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DESIGN AND THERMAL ANALYSIS OF BRAKE ROTOR WITH DIFFERENT MATERIALS

***Sugunarani S and Santhosh V**

Department of Mechanical Engineering, A. C. Government College of Engineering and Technology, Karaikudi, Tamil Nadu- 630004, India

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ABSTRACT

This work deals with the analysis of heat generation and dissipation in the disc brake of a car during braking and the following release period by using computer-aided engineering software for three different materials of the rotor disc and brake pad. The objective of this work is to analyze the temperature distribution of rotor disc during operation using COMSOL Multiphysics. The work uses the finite element analysis techniques to calculate and predict the temperature distribution on the brake disc and to identify the critical temperature of the brake rotor disc. Conduction, convection and radiation of heat transfer have been analyzed. The results obtained from the analysis indicates that different material on the same retardation of the car during braking shows different temperature distribution. A comparative study was made between grey cast iron (GCI), Aluminium Metal Matrix Composite (AMMC), Alloy steel materials are used for brake disc and the best material for making brake disc based on the rate of heat dissipation have been suggested.

Keywords: *Disc Brake, Brake pad, FEA and COMSOL Multiphysics*

1. Introduction

Brake system is one of the most important control systems in an automobile. They are required to stop the vehicle within the smallest possible distance and it is done by converting the kinetic energy of the vehicle into heat energy by friction which is dissipated into the atmosphere[1]. The main necessities of brakes are: The brakes must be strong enough to stop the vehicle within the smallest possible distance in an emergency. But, this should also be reliable with safety. The driver must have proper control over the vehicle during emergency braking and the vehicle must not slip. The brakes must have good anti weaken characteristics and their effectiveness should not decrease with the constant elongated application[2].

The heat generation and dissipation in a disc brake of an ordinary car during panic braking and the following release period. As the brakes slow the car, they transform its kinetic energy into thermal energy or heat energy, resulting in intense heating of the brake disc[3]. If the discs overheat, the brake pads stop working and, in a worst-case scenario, can melt. The thermal behavior of the full and ventilated brake discs of the vehicles using computing code ANSYS it was seen that during the braking phase, the frictional heat generated at the interface of the disc and pads can lead to high temperatures[4]. The governing heat equations for the disc and the pad are extracted in the form of transient heat equations with heat generation that is dependent on time and space. In the derivation of the heat equations, parameters such as the duration of braking, vehicle velocity, geometries, and the dimensions of the brake components, materials of the disc brake rotor and the pad and contact pressure distribution were taken into account[5]. The heat generation and dissipation in a disc brake during braking and the following release period. The surface changes induced by repeated brake applications and tried to provide explanations for how such material modifications might affect friction and wear properties of automotive disc brakes[6]. The wear data analysis of friction composites were the nature and the concentration of the abrasives were varied systematically in steps of 2%. The abrasives selected were Sic, SiO_2, ZrO_2, and Al_2O_3 in the concentration range of 2–6%. The modelled transient analysis of the thermo elastic contact problem for disc brakes of different types using the finite element analysis (FEA) method. This was done by investigating the influence of material properties of the discs on their thermo-elastic behavior[7]. It was found out that their proposed numerical model showed a much-closed fit with experimental results found in the literature. The comparison of two brake pad materials in a disc brake during and after braking action. It was established after from their findings that aramid as brake pad material was a good substitute for asbestos which was reportedly releasing toxic dust to the environment[8].

**Corresponding Author - E- mail: sugunamech@gmail.com*

The long repetitive braking performance of AMC composite and aramid as the brake disc and pad materials, respectively, were studied using COMSOL Multiphysics 5.1 finite element software [9].

2. Theoretical Background

Frictional heat generated on the surfaces of the brake disc and brake pads during braking action is as a result of the thermal energy converted from the kinetic and potential energies of a moving vehicle, neglecting drag and other losses outside the brakes, and no skidding of the car tyres on the road surface[10].

