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Design and Analysis of an Automobile Disc Brake Rotor by Using Hybrid Aluminium Metal Matrix Composite for High Reliability

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Abstract: Due to their superior capabilities for manufacturing lightweight automotive components, aluminium metal matrix composites have gained a lot of attention in the last few years. Aluminium metal matrix composites are an exceptional class of metal matrix composites that can solve all the major problems related to the automobile industry. Aluminium matrix composites in the disc braking system have already been employed and studied by many scientists. However, the developed materials are not yet always sufficiently accurate and reliable. In this article, a new enhanced metal matrix composite material is used and studied to improve the efficiency of an ordinary car's braking system. To improve the accuracy of the designated braking system, an innovative hybrid aluminium matrix composite (Al6061/SiC/Gr)-based brake rotor has been developed, and its effectiveness has been determined by finite element analysis. From the simulation, the product performance confirmed that the hybrid aluminium matrix composite (Al6061/SiC/Gr)-based brake rotor has the potential to replace the standard cast iron brake disc. The new enhanced hybrid composite material used in this study can be used for the efficient design of various braking parts.

Keywords: metal matrix composites; aluminium matrix composites; finite element analysis; braking systems; brake disc

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1. Introduction

In recent years, several advanced and innovative materials have been introduced in the manufacturing and automobile industries. Fiberglass is one of the first advanced composite materials that was developed by engineers in 1940 [1]. In the last few years, demands of metal matrix composites (MMCs) in the automobile industry have promptly increased due to their unique and superior properties [2,3]. Some of the features that distinguish MMCs from other similar materials in their category are high-temperature strength, low density, higher thermal resistance and a higher strength to mass ratio [3,4]. Other significant properties include high fatigue, wear, and creep resistances [4]. All these improved mechanical and thermal properties make the metal matrix composite a viable alternative to cast iron that is most commonly used in the construction of engines and brakes in the automobile industries [5,6]. The metals that have been used for metal matrix composites are mostly aluminium, magnesium and titanium [7]. Super alloys and copper alloys are also used to develop MMCs [8]. The most widely used type of metal matrix composite is the aluminium matrix composite (AMC). The main reason for the greater use of aluminium matrix composites (AMCs) is that they have comparatively lower cost requirements than other MMCs [9]. In addition, they provide excellent performance in all the properties of traditional composites that are already mentioned above. Moreover, the reliability of hybrid metal matrix composites (MMCs) is an important consideration in determining their suitability for various applications. It is to be understood that the reliability of a hybrid MMC depends on several factors, including the selection and compatibility of reinforcement materials, manufacturing processes, design considerations, and the specific operating conditions. Among these, design plays a major role in enhancing system or component reliability performance, thus ensuring system safety.

Aluminium matrix composites are garnering much importance across industrial manufacturing technologies because of their smooth and trouble-free mode of operation [10]. The use of aluminium-based metal matrix composites (AMMCs) with improved mechanical properties has gained significant attention, particularly in the building and servicing industries. This is driven by the need for component weight reduction, enhanced toughness, and improved overall efficiency. Many researchers [11–13] have explained all the main intentions of using AMCs in automobile industries. In the last few years, the use of AMCs in the construction of differential gearboxes and connecting rods has been greatly studied globally. In a recent study [14], researchers examined the differential gearbox designed and fabricated by metal matrix composite material and found that metal-matrix-composites-based gearboxes have better structural properties as compared to the conventional-materials-based gearbox. In another study [15], the assessment of aluminium and silica carbide-based composite material and conventional steel (C70) in the construction of connecting rods was studied profoundly. In this study, the improved mechanical properties (high tensile strength, hardness) of selected composites were studied by finite element analysis and it was determined that they can endure more heat than C70 steel. A study [16] on the analysis of finite elements with various materials for studying the conditions (dynamic and static) of the piston of the engine showed that a piston constructed with aluminium silica carbide composite performed with a smaller number of deflections in comparison with traditional materials for the same set of external conditions.

