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PRODUCT DEVELOPMENT AND PERFORMANCE OF REINFORCED METAL MATRIX COMPOSITE BRAKE DISC: MODELLING, SIMULATION, AND MULTI-CRITERIA DECISION-MAKING TECHNIQUE

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ABSTRACT

Demand for lightweight and durable components for automotive applications, such as brake discs, is increasing. This has led to the emergence of new designs for brake discs using metal matrix composite (MMC), which offers high strength – lightweight performance and high thermal conductivity. Therefore, this research aims to develop a new brake disc material and design with higher braking capability and is capable of replacing the existing one. Additionally, modelling, simulation, and multi-criteria decision-making (MCDM) techniques were used to select the best design of the MMC brake disc. The results showed that Design 6 with angular grooves has the best performance at dissipating heat and is capable of reaching the highest temperature of 284.66°C with the lowest deformation value of 0.589 mm. Therefore, it is the best alternative due to its highest normalized priority of 0.2742. The combination of MMC as the new material and design has the ability to improve thermal and structural performance, thereby enhancing the vehicle's braking capability.

INTRODUCTION

The brake disc is an essential component in a vehicle, which plays a critical role in stopping or decreasing its velocity during normal or sudden braking. Some factors included in the design of this component are reliability, weight, durability, stability, cost, and performance. Presently, there is a significant demand to replace the current cast-iron brake disc with light, more durable, and efficient material with lower fuel consumption. Among these new materials is metal matrix composite (MMC) which offers very good strength, low density, and high thermal conductivity (Kumar et al., 2020).

MMC is a composite composed of at least two different materials, where one of which must be a metal. It is also called a matrix material with a higher content that acts as a binding and protecting role. Aluminum alloys are the most popular matrix to use in MMC because of

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their lower cost, compared to other light metals (Taya and Arsenault, 2016). The material embedded into the matrix is called reinforcement. It is used to change the physical properties of the compound, such as thermal performance, density, or the coefficient of friction. The reinforcement material can be in nano or micro size (Kumar and Devi, 2020), while the most popular reinforcement materials used are SiC, TiC, TaC, WC, and B4C (Taya and Arsenault, 2016).

The hybrid MMC was chosen as the material for the brake disc in this study because it shows a superior property compared to the composite reinforced with only one material. Aluminum alloy was used as the matrix material because it exhibits low density, better wear resistance, good corrosion, excellent mechanical properties, and low thermal coefficient of expansion compared with other conventional alloys and metals (Rino et al., 2012). Furthermore, silicon carbide (SiC) and graphite were used as reinforcement materials because the properties are suited for brake discs. SiC provides excellent thermal conductivity, high hardness, increased tensile strength, good workability, low cost, and chemically compatibility with aluminum. However, it has lower ductility and fracture toughness. Meanwhile, graphite provides a solid lubricant effect and excellent wear resistance properties (Attar et al., 2015; Altıntas et al., 2015; Bodunrin et al., 2015; Kumar and Sabarish, 2014; Zaware et al., 2014).

This study aims to investigate the MMC as the recommended new material to replace the cast-iron brake disc. Additionally, the new and current designs would be analysed and compared to determine their structural and thermal performances.

RESEARCH METHOD

This study used systematic methods, such as Modelling Software CATIA, Finite Element Analysis (FEA), Quality Function Deployment (QFD), and Analytic Hierarchy Process (AHP) to take a proper design selection decision. The investigation is performed to compare the thermal and structural properties of MMC and the existing cast-iron brake discs. Different brake discs designs were also considered to investigate the effect of varying features of MMC brake discs.

CATIA software was the modeling tool used in this study with the original design of the brake disc as shown in Figure 1. Meanwhile, Table 1 shows the 6 alternatives designs modeled by modifying the original brake disc design.