The kinetic energy of the vehicle in motion can be expressed as:

$$E = \frac{1}{2} m(v_1^2 - v_2^2) \quad (1)$$

The brakes retardation power is given by the negative of the time derivative of the car's kinetic energy (COMSOL multiphysics 5.1 software material library)[11].

$$P = -\frac{d}{dt}\left(\frac{mv^2}{2}\right) = -mv\left(\frac{dv}{dt}\right) = -mR^2\omega(t)\alpha \quad (2)$$

Where *m* is vehicle mass, *R* is wheel radius, ω is the angular velocity, and α is the angular Acceleration. and the acceleration is constant in this case so

$$\omega(t) = \omega_0(t) + \alpha t \quad (3)$$

The friction force per unit area, f_f is approximately constant over the surface area of eight

Pads (two pads per brake disc) and is directed opposite the brake disc velocity vector[12].

$$P = -8\iint f_f \, dA . v_d = -8 \, f_f(t)\omega(t)\iint r dA \quad (4)$$

Using the previous two equations, the frictional force can be determined as

$$f_f = -\frac{mR^2\alpha}{8r_m A} \quad (5)$$

Where r_m is the distance between the centre of the brake disc and the pad centre of mass,

And α is negative acceleration during retardation.

The heat power generated in the contact area can be defined as

$$q(r,t) = -f_f . V_d(r,t) = -\frac{mR^2\alpha}{8r_m Ar(\omega_0 + \alpha t)} \quad (6)$$

The heat dissipation from the brake disc and pad surfaces to the surrounding air is described

By convection and radiation as[13]:

$$q_{diss} = -h\left(T - T_{ref}\right) - \varepsilon\sigma\left(T^4 - T_{ref}^4\right) \quad (7)$$

Where *h* is the convective film coefficient, ε is the material emissivity, and σ is the Stefan-Boltzmann constant.

To calculate the convective film coefficient as a function of the vehicle velocity V, we use the following formula[14]:

$$h = 0.0379\left(\frac{k}{d}\right) Re^{0.8} Pr^{0.33} \quad (8)$$

Temperature rise formula is

$$T_{max} = \frac{0.527.q\sqrt{t}}{\sqrt{\rho.c.k}} + T_{amb} \quad (9)$$

Where:

T_{max} = Maximum disc temperature(˚C)
q = Heat flux(Watts/m^2)
t = Brake on time (s)
ρ = Density of disc material (kg/m^3)
c = Brake disc specific heat capacity(J/kg/K)
k = Brake disc thermal conductivity (W/m/K)
T_{amb} = Ambient temperature(˚C)

3. Modelling and Mesh Generation

Modelling of the complete disc brake is created by using the COMSOL software. The model of brake disc has an Outer disc diameter 0.254m and Disc thickness 0.020m, Disc hub inner diameter 0.054m, Disc hub outer diameter 0.140m.

The mass of the vehicle used for analysis is 1800 kg. The initial velocity is 80 km/hr (22.22m/s), 90 km/h (25m/s) and 100km/hr (27.77m/s). Suddenly, the driver hits the brakes for 2 to 4 seconds, causing the vehicle to retard at a rate of 10 m/s^2, after which the driver releases the brake and the car moves at 5m/s for additional 8 s without any braking[15].

Meshing is done for converting a continuous object into finite no. of parts known as elements. The meshing of the brake disc and pad has been done using COMSOL Multiphysics 5.1. The element used for meshing is of tetrahedral shape. The initial temperature used during the simulation was set as 300K (27 ˚C).