One of the most critical parts of an automobile is the braking system [17,18]. This acts as a safety-critical system for the automobile and its failure will cause catastrophic accidents leading to major losses in terms of human life and economy [19]. The National Transportation Safety Board (NTSB) has reported the results of various accident investigations of braking system failures and made recommendations to avert the accidents. However, there are limited studies on enhancing brake safety and limited research on how to improve brake safety in terms of better design and material selection. The brakes with the highest efficiency and effectiveness shall provide better braking effects under constant and prolonged application [19,20]. Hence, a better design of the braking system is key to obtaining reliable performance during operation. Though the design ensures better characteristics for braking, the friction generated during operation can cause degradation of the brake pads and rotors, thus leading to poor reliability. Better quality materials will help eliminate the cause of degradation failures. Therefore, designing braking system components such as disc rotor and disc pads with proper materials is extremely important in achieving a better operational reliability of the brake pads and rotors. A few researchers [21,22] studied the effects of aluminium matrix composite in braking systems in automobiles. Another researcher [23] analysed the braking system of motorcycles, compared the brake disc made of aluminium matrix composite with a grey-cast-iron-based disc, and noticed that more strength was provided by the AMC-based rotor. Similarly, ref. [24] evaluated both aluminium and grey cast iron braking systems in designing an efficient braking system for go-karts and discovered that AMC-based brake rotors have high wear resistance when reinforced with silicon carbide (SiC). In some other studies [25,26], AMC is used to manufacture calipers and brake pads. It was concluded that aluminium matrix composite brake discs show better performance than conventional-material-based brake discs. However, the researchers are still trying to enhance the strength and wear resistance of the AMC-based brake rotor by reducing the overall weight to lower the fuel consumption. High reliability is one of the essential characteristics of any engineering system, and automobile systems are no exception [27]. Modern automotive vehicles, be it fossil-fuel-based or electrically operated, must be designed with improved dynamics and controls [28]. The hybrid metal matrix composite (HMMC) is an advanced class of material made up by adding at least two different reinforcements in the base material. The high wear resistance, high compressive stiffness, and a higher strength-to-weight ratio while having less weight, make a hybrid metal matrix composite an ideal material with high reliability to use in the automotive industry [29]. In a hybrid metal matrix composite, the mixture of two different reinforcements provides superior properties as compared to their individual constituents [30]. All these properties make HMMCs an efficient substitute for the automobile disc brake rotor construction. There are numerous studies existing in the literature that review the application of AMC in developing various engineering systems including its processing techniques, mechanical testing, machining characteristics, etc. Nonetheless, no significant research on HMMCs in the construction of the brake rotors of an automobile has been performed in recent years. As cited above, most of the previous studies have been done on traditional MMCs.

Hence, this is the first time an advanced aluminium-based hybrid metal matrix composite (Al6061/SiC/Gr) is used to design an automobile disc brake plate. In this numerical analysis, the mechanical properties of Al6061/SiC/Gr hybrid composite fabricated by the stir casting technique are used in an effective finite element analysis (FEA) to perform appropriate simulation assessment. To validate the effectiveness of this new HMMC in the braking system, all the calculated simulation results are compared with other simulation results derived after using a typical traditional material (cast iron) for the same disc rotor in the same braking system. By doing this advanced analysis, braking efficiency can be examined and improved. In addition, this proposed approach can be implemented to optimize the other hybrid metal matrix composites for different braking system components. The rest of the paper is organized as follows. The materials and the methodology used in this study are discussed in Section 2. The finite element analysis is explored in Section 3. All the results and main discussions are made in Section 4. The conclusion of the study is provided in the last section.

