Investigation of Product Performance of Al-Metal Matrix Composites Brake Disc using Finite Element Analysis

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Abstract. The increasing demand of fuel efficiency and light weight components in automobile sectors have led to the development of advanced material parts with improved performance. A specific class of MMCs which has gained a lot of attention due to its potential is aluminium metal matrix composites (Al-MMCs). Product performance investigation of Al-MMCs is presented in this article, where an Al-MMCs brake disc is analyzed using finite element analysis. The objective is to identify the potentiality of replacing the conventional iron brake disc with Al-MMCs brake disc. The simulation results suggested that the MMCs brake disc provided better thermal and mechanical performance as compared to the conventional cast iron brake disc. Although, the Al-MMCs brake disc dissipated higher maximum temperature compared to cast iron brake disc’s maximum temperature. The Al-MMCs brake disc showed a well distributed temperature than the cast iron brake disc. The high temperature developed at the ring of the disc and heat was dissipated in circumferential direction. Moreover, better thermal dissipation and conduction at brake disc rotor surface played a major influence on the stress. As a comparison, the maximum stress and strain of Al-MMCs brake disc was lower than that induced on the cast iron brake disc.

Keywords: Product Performance, Metal Matrix Composites, Brake Disc, Finite Element Analysis.

1. Introduction
Aluminium metal matrix composites (Al-MMCs) have a great potential for several applications in automobile parts. This specific class possesses high wear resistance and high specific mechanical properties, 67% lower density than cast iron and three times the thermal conductivity, thus Al-MMCs are ideal materials for the manufacture of lightweight automotive components [1,2]. Initialization of Al-MMCs application in the automotive industry was in car engines, which utilized reinforced Al-MMCs for pistons in the Toyota diesel engine [3,4]. Experimental studies have been carried out to evaluate the effect of sliding velocity and applied load on the wear characteristics of Al-MMCs [5], which indicated some potential for application in the vehicle braking system.

Automotive braking system is subjected to mechanical and thermal stresses, hence depends on a combination of properties. Thus, it is hard to select a material based only on one of these properties. The material applied in brake disc must bear thermal fatigue, moreover, it should absorb and dissipate...
heat quickly that generated during braking [6]. Although MMCs have been applied for brake disc, the product has not yet been highly produced and used widely for replacement of the existing iron brake disc due to high manufacturing cost for mass production [7]. Therefore, this indicates a potential avenue of further investigation in the field of MMCs and to identify its potential as a replacement for the existing conventional brake disc.

Product performance analysis involves numerical modeling such as finite element analysis (FEA). Soderberg and Andersson [8] discussed how FEA software can be used to analyze the pad-to-disc contact interface in passenger car disc brakes. An FEA-based model of a subsystem consisting of the piston, the brake pad and the rotor were developed using a modular modeling approach. While, Choi and Lee [9] performed a study on the transient thermoelastic analysis of disk brakes in repeated brake applications. The FEA was applied to the thermoelastic contact problem with frictional heat generation. To obtain the numerical simulation of thermoelastic behavior appearing in disk brakes, the coupled heat conduction and elastic equations were solved with contact problems. Belhocine and Bouchetara [10] have worked on a modeling of the temperature distribution in the disc brake and identified all the factors and the entering parameters concerned at the time of the braking operation such as the type of braking, the geometric design of the disc and the used material. They have concluded that the quality of the results concerning the temperature field has been influenced by several parameters such as:

a) Technological parameters illustrated by the design,
b) Numerical parameters represented by the number of elements and the step of time,
c) Physical parameters expressed by the type of materials,
d) Braking mode implemented.

In this study, the product performance is measured by the braking ability which is significantly affected by the temperature rise in the process of halting the vehicle. The objective of a braking system is to dissipate the kinetic energy of a vehicle in the form of heat. Producing braking systems that dissipate this energy both uniformly and efficiently is a challenging problem [11]. Thermal stresses due to high temperatures may induce a number of unfavorable conditions such as surface cracks and permanent distortions. Frictional heating, thermal deformation and elastic contact in sliding contact systems affect the contact pressure and temperature on the friction surfaces [9, 12].

The objective of this investigation is to perform product performance analysis and thus to identify the potentiality of replacing the conventional cast iron brake with MMCs brake disc. The performance of the brake disc component will be analyzed by its temperature distribution during braking operation and its maximum stress and strain experienced by brake disc. The component being analyzed is the brake disc applied in Proton Wira 1.3L and this component originally is produced from cast iron as shown in Figure 1.

![Proton Wira 1.3L cast iron brake disc](image)

**Figure 1.** Proton Wira 1.3L cast iron brake disc
2. Methodology

2.1. Finite element analysis (FEA)

In this investigation, the performance of the brake disc was evaluated using finite element analysis (FEA). This technique proved to be an accurate method of predicting the brake disc temperatures during vehicle braking operation. Furthermore, FEA has the ability to investigate the thermal and mechanical performance by providing solutions to problems involving advanced material component [13].