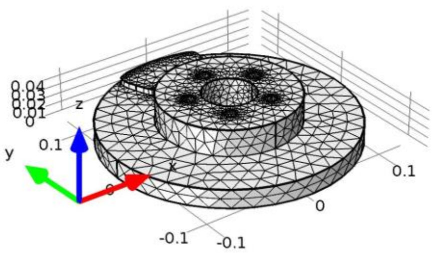

Fig. 1 Meshed model of disk brake

The Material Properties of Brake Disc and Pad are outlined in Table 1

Table 1 Material Properties of Brake Disc and Pad

Properties	Brake disc materials			Brake pad
Materials	CI	AMMC	Alloy steel	Aramid (Kevlar29)
Thermal conductivity (W/mK)	57	167	44.5	0.25
Density (kg/m3)	7250	2700	7850	1440
Emissivity	0.28	0.24	0.7	0.82
Specific heat capacity (J/kg K)	460	980	470	1400
Modulus of elasticity (GPa)	138	110	200	70.5

4. Results and Discussion

The three-dimensional finite element analysis of the temperature of the brake disc during the braking was done using COMSOL Multiphysics 5.1.

Temperature is 300 K at the beginning of the braking process in contact brake disc and pads, for a car travelling at an initial velocity of 22.22 m/s ,25m/s and 27.77m/s and then brakes for 2-4 seconds. The highest temperature occurs at the contact surface of the disc and pads[16].

The strong increase in temperature is due to the short duration of the braking phase and the speed of the physical phenomenon. At the beginning of the braking action, the generated heat due to friction is very high and this frictional heat generated decreases gradually because the relative sliding velocity between the pad and the disk drops with time during the braking action.

A car travelling at a velocity of 25 m/s as the process of continues braking, the temperature rises quickly and reaches a maximum value of 558 K at t=3.8 seconds in Cast iron. Also, with this simulation, we are required to show how the brake disc cools after completing the braking. The temperature distribution now is shown below.

Case 1. Cast iron Disc and aramid pad

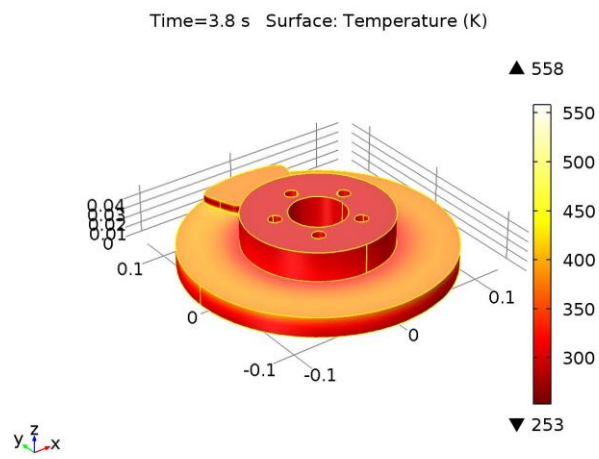

Fig. 2 Temperature distribution for Cast iron and Aramid at t=3.8 seconds and velocity of 25m/s.

Case 2. Aluminium Metal matrix Disc

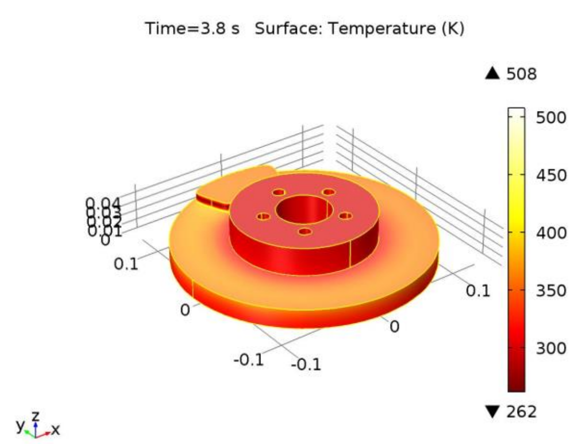

Fig. 3 Temperature distribution for AMMC and Aramid at t=3.8 seconds and velocity of 25m/s.