2. Materials and Methods

2.1. Materials

Generally, during the fabrication of an advanced hybrid metal-matrix composite, the combination of the reinforcement and matrix can be varied as per the requirements of industries [31]. The manufacturing of composites depends on their phases, i.e., matrix and reinforced (dispersion) phases, and on the basis of the matrix phase and dispersed phase, composite materials can be classified as shown in Table 1. The matrix phase is the primary phase which shows a continuous character resulting in a ductile and less hard phase [32]. The matrix phase holds the dispersed phase and shares a sustainable load with it [33]. On the other hand, the dispersed phase is embedded in the matrix in a discontinuous form and is relatively stronger than the matrix phase [34]. In this study, the aluminium alloy Al6061 is used as the base material (matrix phase), where the silicon carbide (SiC) and graphite (Gr) particles of 200 mesh sizes with an average particle size of 75 μm are used as the reinforcement materials. The SiC and Gr are selected as reinforcements due to their unique sets of properties and previous results [34–36]. As they are both hard ceramic materials, by adding them up in the selected matrix alloy, the tensile strength, yield strength, and hardness are rapidly increased as compared to the previously used traditional composite in automobile applications.

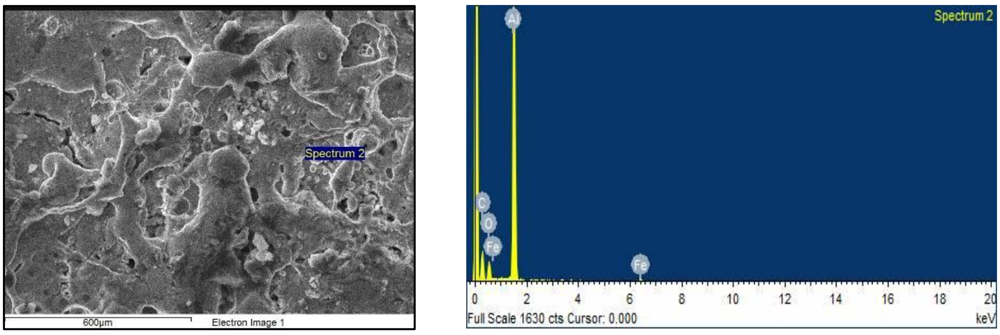
Table 1. Classifying composites on the basis of matrix phases and dispersed phases [33].

Matrix phase:
• Metal Matrix Composites: MMCs comprise a metallic matrix (aluminium, cobalt and copper) and a dispersed ceramic matrix composite (oxides, carbides).
• Ceramic Matrix Composites (CMCs): CMCs comprise a ceramic matrix and embedded fibres of another ceramic material as the dispersed phase.
• Polymer Matrix Composites (PMCs): PMCs comprise a thermostat or thermoplastic matrix and embedded glass, with carbon as the dispersed phase.
Dispersed phase:
• Particulate composites: These composites comprise a matrix reinforced by a dispersed phase in the form of particles.
• Fibrous composites: These composites comprise a matrix reinforced by a discontinuous or continuous fibre.
• Laminate composite: This is the more advanced version of a fibrous composite when a fibrous composite comprises different layers of fibre orientation.

In recent studies [37,38], it is deeply investigated and demonstrated that a newly developed HMMC (Al6061/SiC/Gr) is a significant advanced material as compared to the usual MMC (Al6061/SiC). Therefore, in this study, an advanced hybrid metallic composite fabricated by the stir casting technique, the same technique used in [38], is selected for further investigation of the automobile disk brake plate. For a clear understanding, the calculated mechanical and wear behaviour results of new HMMCs and conventional MMCs from [38] are stated in Table 2. Additionally, the non-destructive analysis (as shown in Figure 1) was also carried out using a scanning electron microscope (SEM) equipped with an EDS energy-dispersive X-ray spectrometer (EDS) to verify the microstructure and homogeneity of the fabricated sample.

Table 2. Mechanical and wear properties comparison [38].

	Ultimate Tensile Strength (MPa)	Yield Strength (MPa)	Hardness (Hv)	Wear Rate (mm^3/Nm)
Al6061/SiC	178.1	139.4	92.5	5.21×10^{-3}
Al6061/SiC/Gr	192.8	152.7	101.7	4.34×10^{-3}



(**a**) (**b**)

Figure 1. (**a**) SEM and (**b**) EDS analysis of fabricated HMMC.