Figure 1: Original brake disc design

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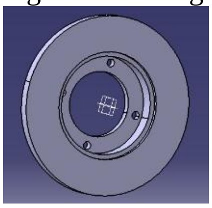
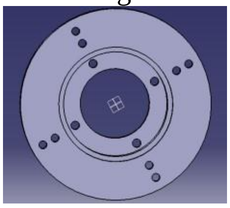
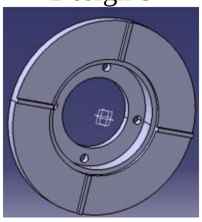
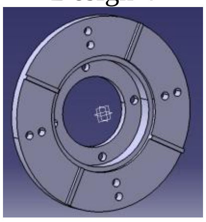
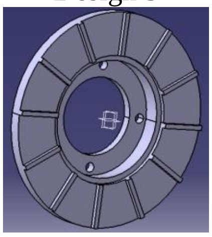
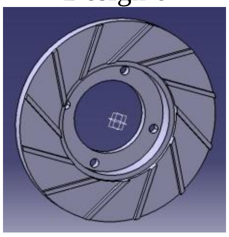
Table 1: Alternative designs of a brake disc

MMC (Design 1-6) and cast iron (Design 7) brake discs	
Design 1 and Design 7  Design 1: MMC and Design 7: cast iron using the original design of the current brake disc.	Design 2  MMC with 8 air vents added to the surface of the brake disc.
Design 3  MMC with 4 grooves added on the surface of the brake disc. These grooves are expected to improve the airflow and increase the heat transfer.	Design 4  MMC with grooves and air vents are added to the brake disc.
Design 5  MMC The number of grooves is tripled to12 compared to Design 3.	Design 6  MMC is the same number of grooves as Design 5 withangles added to the slot.

FEA consists of a material's computer model that is focused and analysed for specific results. ANSYS, which is generally applied in designing and optimizing a complicated system, was used as the FFEA software in this study. According to Parab et al. (2014), FFEA executes equations that manage the characteristics of these elements and solves them by creating a detailed explanation of how the system acts as a whole. It involves the interaction of 2 stages of activities, namely pre-processing and post-processing. The pre-processing stage consists of the preparation of finite element data. The solution within this phase describes the behaviour of each element that is generated and assembled. Meanwhile, the post-processing stage shows the results in numerical and graphical manners. The important parameters used as input values during this FEA are shown in Table 2. Meanwhile, figure 2 shows the location and direction of force applied and the fixed support exerted on the brake disc.

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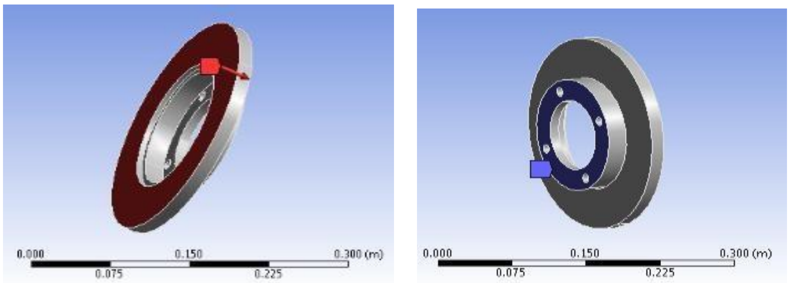
Table 2: Input parameters used in the Finite Element Analysis

Parameter (Unit)	Value
Mass of vehicle (kg)	1300
Area of the surface of the brake disc (m^2)	0.0276
Speed of vehicle (km/h)	150
Force applied on the brake disc (N)	2550.6
Deceleration (m/s^2)	1.962
Time for stopping a vehicle (s)	21.24
Power (kW)	53.138
Assumed 60% of mass located at the front and 2 wheels (kW)	15.941
Heat Flux (W/m^2)	27193



(a) (b)

Figure 2: a) Location and direction of force applied; b) Location of fixed support applied on the brake disc

The MMC properties, such as elastic modulus, density, Poisson's ratio, ultimate tensile strength thermal conductivity, and thermal expansion coefficient were calculated by an equation based on the rule of the mixture as implied in the studies by Sujan et al. (2012), Prasad et al. (2014) and Krishna et al. (2016). The material properties of the MMC and cast iron used as the brake disc are shown in Table 3.