Case 3. Alloy steel and Aramid

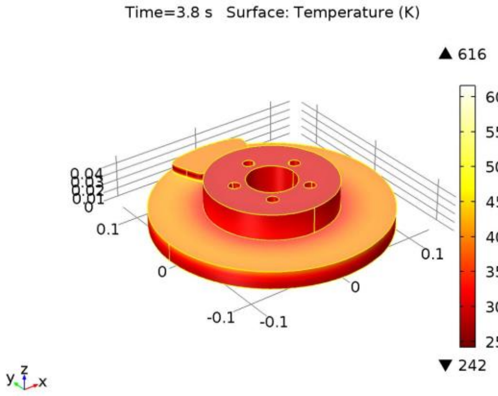

Fig. 4 Temperature distribution for Alloy steel and Aramid at t=3.8 seconds and velocity of 25m/s.

Temperature distribution of Cast iron Brake Disc at the different vehicle, speeds are outlined in Table 2.

Table 2 Temperature distribution of Cast iron Brake Disc

Time(S)	Material Temperature(K) CI at 22.22m/s	CI at 25m/s	CI at 27.77m/s
1	300	300	300
2	317	318	319
3	482	512	540
3.8	512	558	603
4	508	557	603
12	439	468	493

Temperature distribution of AMMC Brake Disc at different vehicle speeds are outlined in Table 3. Temperature distribution of Alloy steel Brake Disc at different vehicle speeds are outlined in Table 4

At t = 3.8 seconds, the temperatures of the 3 models were as follows:

GCI disc and aramid pad were obtained the maximum temperature of 512 K at a velocity of 22.22m/s. the maximum temperature of 558K was obtained at a velocity of 25m/s. the maximum temperature of 603 K was obtained at a velocity of 27.77m/s.

AMMC disc and aramid pad were obtained the maximum temperature of 473 K at a velocity of 22.22m/s. the maximum temperature of 508 K was obtained at a velocity of 25m/s. The maximum temperature of 544 K was obtained at a velocity of 27.77m/s.

Table 3 Temperature distribution of AMMC Brake Disc

Time (S)	Material Temperature(K) AMMC at 22.22m/s	AMMC at 25m/s	AMMC at 27.77m/s
1	300	300	300
2	320	321	322
3	448	470	493
3.8	472	508	544
4	469	507	543
12	414	436	458

Table 4 Temperature distribution of Alloy steel Brake Disc

Time(S)	Materials Temperature(K) Alloy steel at 22.22m/s	Alloy steel at 25m/s	Alloy steel at 27.77m/s
1	300	300	300
2	316	317	318
3	524	560	595
3.8	560	616	672
4	556	614	671
12	469	503	535

Alloy steel disc and aramid pad were obtained the maximum temperature of 560 K at a velocity of 22.22m/s. the maximum temperature of 616 K was obtained at a velocity of 25m/s. The maximum temperature of 672 K was obtained at a velocity of 27.77m/s.

These temperatures occur at the centre of mass-radius of the pad and disc contact surface. The combination of these three materials an Alloy steel brake disc and an aramid brake pad had produced the highest temperature of at the time of 3.8 seconds out of all 3-disc models. The temperature in the disc brake modelling was carried out by taking an account of the effect of the brake disc and brake pad material.

To inspect how much of the generated heat is dissipated to the air, the surface integrals of the produced heat and the dissipated heat have been studied. These integrals provide the total heat flux (J/s) for heat production, Qprod, and heat dissipation, Qdiss, as functions of time for the brake disc. The time integrals of these two quantities give the total heat (J) produced and dissipated, respectively, in the brake disc.

Figure 6 shows the plot of the total produced heat and dissipated heat versus time. We can see that 8 s after disengagement the brake has dissipated only a fraction of the produced heat. The plot indicates that the resting period must be extended significantly to dissipate all the generated heat.