2.2. Methodology

In all research, the appropriate methodology ensures that research is conducted thoroughly and provides a clear statistic of its efficiency [39]. In this study, a particular set of procedures and techniques were used and followed to inspect and evaluate the properties of HMMC in the braking system. Due to the complexity involved in the structure of the disc brake plate, all the simulations were carried out by FEA. Here, the commercial package ANSYS R19.2 was employed for the FEA simulation. Before performing the final analysis, designing the disc brake plate was essential.

In this study, we focused on the brake disc of the Opel Corsa D car model. In this particular automobile model, the brake rotors are made of grey cast iron (G3000). Therefore, to provide better performance in the braking system of this car, a detailed analysis of the brake disc centred on both selected materials, HMMC (Al6061/SiC/Gr) and cast iron, is carried out. The model of the brake rotor of the selected automobile with a diameter of 255 mm, and 20 mm thickness is designed in an advanced computer-aided designing software (Solid Works). Two different views (2D and 3D) of the designed brake disc can be seen in Figures 2 and 3. The calculated material properties of both selected materials that are used in the FEA are shown in Table 3. Further, the specifications and data of the disc rotor and selected car model are listed in Tables 4 and 5.

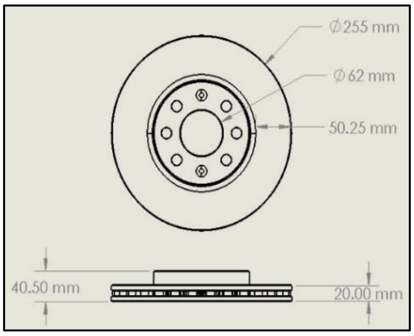


Figure 2. 2D view of brake disc.

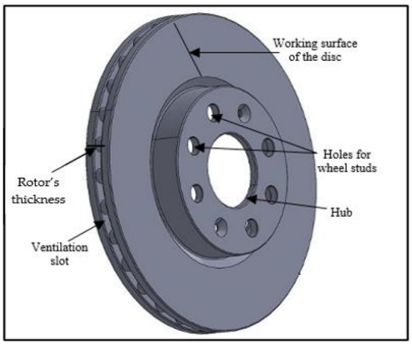


Figure 3. 3D view of brake disc.

Table 3. Material properties of new Al based HMMC and cast iron.

	Density (kg/m^3)	Young's Modulus E (MPa)	Poisons Ratio	Specific Heat ($J{\cdot}kg^{-1}{\cdot}K^{-1}$)	Thermal Expansion Coefficient (K^{-1})	Thermal Conductivity (W/m °C)	Hardness by Vickers (N/mm^2)
$Al/SiC_{12\%}/Gr_{5\%}$	2815	114	0.24	820	$2.3^{-0.5}$	125	101.7
Cast iron	7150	119	0.27	460	$1.2^{-0.5}$	52	225

Table 4. Disc rotor's specifications.

Rotor's diameter	255 mm
Rotor's height (H)	48 mm
Rotor's thickness (T)	20 mm
Centre hole (Hub)	60 mm
No. of bolt holes	8
Contact area	25%

Table 5. Selected vehicle's data.

Mass of the vehicle	1275 kg
Initial velocity	30 (m/s)
Time to stop (Bt)	5 (s)
Radius of the wheel	380 (mm)
Axle weight distribution ratio (Ar)	0.3

3. Finite Element Analysis

To obtain a better understanding of the newly developed composite-based disc brake, numerical simulation was also carried out in addition to the physical experiments. However, it was not easy to conduct the simulation analysis as it required the use of an innovative approach to perform real-time analysis. In this study, the FEA approach was used to achieve this goal. FEA is an advanced technique used to calculate complex structures' different properties (physical and structural) [40–42]. These days, the FEA approaches are often used to analyse and simulate complicated engineering designs. In this study, the performance of the brake disc is evaluated using finite element analysis. In finite element analysis, the meshing ensures a continuous geometric space in the structure, and in this study, the size of 1.0 mm was set for the meshing of the brake rotor. The meshed brake disc can be seen in Figure 4, and all the mesh details are stated in Table 6.