Table 3: Properties of MMC and cast iron

Property	Al Alloy (87%)	SiC (10%)	Gr (3%)	MMC AlSiCGr	Cast Iron
Elastic Modulus (GPa)	69.9	400	20	101.4	100
Density (g/cm^3)	2.70	3.10	2.49	2.73	7200
Poisson's Ratio	0.33	0.14	0.23	0.31	0.27
Hardness (MPa)	340	2650	326	2931	2040
Ultimate Tensile Strength (MPa)	310	336	76	306	250
Thermal Conductivity (W/mK)	167	120	114	161	54
Thermal Expansion Coefficient (/K)	$2.34^{10^{-6}}$	$4.00^{10^{-6}}$	$5.20^{10^{-6}}$	$2.60^{10^{-6}}$	$1.20^{10^{-5}}$

QFD is an approach that translates customer requirements into design quality and technical models for each stage of the product development process (Childs, 2013). However, in this study, it is used to determine and rank the important parameters of the brake disc while analyzing the House of Quality (HoQ). The first step of HoQ is to collect data or information on customer requirements, also known as Voice of Customer (VOC). This is followed by determining the related product performance that is correlated with the customer requirements. After analysing and collecting sufficient information, the important criteria of the brake disc in customers' views are listed out and put into HoQ. Next, these views are ranked based on their priorities and preference using a scale of 1-5. Meanwhile, the correlation between the product performances is carried out at the roof matrix, with the relationship illustrated using positive and

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negative signs. After that, the customer requirements are correlated with product performance while rating the calculation importance.

According to Azeez et al. (2013), AHP used a weighted scoring process to assist the decision-making by organising priorities. This process is carried out by developing a hierarchy framework, followed by the construction of pair-wise comparison matrices that presents the relative importance of the factors at the current and higher levels. Each element is compared using Saaty's relative importance 1-9 point scale, and the judgments are carried out based on the decision makers' experience and knowledge. This is followed by synthesizing the pair-wise comparison, which involves assessing priorities and overall priority vectors.

The consistency ratio (CR) was used to estimate the consistency of the judgments among the pair-wise comparisons, which is accepted or rejected at values above or below 0.1, respectively. The judgments need to be carried out to obtain a consistent matrix. Lastly, the best design concept was selected based on the highest value of priority.

RESULTS AND DISCUSSION

The result from the QFD analysis is shown on the HoQ diagram in Figure 2. The outcome indicates that the most important criteria for the brake disc from customers' views are thermal performance, safety, and reliability, with a priority ranking of 5. Thermal performance is related to the safety and reliability of a brake disc because over-heating leads to the malfunction of the braking system, which also affects a vehicle's safety. In terms of product performance, thermal dissipation and conductivity have the highest score of 21.3, followed by hardness and deformation.

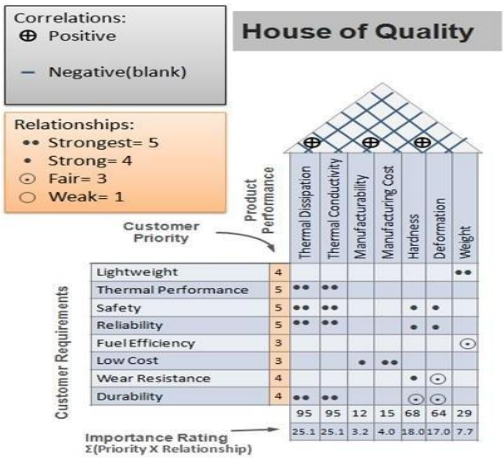

Figure 2: The outcome of House of Quality

These 4 criteria directly affect the thermal performance, reliability, and safety of the brake disc by prolonging its lifetime, thereby assuring the functionality and safety of the vehicle and users. Therefore, by improving the most important criteria stated above, a brake disc is capable of satisfying and fulfilling customers' requirements is designed.

In this study, ANSYS was used to carry out the thermal analysis and structural analysis of 6 alternative designs of brake discs. Thermal analysis was used to investigate the performance and heat dissipation, while the structural analysis investigated the deformation of the brake disc under the force applied. The objective of thermal analysis of brake disc is to evaluate the performance of different designs under the applied condition and in accordance with the maximum temperature. An example of thermal analysis applied on the cast iron and MMC brake discs in Design 1 and 6 are shown in Figure 3.