Case 1. Cast iron Disc and aramid pad

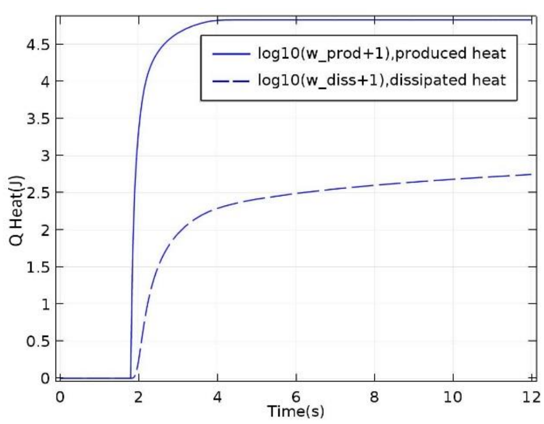

Fig. 6 Comparison of total heat produced (solid line) and dissipated (dashed) in Cast iron.

Case 2. Aluminium Metal matrix Disc

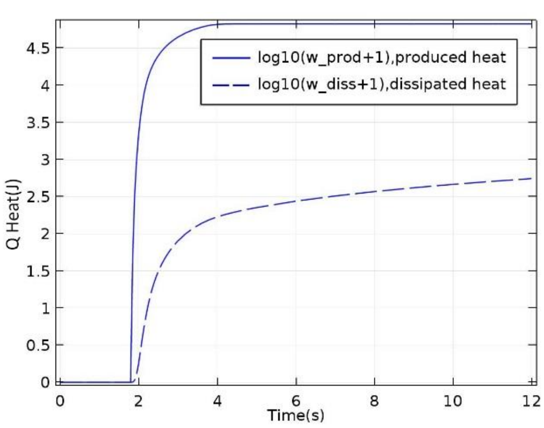

Fig. 7 Comparison of total heat produced (solid line) and dissipated (dashed) in AMMC.

Case 3. Alloy steel and Aramid

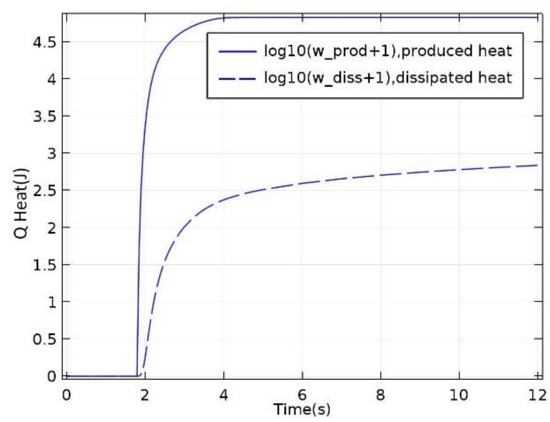

Fig. 8 Comparison of total heat produced (solid line) and dissipated (dashed) in Alloy steel.

In comparison to the three materials at three speeds, cast-iron disc produced the maximum heat dissipation of 73K,90K and 110K at a velocity of 22.22m/s,25m/s and 27.77m/s. AMMC disc produced the maximum heat dissipation of 59K,72K and 86K at a velocity of 22.22m/s,25m/s and 27.77m/s and an Alloy steel disc produced the maximum heat dissipation of 91K,113K and 137K at a velocity of 22.22m/s,25m/s and 27.77m/s. so this three materials cast iron produced a moderate heat dissipation AMMC produced a minimum heat dissipation and Alloy steel produced a maximum heat dissipation.

5. Conclusions

Based on the recent work, it is decided that the different material have different qualities as used for brake disc.

- Compared to the temperature distribution characteristics of these three different materials the cast-iron has produced the maximum temperature which is low as compared to Alloy steel and high as an aluminium metal matrix. But the rate of heat dissipation is good as compare to AMMC.
- Compared to the heat dissipation characteristics of these three different materials alloy steels produced a maximum heat dissipation cast iron produced moderate heat dissipation and AMMC produced minimum heat dissipation

The following conclusions can be made from the results as discussed above. In the case of the aluminium metal matrix composite, it has a lower density, higher thermal conductivity, and less weight as compared to CI and Alloy steel .so it can be applied in lightweight applications. But heat dissipation is low when compared to alloy steel. Alloy steel has produced minimum wear and high strength compared to others and also the rate of heat dissipation is high in the other two materials. So, the alloy steel is a suitable material for disc brake applications.

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