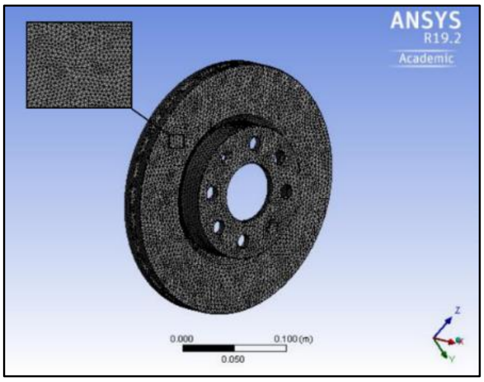


Figure 4. Meshed brake disc.

Table 6. Mesh details.

Mesh Type	Fine
Total nodes	190,680
Total elements	131,890

FEA has the capability to explore mechanical and thermal performance by providing solutions to problems involving advanced material components [43–45]. Therefore, for the real-time analysis, some of the most significant factors, such as braking torque, total force, tangential force, and braking distance, need to be calculated. Similarly, the thermal diffusivity, heat penetration time, rise in temperature and heat flux are also determined to examine the product's performance. To determine the specific values of all the mentioned substantial factors for an appropriate analysis, all the calculations have been made by following standard equations (as stated in Table 6). Some factors such as braking energy, braking time, braking power, brake pressure, vehicle load on disc and normal force were considered as constants for both materials, and their values can be seen in Table 7.

During the analysis, it was assumed that the brake pressure was uniformly distributed over the contact area of the brake disc. The coefficient of friction (μ) was always dependent on the type of material used for the brake disc, and a high coefficient of friction meant more brake power was required. For a precise evaluation, the actual coefficients of friction of both materials were used.

Table 7. Major calculations.

	Cast Iron	$Al/SiC_{12\%}/Gr_{5\%}$
• **Braking energy:**	125×10^3 (J)	125×10^3 (J)
• **Braking power:** Braking power = Braking energy/Time	245.7 (kW)	245.7 (kW)
• **Brake pressure:** Brake pressure = (1.5 × weight of car)/contact Area	5 N/mm^2	5 N/mm^2
• **Normal force (NF):** Normal force = (Max pressure/2) × Area of pad	14,675 N	14,675 N
• **Vehicle load on disc (VL):** Vehicle load on disc = Weight of vehicle × (A_r)	5880 N	5880 N
• **Tangential force (TF):** Tangential force = μ × Normal force where μ = 0.42 (Cast iron), and μ = 0.55 ($Al/SiC_{12\%}/Gr_{5\%}$)	6114 N	7510 N
• **Total force (F):** Total force = $N_F + V_L + T_F$	26,684 N	28,405 N
• **Braking Torque:** Braking Torque = F × R_e	2795.12 Nm	2842.3 Nm
• **Braking distance:**	47 m	42 m
• **Rise in temperature:** Rise in temperature = Braking energy/(ρ × V × Specific heat) where ρ is density, V is volume	200 °C	320 °C
• **Heat flux:** Heat flux = Heat generated/(surface area × (B_t))	9241 KW/m^2	9357 KW/m^2
• **Thermal diffusivity:** Thermal diffusivity = Thermal conductivity/(ρ × Specific heat)	16 mm^2/s	54 mm^2/s
• **Heat penetration time:** Heat penetration time = (T/2)2/(5 × thermal diffusivity)	1.7 s	0.47 s

4. Result and Discussion

Generally, to investigate the applications of a new braking component, variations in vehicle speed and braking pressure must be considered. In this study, the performance of the Al6061/SiC/Gr and cast-iron-based brake rotors is studied by assessing temperature variations and deformation. As the selected vehicle has a front-wheel drive transmission, thermal and mechanical loading effects in the front brake rotors were measured.