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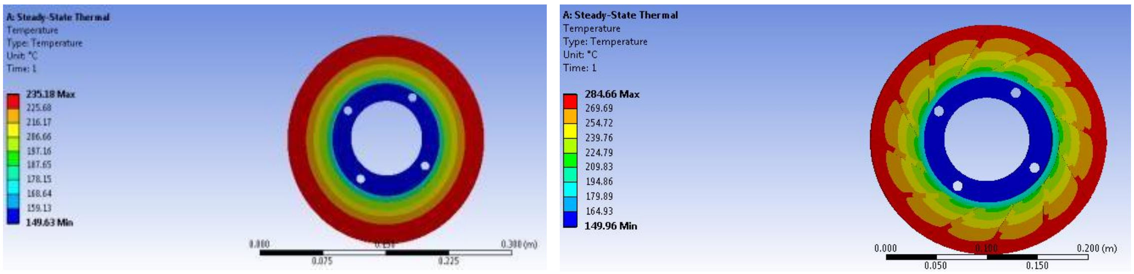

Figure 3: FEA thermal analysis

The objective of structural analysis of brake disc is to evaluate the deformation of different designs under the condition applied. Figure 4 is an example of structural analysis applied on the cast iron and MMC brake discs in Designs 1 and 6. The results of the thermal and structural analysis are summarised in Table 4.

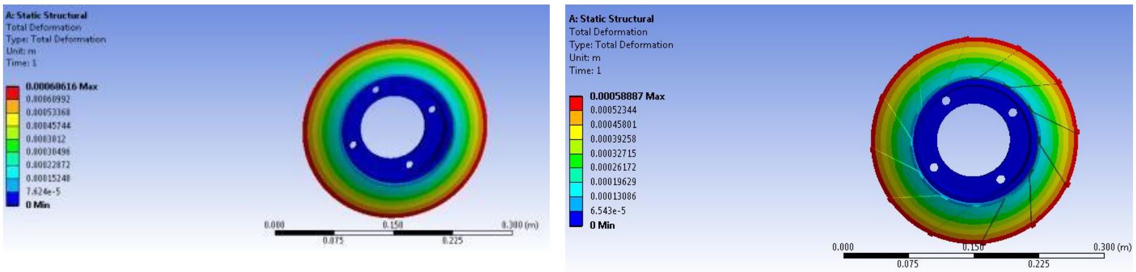

Figure 4. FEA structural analysis

Table 6: Analysis result from ANSYS

Alternative Design	Thermal Dissipation (°C) Max	Deformation (mm) Max	Mass (kg)
1.	237.68	0.6677	1.4117
2.	241.43	0.6903	1.3817
3.	256.68	0.6655	1.4185
4.	259.79	0.6774	1.3946
5.	271.97	0.6297	1.4441
6.	284.66	0.5889	1.4569
7.	235.18	0.6862	3.7231

A higher maximum temperature means the brake disc has the ability to dissipate heat faster, thereby preventing the possible occurrence of overheating and malfunction of the brake system. The analysis showed that higher temperature was at the outer part of the brake disc's surface, and the heat was transferred in a circular direction from the middle to the outside. Khalid et al. (2011) stated that the material needs to be able to withstand the highest temperature generated on the brake disc's surface after repeated braking for adequate performance and safety.

The result shows that the MMC brake disc could dissipate heat faster than cast iron due to the higher thermal conductivity of MMC material. The thermal analysis also indicated that the design of adding air vents and grooves enhanced the thermal performance of the brake disc. Grooves create a path for better air circulation and fasten the heat transfer rate. The combination of grooves and air vents further enhanced the heat dissipation as shown in Design 4 with a maximum dissipated temperature of 271.94°C. The alternative Design 6 (angled grooves) has

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the best performance due to its ability to dissipate heat at a maximum temperature of 284.66°C. Research by Carley (2006) stated that adding air vents (holes) and grooves (slots) improves air circulation and venting throughout the disc, thereby providing positive effects such as better heat transfer and an increase in cooling rate. Furthermore, this is supported by Callahan and Talia (2004), where grooves were used as an additional feature in manufacturing brake discs.