In this study, SolidWorks™ and SolidWorks Simulation™ softwares were used to carry out the design and simulation of the brake disc component. The brake disc’s features and the main views are illustrated in Figure 2.

The thickness of the selected MMCs brake disc would be calculated using the deflection of solid disc formula as implied in the Equation (1).

\[ d = C \frac{W(R_2^2 - R_1^2)}{Et^3} \]  

where, \( d \) refers to the deflection caused by external load, \( C \) is constant, \( W \) is the load on the disc, \( R_1 \) and \( R_2 \) are the inner and outer radius respectively, \( E \) is the modulus of elasticity and \( t \) is the thickness of the disc. Assuming that the variables of \( d \), \( C \), \( W \), \( R_1 \) and \( R_2 \) are the same for both cast iron brake disc and MMCs brake disc. Then the thickness of the MMCs brake disc can be calculated using the thickness of the cast iron brake disc, as implied in Equation (2).

\[ t_b = \left[ \frac{E_a t_a}{E_b} \right]^{\frac{3}{3}} \]  

where, \( t_b \) and \( t_a \) refer to the thickness of MMCs brake disc and cast iron brake disc respectively. While, \( E_a \) and \( E_b \) are the modulus of elasticity of cast iron brake disc and MMCs brake disc correspondingly.

The FEA modeling utilized the solid element type and curvature based mesh were applied for the three-dimensional simulation of the brake disc structure. The finite element model of the brake disc is shown in Figure 3 and the mesh details of the brake disc are presented in the Table 1.
Figure 3. Solid brake disc finite element model

Table 1. The finite element mesh details

| MESH DETAILS       |        |
|--------------------|--------|
| Mesh Type          | Solid Mesh |
| Mesher Used        | Curvature Based Mesh |
| Max. Element Size  | 16.349 mm |
| Min. Element Size  | 3.269 mm  |
| Total Nodes        | 6432    |
| Total Elements     | 3190    |
| Max. Aspect Ratio  | 10.004  |

The boundary condition for temperature was specified for coupled thermal-structural analysis of the brake disc by the load representing temperature versus time interval. The dissipated energy converted into heat was specified as all the mechanical energy and converted into thermal energy [12]. Energy dissipated as heat between the surfaces and the distributions were equal on the surfaces of the brake disc. Additionally, the significant material properties used for the analysis include: density, heat capacity, thermal conductivity, Young’s modulus, Poisson’s ratio and tensile strength. The material properties of the FEA model would follow the Al-MMCs material to be selected as the best option for the brake disc application. Whereas, the material properties of the cast iron brake disc (J431 G3000) are presented in Table 2. The product performance was studied by evaluating the temperature distribution, stress and strain caused by thermal and mechanical loading during braking operations.
Table 2. Material properties of Al-MMCs and cast iron brake disc

| PROPERTY                  | VALUE | UNITS |
|---------------------------|-------|-------|
| Tensile Strength          | 484   | MPa   |
| Cast Iron                 | 207   | MPa   |
| Yield Strength            | 437   | MPa   |
| Cast Iron                 | 330   | MPa   |
| Young's Modulus           | 114   | GPa   |
| Cast Iron                 | 114   | GPa   |
| Poisson's Ratio           | 0.33  |       |
| Cast Iron                 | 0.27  |       |
| Density                   | 2.822 | gr/cm³ |
| Cast Iron                 | 7.2   |       |
| Thermal Conductivity      | 140.2 | W/m.K |
| Cast Iron                 | 45    |       |
| Thermal Expansion Coefficient | 2.3^-0.5 | K |
| Cast Iron                 | 1.2^-0.5 |       |
| Specific Heat             | 800   | J/kg.K |
| Cast Iron                 | 510   |       |

The finite element model ran on a transient analysis, this was because the heat distribution was analyzed over a time period during the braking process. The breaking mode chosen for this analysis was autobahn stop, where it represented an immediate stop from a high velocity to a complete stop. The heat power \( Q \) in Watts, for an autobahn stop could be calculated using the formula as specified in Equation (3).

\[
Q = \frac{m(V_f^2-V_i^2)s}{4At}(1-p)(1-d)
\]

Where, \( m \) is the vehicle mass, the notations of \( V_i \) and \( V_f \) are the vehicle's initial velocity and final velocity respectively. Whereas \( A \) is referred to the area of the rubbing surface, \( t \) is the braking time, \( p \) is the portion of the heat flux rubbing surfaces generated to the pads, \( d \) is the drag losses, and \( s \) referred to the brake split. The generated heat produced by this test condition was applied as a heat power to the rubbing surfaces of the disc, assuming that only 5% of the heat generated was transferred to the pads, drag losses for a vehicle were 27.4%, whereas; brake split for the vehicle was 72.5% to the front discs [14].