4.1. Thermal Analysis

Thermal analysis plays a crucial role in assessing the reliability of various systems and components, especially those subject to temperature variations and thermal stresses. It helps in understanding how temperature affects the performance, durability, and lifespan of materials and structures. The thermal analysis of aluminium metal matrix composites (AMCs) involves studying the thermal behaviour and properties of the composite material, particularly its response to temperature changes. In the thermal analysis, the temperature distributions and other thermal quantities must be calculated. The typical thermal quantities include temperature distribution analysis, amount of heat lost or gained, and heat fluxes, as shown in Figure 5a,b and Figure 5c,d, respectively. The importance of carrying out thermal analysis in the disc brake system is to provide a detailed view on how the brake responds to the change in temperature when it is applied. The friction causes heat generation which must be conducted and dispersed over the rotor cross-section of the brake. Generally, there are two types of thermal analysis which could be performed for evaluation. The first is a steady state thermal analysis, and the other is a transient thermal analysis. A steady state thermal analysis enables determining the distribution of the temperature and other thermal quantities under conditions of steady state loading, and the heat storage effects that may vary over time can be ignored. On the other hand, transient thermal analysis enables the determination of the distribution of the temperature and other thermal quantities under conditions that vary over time.

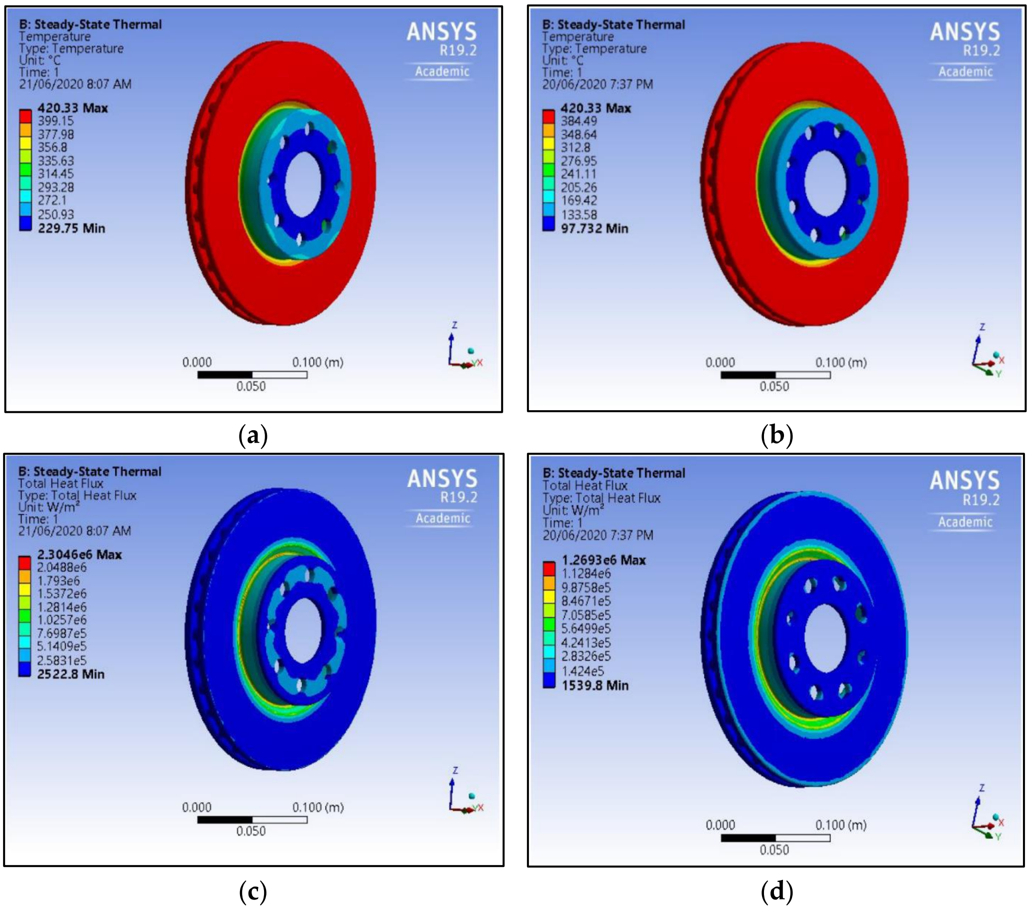


Figure 5. Thermal analysis of Al/SiC/Gr- and cast-iron-based brake rotors. (**a**) Temperature variation—Al6061/SiC/Gr, (**b**) Temperature variation—cast iron, (**c**) Total heat flux—Al6061/SiC/Gr, and (**d**) Total heat flux—cast iron.