For structural analysis, a higher deformation value means that the brake disc deformed more under the force applied. The result showed that the MMC deformed less compared to cast iron due to the higher tensile strength, hardness, and elastic modulus of hybrid Al-MMC. The structural analysis result also showed that adding air vents increases the deformation of the brake disc, which is undesirable, while the reverse is achieved when adding grooves. This can be observed from the comparison result between alternative Design 2 (8 air vents added) and 3 (4 grooves added), which deformed by 0.6903 mm and 0.6655 mm, respectively. Modifying the angle of grooves would further improve the brake disc deformation by 0.589 mm, which is shown in the alternative Design 6. The mass of MMC was 63% lower compared to cast iron at a higher cost compensated by better thermal performance, lower deformation, and lower mass. Therefore, this tends to improve reliability, fuel consumption efficiency, and durability potentially. This result is supported by Romanov et al. (2019), showing that Al-MMC had improved tribological property compared to cast iron, thereby potentially replacing the disc.

The final phase of this study was the Multi-Criteria Decision Making (MCDM) analysis using an AHP software known as SuperDecisions. This investigation was used to select the best design for brake discs among the 6 alternatives by using weighted scoring and organising priorities. Table 7 compares the thermal performance, deformation, mass, and hardness of all the alternatives involved in the selection for easier and increased accuracy of the ranking process.

Table 7: Properties and FEA results of MMC and cast iron brake discs

Design	**Thermal Dissipation (°C) Max**	**Thermal Conductivity (W/m.K) Max**	**Deformation (mm)**	**Mass (kg)**	**Hardness (MPa)**
1.	237.68	161	0.6677	1.4117	2931
2.	241.43	161	0.6903	1.3817	2931
3.	256.68	161	0.6655	1.4185	2931
4.	259.79	161	0.6774	1.3946	2931
5.	271.97	161	0.6297	1.4441	2931
6.	284.66	161	0.5889	1.4569	2931
7.	235.18	54	0.6862	3.7231	2040

The AHP hierarchy consists of 4 levels, namely goal, criteria, sub-criteria, and alternative design. The aim is to select the best design of brake disc among 6 and 7 designs of MMC and cast-iron brake disc. Based on HoQ, the criteria that affect the design of brake discs are durability, fuel efficiency, lightweight, low cost, reliability, safety, thermal performance, and wear resistance. Meanwhile, the sub-criteria are deformation, hardness, thermal conductivity, thermal dissipation, and weight. The pair-wise comparison of criteria and relative advantages of each alternative design was also conducted. The inconsistency ratio of pair-wise comparison needs to be less than 0.1 to make the judgments acceptable and above 0.1 to implement a revision. Figure 5 concluded that thermal performance with a relative priority of 0.25911 and inconsistency ratio of 0.2474 was the most important criterion that affected the design of the brake disc, followed by reliability, safety, and durability.

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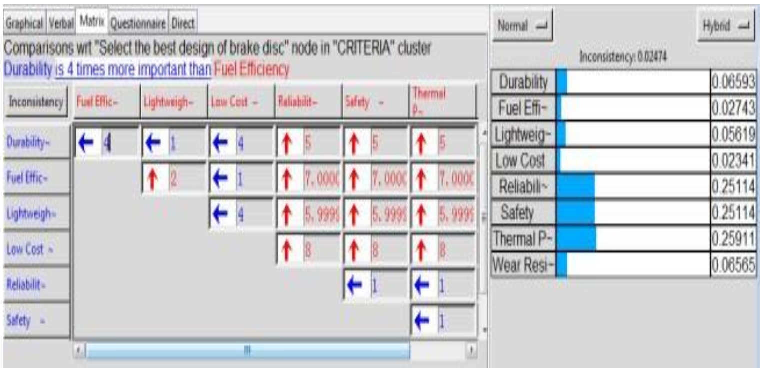

Figure 5: Pair-wise comparison of sub-criteria relative to the main criteria and its priority level

Figure 6 is an example of a pair-wise comparison and relative priority deformation between alternative designs relative using AHP. Design 6 has the highest relative priority of 0.48846, which means that the design has the ability to resist itself from experiencing deformation with an inconsistency ratio of 0.04603. Another example is in Figure 7, where Design 1-6 had the same relative priority of 0.16216 in hardness because they are made of the same material, MMC. Meanwhile, Design 7 was made of cast iron, which shows that MMC has a higher hardness value. Also, the inconsistency ratio was 0.

