3</td>
<td>0.58</td>
<td>4.42</td>
</tr>
<tr>
<td>TMC</td>
<td>1300</td>
<td>0.31</td>
<td>8.19</td>
<td>0.51</td>
<td>4.68</td>
</tr>
<tr>
<td>AMC 1</td>
<td>406</td>
<td>0.35</td>
<td>3.25</td>
<td>0.98</td>
<td>2.7</td>
</tr>
<tr>
<td>AMC 2</td>
<td>761</td>
<td>0.44</td>
<td>2.91</td>
<td>0.92</td>
<td>2.8</td>
</tr>
</tbody>
</table>

**IV. MATERIAL ANALYSIS**

![Fig. 1: coefficient of friction of different materials.](image)
V. THERMAL TRANSMISSIBILITY

If you are using Word, use either the Microsoft Equation Editor or the MathType add-on (http://www.mathtype.com) for equations in your paper (Insert | Object | Create New | Microsoft Equation or MathType Heat transfer is the energy interaction due to temperature difference in medium or between the medium. When system is at different temperature then its surrounding environment tries to reach thermal equilibrium. To do so heat transfer utilizes first and second law of thermodynamic, which explains heat is not a storable quantity and is always transfers from the system of higher temperature to the system of lower temperature.

This transfer of heat takes place in basically three modes: conduction, convection and radiation.

Conduction: Heat conduction is essential transmission of energy by molecular motion. When one part of body is at higher temperature than other, energy transfer takes place from high temperature region to low temp region. In such case the energy is said to be transferred by conduction[9].

The rate equation for conduction is given by fourier’s law of heat conduction. For heat conduction in x-direction, normal to area (A), assuming that the material is isotropic and homogeneous, the rate of heat flow (q) is described by

\[ q = -kA \frac{\partial T}{\partial x} \]

As the disc is circular in shape heat transfer takes place in cylindrical coordinates. Hence the Fourier’s equation of conduction is

\[ q = -kA \frac{\partial T}{\partial r} \]

Where q is the heat flux perpendicular to a surface of area A, [W]; A is the surface area through which the heat flow occurs, [m²]; k is the thermal conductivity, [W/(m·K)]; T is the temperature, [K] or [°C]; and r is the radius of disc.[9]

Convection: Convection is a process by which thermal energy is transferred between a solid and fluid flowing past it. Strictly speaking, convection is not a separate mode of heat transfer. It denotes a fluid system in motion and heat transfer occurred by mechanism of conduction alone.

The rate equation used to describe the mechanism of convection is called Newton’s law of cooling.

\[ q = -hA(T_\infty - T_1) \]

Where h is the convective heat transfer coefficient [W/m²·K]; \( T_\infty \) is the temperature of the ambient air; and \( T_1 \) is the temperature of the surface of the body[9].

Radiation: radiation is a mode of heat transfer which is distinctly different from conduction, convection. Whereas a material medium id must for conduction and convection, heat may also be transferred through perfect vacuum.

\[ q = \varepsilon \sigma A(T_1^4 - T_2^4) \]

Where \( \varepsilon \) is the coefficient of emissivity =1 (for ideal radiator); \( \sigma \) is the Stefan-Boltzmann constant of proportionality (5.669E-8 [W/m²·K⁴]); \( A \) is the radiating surface area; \( T_1 \) is the temperature of the radiator; and \( T_2 \) is the temperature of the surroundings [9].

VI. METHOD OF ANALYSIS

The authors Mr. Pravin N. Jawarikar and Dr. Subim N. Khan have made suitable assumptions and numerical calculations of disc brake rotor of Bajaj 220. The CAD model is prepared in Creo 2.0. And CAE Analysis is done in Ansys 14.5. For efficient models, thermal analysis is done to determine the stress and deformation. The results are then compared with existing models and other samples [8].