In this study, the clamping forces are applied for several seconds on brake discs to bring them to the rest position; therefore, this study performed transient thermal analysis. The heat flux variation and the temperature variations were analysed for the area of the brake disc. The thermal analysis (Figure 5a,b) shows that the heat was dissipated in the circumferential direction in both cases. It is found that the cast iron material heats to a lower temperature of 98 °C, while Al6061/SiC/Gr heats to 230 °C. It can also be observed that the highest operating temperature of Al6061/SiC/Gr was below the maximum operational temperature of the aluminium-based composite (525 °C). Due to high thermal conductivity, Al/SiC/Gr can disperse the generated heat more quickly than cast iron. Moreover, from this analysis, the good temperature distribution in the Al6061/SiC/Gr-based brake rotor can lead to a decline in heat generation, which is the main cause of the hot spot zones. The better thermal properties of the Al6061/SiC/Gr material help to minimize or completely eliminate the thermal failures of brake pads and rotors, thus sustaining their operational reliability.

4.2. Structural Analysis

Structural analysis plays a vital role in assessing the reliability of engineering structures and components. It involves the evaluation of structural integrity, strength, and stability under different loads and operating conditions. Structural analysis of aluminium metal matrix composites (AMCs) involves assessing the mechanical behaviour, strength, and structural integrity of the composite material. In other words, structural analysis is a study of changes in the structure of an object that usually happen due to variations in applied load, material, and heat. In structural analysis, the deformation and stress values of the selected materials were determined. In general, there are two forms of structure failures (analysis) in mechanical engineering: the first one is a static failure, and the other is fatigue failure. Static structural failures occur when a force applied on the object either deforms the object or breaks it down. In fatigue structural failures, an object fails after several loading and unloading cycles. The possible reasons for these imperfections are design flaws and pre-existing microscopic cracks in the surface.

The deformation and stress distributions produced from the simulations on the brake rotors are displayed in Figure 6a,d. For both Al6061/SiC/Gr and cast iron brake rotors, it was confirmed that the maximum stress was produced at the circumference of the rotors. The maximum stress of that Al6061/SiC/Gr (279 MPa) brake rotor was lower than that induced in the cast iron (282 MPa) brake disc. Moreover, better thermal dissipation and conduction at the brake disc rotor's surface significantly influenced the stress. Based on the findings of the structural analysis, it is understood that the superior mechanical property of the Al6061/SiC/Gr material helps to retain the reliability of the pads and rotors in the long run.