Figure 6: Pair-wise comparison and relative priority of deformation in the seven alternative designs of brake discs

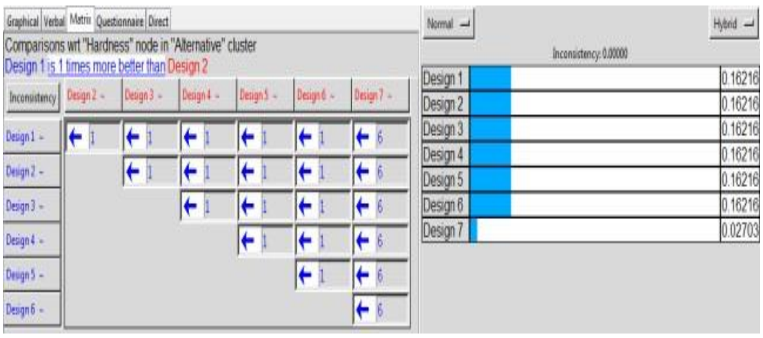

Figure 7: Pair-wise comparison and relative priority of hardness in the seven alternative designs of brake discs

After all the pair-wise comparisons has been made, AHP was used to determine the final ranking and priority values to all the alternative designs, as shown in Figure 8. Design 6 was selected as the best because it has an MMC brake disc with annular grooves and the highest

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normalised priority of 0.2742. The addition of grooves improved thermal performance by creating a path for better air circulation and increasing the heat transfer rate. The structural analysis results also showed that adding grooves decreases deformation, thereby improving the structural performance. The last ranking was the cast-iron brake disc, indicating that the MMC brake disc can improve the overall performance in terms of all the criteria and sub-criteria.

Graphic	Alternatives	Total	Normal	Ideal	Ranking
	Design 1	0.0356	0.1077	0.3926	6
	Design 2	0.0425	0.1285	0.4687	4
	Design 3	0.0415	0.1254	0.4571	5
	Design 4	0.0501	0.1514	0.5522	3
	Design 5	0.0600	0.1814	0.6613	2
	Design 6	0.0907	0.2742	1.0000	1
	Design 7	0.0104	0.0314	0.1146	7

Figure 8: Total relative priority and ranking of the seven alternative designs of a brake disc

CONCLUSIONS

In conclusion, MMC has the potential of replacing cast iron as one of the materials for designing brake discs. This is because it exhibits excellent dissipate heat, has high structural performance, and is 63% lighter than cast iron. However, the material and the manufacturing cost in fabricating MMC is higher than cast iron. It can also be compensated by the high fuel usage efficiency, increased performance, and a longer lifetime.

Furthermore, the simulation approach and MCDM were used to select the best design of the MMC brake disc. The results showed that Design 6 was the best because it contained angular grooves acting as air vents. This feature enhanced the airflow and centrifugal forces moving air in and out of the grooves, thereby improving its circulation with the rise in heat transfer rate. Furthermore, the structural analysis indicated that adding grooves reduces deformation, hence improving the structural performance. Therefore, the combination of MMC as the new material application and new design improves thermal and structural performance, thereby enhancing the vehicle braking capability.

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REFERENCES

Altıntas, Y., Aksoz, S., Keslioglu, K. and Marasli, N. (2015). Determination of Thermodynamic Properties of Aluminum Based Binary and Ternary Alloys. Journal of Alloys and Compounds, 649, 453–460.

Attar, S., Nagaral, M., Reddappa, H. N., Aurabi, V. (2015). A Review on Particulate Reinforced Aluminum Metal Matrix Composite. Journal of Emerging Technologies and Innovative Research, 2(2), 225–229.