In the present investigation, the simulation was conducted using the platform of Proton Wira 1.3L with curb mass of 1250kg. Intended for vehicle safety consideration, the test condition followed the requirement of the Motorway Braking Check as recommended by Society of Automotive Engineers (SAE) with standard code: SAE J2522. Hence, in this study the brake discs would be evaluated with vehicle initial velocity of 90% of its velocity maximum i.e. 180km/h, 50% of velocity maximum as final velocity (100km/h), deceleration of 0.3g and initial braking temperature of 150°C, thus \( Q \) (heat power) was calculated at 1166.714kWatts, additionally the convection coefficient used was 90W/m²K. Furthermore, mechanical loading was subjected to the brake discs by applying brake pressure of 2MPa, brake force of 38.3kN and coefficient of friction of 0.35 [12,15].

3. Result and discussion

Investigation of the transient behaviour of disc brake was performed during braking operations. In actual brake application, variation of the rotating speed during braking must be considered through vehicle dynamics [9]. However, in this study, finite element analysis (FEA) was used to measure the effect of thermal and mechanical loading in the front brake disc of a medium-sized vehicle. The brake discs’ material properties were in accordance with the selected 2124-Al reinforced 10% SiCp MMCs brake disc and gray cast iron.

The results presented in Figure 4 show temperature distribution on the Al-MMCs brake disc at half of the braking procedure, time step 3.81 (ts=3.81) and the end of braking procedure (ts=7.62).
Additionally, the procedure was applied on the surface of the cast iron brake disc and the results are presented in Figure 5.

![Figure 4. Temperature distribution on the Al-MMCs brake disc (a) ts=3.81 (b) ts=7.62](image)

![Figure 5. Temperature distribution on the cast iron brake disc (a) ts=3.81 (b) ts=7.62](image)

The results show the cooling effect through a heat transfer process which depended on the material property of the brake disc. The Al-MMCs brake disc shows a well distributed temperature than cast iron brake disc, additionally; higher temperature occurred in the ring of the disc and heat was dissipated in circumferential direction. The Al-MMCs brake disc dissipated higher maximum temperature 234.1°C as compared to cast iron brake disc’s maximum temperature of 217.3°C. However, the highest temperature was below the maximum operating temperature of Al-MMCs (502°C). This was due to higher thermal conductivity of Al-MMCs brake disc compared to cast iron brake disc, but this would enable Al-MMCs brake disc to dissipate heat quicker than cast iron brake disc. Furthermore, fine temperature distribution of Al-MMCs brake disc could reduce the localization of heat generation which can produce hot spot zones and influences thermal elastic instability. These results could be explained as Al-MMCs brake disc possessed better thermal property compared to cast iron brake disc. The simulation results matched with the experimental studies performed by Adebisi [12], where the hottest spots occurred in the ring and Al-MMCs brake disc shows even distribution of temperature compared to the cast iron brake disc.

The next simulation results show the stresses and strains caused by thermal and mechanical loadings on the brake discs. This analysis would check whether the distribution of heat, pad pressure and force applied to the surface of brake disc rotor could cause severe consequence to the rotor material and by comparing stress generated with the maximum allowable tensile strength of brake disc.
material. Normally, brake disc surface cracking will only occur when the stress exceeds the strength of the material [16,17]. The stress and strain distributions were produced from the FEA simulations on the brake discs and presented in Figures 6 and 7. For the MMCs brake disc, it was proved that the maximum stress produced at the circumference of the disc to be 168.72 MPa and highest strain produced was 1.980e-03. The maximum stress for Al-MMCs brake disc was still below the tensile strength (484 MPa), thus this would not cause failure to the structure of the brake disc. Moreover, better thermal dissipation and conduction at brake disc rotor surface played a major influence on the stress. As a comparison, the maximum stress and strain of Al-MMCs brake disc were lower than that induced in the cast iron brake disc which were 184.87MPa and 2.139e-03. This signifies that Al-MMCs brake disc has the potential of better mechanical performance than that of cast iron brake disc.

4. Conclusion
The investigation objective was accomplished by product performance analysis and thus identified the potential of replacement of the conventional iron brake disc with aluminium based MMCs (Al-MMCs) brake disc. The results suggested that the Al-MMCs have the potential to replace the conventional cast iron brake disc. This is supported by better thermal and mechanical performance by the MMCs brake disc during simulated braking operation. Therefore, this implied that the proposed concept of MMCs brake disc is to be further developed into the next design stages i.e. detail design and prototyping.
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