Aleksander Grkic and Davorin Mikluc have studied temperature measurement techniques and mathematical models for prediction of contact surfaces temperature. It is very difficult to measure and predict the values and characters of temperature changes in the brake. Due to physics of friction process, temperature measurements on the contact surface are practically impossible. Apart from that, automotive brakes work in different operating conditions, which are reflected in the appearance of wear, the presence of water, corrosion and so on. Through this task, it is possible to apply several different temperature non-contact measurement methods such as optical and infrared methods, and contact type methods, as well as temperature measurement using thermocouple or different temperature sensitive materials. According to the most effective ways of determining the temperature on the contact surface of disc and brake pads in the vehicle during braking is by applying thermocouples. In contrast, a number of authors used different mathematical methods to describe and present temperature in the contact zone of the friction pair and the behaviour of the temperature field in the braking process, as well as their impact on wear and brake performance. In recent years, the application of artificial intelligence (AI) methods (such as neural networks) has become a particularly interesting as a tool for predicting temperature in automotive brakes [7].

The following calculations are taken from theory based input parameters of two wheeler disc brake rotor, done by Mr. Pravin N. Jawarikar and Dr. Subim N. Khan [8].

A. Input Parameter for standard disc brake of Bajaj Pulsar 220 cc;

- Rotor disc dimension = 230 mm
- Rotor disc material = SUS M 410
- Pad brake area = 1692 × 10^{-6} m^2
- Pad brake material = Asbestos
- Permissible temperature = 250°C
- Maximum pressure = 1×10^6 Pa
- Vehicle speed = 27.77 m/s
- Mass of vehicle = 150 Kg

**B. Calculation**

Tangential force between pad and rotor on inner face (Ft1)

\[ Ft1 = \mu_1 \times Fn1 \]
\[ \mu_1 = 0.4 \]
\[ Fn1 = P_{max} \times A_p \]
\[ Ft1 = \mu_1 \times Fn1 \]
\[ Ft1 = (0.4)(1 \times 10^6)(1692 \times 10^{-6}) \]
\[ Ft1 = 338.4 \text{ N} \]

Tangential force between pad and rotor on outer face (Ft2)

In this case Ft2 = Ft1 because same normal force and same material

Brake torque (Tb)

With the assumption of equal coefficients of friction and normal forces Fr on the inner and outer faces:

\[ Tb = Ft \times R \]

Where

Tb = Brake torque
\[ \mu = \text{coefficient of friction} \]
Ft = Ft1 + Ft2
\[ Ft = 338.4 + 338.4 \]
\[ = 676.8 \text{ N} \]
\[ Tb = 676.8 \times 115 \times 10^{-3} \]
\[ Tb = 77.78 \text{ Nm} \]

Stopping distance

\[ FT \times x = \frac{m v^2}{2} \]
\[ x = \frac{57837.96}{77.78} \]
\[ x = 85.45 \text{ m} \]

As per the Indian traffic regulations

The stopping distance after application of brake for two wheelers is given as
\[ S \leq 0.1 V + 0.011 V^2 \]
\[ S \leq 0.1 \times 100 + 0.0087 \times 100^2 \]
\[ S \leq 97 \text{ m} \]

Heat Generated (Q) = M \cdot C_p \cdot \Delta T \ J/S

Mass of disc = 1.5 kg
Specific Heat Capacity = 460 J/kg \cdot 0 \text{ c}
Time taken Stopping the Vehicle = 8 sec
Developed Temperature difference = 70 °C

\[ Q = 1.5 \times 460 \times 70 = 48300 \text{ J} \]

Area of Disc = Π \times (D^2 - d^2)
\[ = 0.04 \text{ m}^2 \]

Heat Flux = Heat Generated /Second /area
\[ = \frac{48300}{8 / 0.04} \]
\[ = 150.93 \text{ kw/m}^2 \]

Convective film coefficient (h) = \[ \frac{0.037 \times k}{1} \times (\rho l v / \mu)^{0.8} \times (C_p \mu / k)^{0.33} \]
\[ = 28584.48 \]
VII. FE A ANALYSIS

Fig. 2: Temperature Distribution under Thermal Loading

Fig. 3: Total Heat Flux

VIII. FUTURE SCOPES

As previously stated, temperature measurement in the friction surfaces of a brake is a difficult task. This is due to numerous influencing factors specific to rubbing surfaces such as those in friction brakes, especially since it is necessary to provide temperature measurement with an appropriate accuracy and minimum delay.

When comparing all the available techniques of temperature measurement, the method using thermocouples shows significant advantages over others; they are very effective for measuring the temperature in contact of the friction pair. In this case, a so-called “hot end” or hot junction is located very close to the friction surface.
REFERENCES