Azeez, S. A., Nandagopan, O. R. Dhiwakar, V. M. (2013). Application of Analytic Hierarchy Process for Optimal Design Decisions in Product Development. International Journal on Theoretical and Applied Research in Mechanical Engineering, 2(3), 47–54.

Bodunrin, M. O., Alaneme, K. K. Chown, L. H. (2015). Aluminium Matrix Hybrid Composite: A Review of Reinforcement Philosophies; Mechanical, Corrosion and Tribological Characteristics. Journal of Materials Research and Technology, 4(4), 434–445.

e-ISSN : 2442-2630
p-ISSN : 1693-6590

Callahan, F. and Talia, G., Callahan F. J. and Talia G. E. (2004). Method of making brake discs and rotors with open grooves and brake discs and rotors made therewith. US20050252739A1 (U.S. Patent).

Carley, L. (2006). Slotted and Drilled Rotors: Show or Slow?. http://www.brakeandfrontend.com/slotted-and-drilled- rotors-show-or-slow/.

Childs, P. R. N. (2013). Mechanical Design Engineering Handbook. Oxford: Butterworth: Heinemann.

Khalid, M. K., Mansor, M. R., Kudus, S. A., Tahir, M. M., & Hassan, M. Z. (2011). Performance investigation of the UTeM eco-car disc brake system. Journal of Mechanical Engineering and Technology, 11(6), 1-6.

Krishna, S. A., Shridhar, T. N. and Krishnamurthy, L. (2016). Characterization and Analysis of Thermomechanical and Thermoelastic Properties for Aluminium-Silicon Carbide-Graphite Hybrid Metal Matrix Composite. International Journal of Engineering Sciences and Management Research, 3(3), 44-60.

Kumar, P. A., Rohatgi, P., & Weiss, D. (2020). 50 years of foundry-produced metal matrix composites and future opportunities. International Journal of Metalcasting, 14(2), 291-317.

Kumar, A. and Sabarish, R. (2014). Structural and Thermal Analysis of Brake Drum. Middle - East Journal of Scientific Research, 20(6), 715–719.

Kumar, P. V., and Devi, S. B. (2020). Machinability Investigation of Aluminium Based Hybrid Metal Matrix Composite. International Journal of Multidisciplinary Research in Science, Engineering, and Technology, 03(1), 35–41.

Parab, A., Sakarwala, A., Paste, B., Patil, V., Mangrulkar, A. (2014). Aerodynamic Analysis of a car model using fluent–Ansys 14.5. International Journal on Recent Technologies in Mechanical and Electrical Engineering, 1(4), 7-13.

Prasad, D. S., Shoba, C., Ramanaiah, N. (2014). Investigations on Mechanical Properties of Aluminum Hybrid Composite. Journal of Materials Research and Technology, 3(1), 79-85.

Rino, J. J., Chandramohan, D. and Sucitharan, K. S. (2012). An Overview on Development of Aluminium Metal Matrix Composite with Hybrid Reinforcement. Matrix. International Journal of Science and Research, 1(3), 196–203.

Romanov, I., Chernyshov, E., & Romanov, A. (2019). Assessment of the possibility for substituting cast iron in vehicle brake disc with Aluminum-Based Metal-matrix composite material produced by internal oxidation. Materials Today: Proceedings, 19, 2125-2128.

Sujan, D., Oo, Z. Y., Rahman, M. E., Maleque, M. A., Tan, C. K. (2012). Physio-Mechanical Properties of Aluminium Metal Matrix Composite Reinforced with Al2O3 and SiC. World Academy of Science, Engineering and Technology, International Journal of Chemical, Molecular, Nuclear, Materials and Metallurgical Engineering, 6, 678-681.

Taya, M., and Arsenault, R. J. (2016). Metal Matrix Composite, Thermomechanical Behavior, 1st Edition. New York: Pergamon Press.

Zaware, P. K., Patil, R. J. and Sonawane, P. R. (2014). Design Modification & Optimisation of Disc Brake Rotor. International Journal of Research in Engineering and Advanced Technology, 2(3), 1–6.