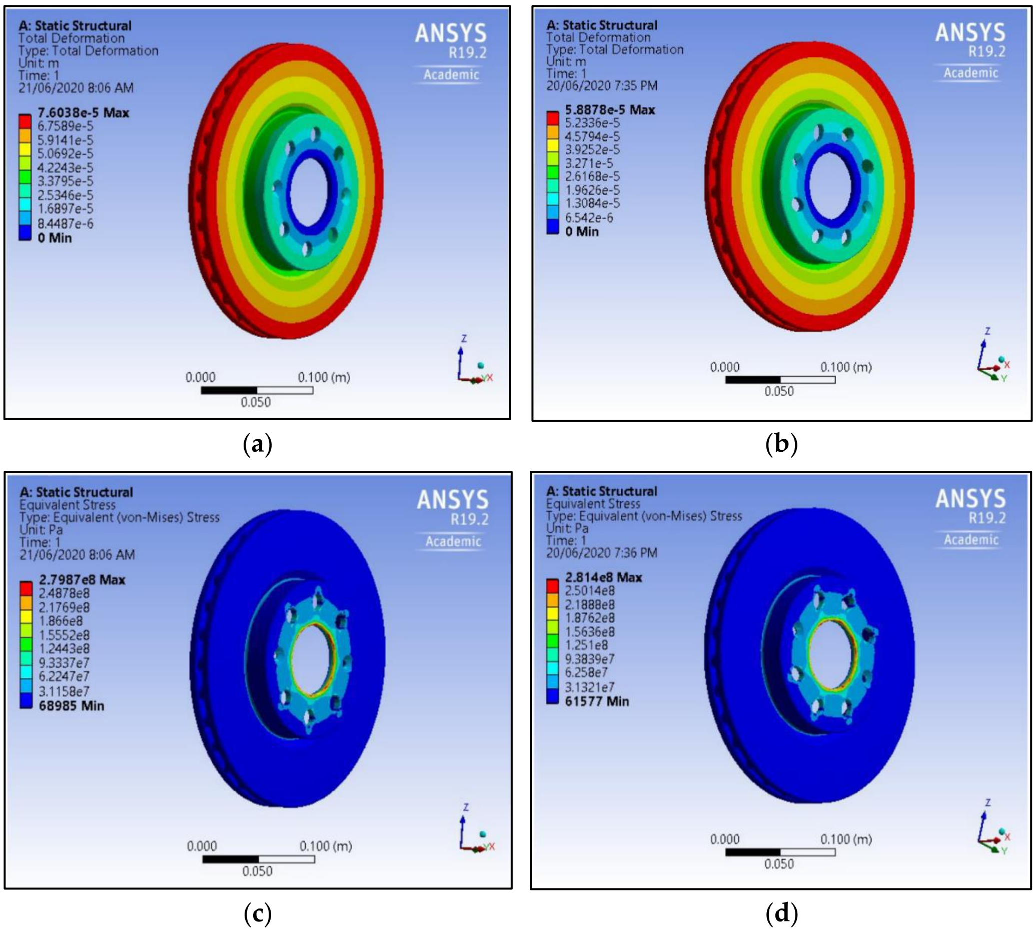


Figure 6. Structural analysis of Al/SiC/Gr- and cast-iron-based brake rotors. (**a**) Deformation—Al/SiC/Gr, (**b**) Deformation—cast iron, (**c**) Equivalent stress—Al/SiC/Gr, and (**d**) Equivalent stress—cast iron.

5. Conclusions

The continuing trend of using metal matrix composite materials has motivated many researchers to focus on the production of lightweight automotive components. A better understanding of metal matrix composite materials is very important for the design of new locomotive parts. The study of hybrid aluminium metal matrix composites in braking systems is very new. This research proposed an advanced aluminium-based hybrid metal matrix composite (Al6061/SiC/Gr) material for brake rotors of a medium-sized vehicle. In the process of manufacturing the brake rotors with the hybrid metal matrix composite for an efficient braking system, thermal and structural analysis played a major role. The effectiveness and high efficiency of the proposed hybrid composite material have been verified with a symmetrical computerized method (FEA). In the simulation, the superior thermal and mechanical performances of the Al6061/SiC/Gr-based brake rotor indicated that this advanced material could replace the traditional cast-iron-based brake disc. After carefully examining the strength, stiffness, and thermal conditions, the brake disc made of Al6061/SiC/Gr is safe as it shows better operational reliability. The proposed idea of using hybrid aluminium metal matrix composite can be further studied in designing and developing other essential components of the braking system, i.e., brake pads and calipers. Moreover, developing different types of hybrid composites other than those involving silicon carbide and graphite as reinforcements can also be considered and tested for automobile applications.

Author Contributions: Conceptualization, data curation, formal analysis, methodology, writing—original draft, writing—review and editing, M.S. and H.K.G.; data curation, writing—review and editing, H.K.G., A.M. and S.M.; data curation, formal analysis, M.S., H.K.G., S.M., T.V.T.N., M.K.L. and V.V. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

MMC	Metal Matrix Composites
AMC	Aluminium Matrix Composite
HMMC	Hybrid Metal Matrix Composites
FEA	Finite Element Analysis
SiC	Silicon Carbide
Gr	Graphite
SEM	Scanning Electron Microscope
A1	Aluminium

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