THERMAL AND MECHANICAL ANALYSIS OF WHEEL RIM IN FORMULA 1 VEHICLES

by

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The wheel rim is a metal or alloy component that holds the tire and connects it to the vehicle. The wheel rims of Formula 1 cars are exposed to thermal stresses during the race and frequent braking at high speeds. In addition to thermal resistance, wheel rims must possess high mechanical durability. Therefore, material selection is crucial, along with the designs of the wheel rims. In the production of wheel rims for Formula 1 vehicles, magnesium, aluminium, and carbon fibre wheel rims are commonly used. Each of these materials has its advantages and limitations. Optimization processes in Formula 1 technology aim to reduce mass while increasing mechanical and thermal properties. Therefore, alloys used in wheel rim production are continuously evolving. In this study, deformation, stress, and temperature values were investigated using the Computational Fluid Dynamics (CFD) method by exposing Mg AZ80, Al 6061-T6, and carbon fibre to conditions of 300 °C temperature, 1 MPa pressure, and 300 km/s speed. Turbulence modelling was carried out using the k-ε method in numerical analyses, which utilized a mesh file consisting of approximately 2 million grids. As a result, the highest deformation in mechanical pressure analyses was obtained using Mg AZ80 material. In contrast, carbon fibre achieved the lowest deformation value in the analysis. Regarding thermal results, the lowest temperature value of 282.75 °C was obtained from the wheel rim made of carbon fibre, whereas with the use of Mg AZ80 material, this value reached up to 292.03 °C. Considering these values, it was concluded that carbon fibre is the most suitable wheel rim material for Formula 1 race cars.

Key words: computational fluid dynamics, wheel rim, Mg AZ80, Al 6066-T6, carbon fiber

1. Introduction

Wheels are a crucial element that can affect the performance of any moving vehicle [1]. The wheels' size, weight, material, and design directly impact a vehicle's speed, safety, fuel economy, and driving comfort. The wheels' size determines the tyres' size in contact with the ground. The wheels' weight affects the vehicle's total weight, and lighter wheels can enhance overall performance [2]. The wheel rim is a metallic or alloy component that holds the tire and connects it to the vehicle. It is a significant part that contributes to the vehicle's aesthetic appearance. The wheel rim plays a crucial role in every vehicle equipped with wheels, including automobiles, trucks, motorcycles, bicycles, and even aircraft. Material selection can influence wheel rims' durability, temperature tolerance, and aerodynamic performance. Design directs airflow around the wheel rims, potentially enhancing the vehicle's aerodynamic efficiency. In summary, all mechanical system components interact, contributing to the overall functionality of each system section [3-4].

F1 cars involve specially designed vehicles that bring together top-level technology and innovation in engineering [5]. The examination of factors influencing the performance of these fast and technological vehicles requires a continuous process of research and development. In this context, the static and thermal analysis focused on the wheel rims of Formula 1 cars plays a crucial role in determining the overall performance and reliability of the vehicle. Beyond being merely aesthetic elements, wheel rims provide aerodynamic and thermal advantages to vehicles [6]. Therefore, analyzing thermal and mechanical factors for wheel rims is considered an essential aspect of the performance and durability of race cars.

The primary objective in evaluating the thermal properties of wheel rims is to mitigate the potential adverse effects of heat generation. Formula 1 cars operate at extremely high speeds and are subject to significant aerodynamic resistance due to their advanced aerodynamic designs. This resistance can lead to excessive wheel rim heating, adversely affecting the vehicle's overall driving performance [7,8]. Excessive heat can impair tyre performance by reducing grip and increasing wear, adversely impacting the brake systems, causing them to overheat and straining the vehicle's overall durability [9,10]. Overheating the tyres can result in catastrophic failures or accidents, particularly at high speeds, leading to potentially fatal consequences [11]. Thus, effective thermal management of wheel rims is critical for maintaining vehicle performance and ensuring driver safety. This research addresses these issues by investigating the thermal and mechanical properties of different wheel rim materials to identify the most effective solution for managing heat and enhancing overall performance in high-speed conditions.

Wheel rims must also be designed to withstand centrifugal forces generated during high-speed turns. Centrifugal force is the outward force experienced by a rotating object [12]. At any point on the outer edge of a rotating object, a force is felt as it moves away from the centre during a rotating motion. This force is directed towards the outer part of the object and is typically perceived opposite to the direction of the vehicle's motion. In high-speed turns, it becomes more pronounced around the vehicle's axis of rotation. In this scenario, the outer edge of the Wheel rims experiences centrifugal force because it moves faster than the edge on the inside of the turn [13]. Therefore, wheel rim designs for high-speed vehicles must be engineered to withstand centrifugal forces.

Numerous studies have been conducted on this topic in the literature. Some of them are as follows. Josefsson and colleagues stated that approximately 25% of the total aerodynamic resistance of a passenger vehicle is attributed to wheels and rims, emphasizing the need for a specific design in this region. To better understand the impact of the rotating mechanical axis on vehicle performance, analyses were conducted using experimental and Computational Fluid Dynamics (CFD) methods. It was concluded that results obtained through the CFD method can be accurately interpreted [14-15]. Gadwala and Babu advocated optimizing the weight of various components to enhance the performance of vehicles [16]. In pursuit of this goal, carbon fibre rims were designed and produced instead of conventional aluminium rims. Calculations demonstrated higher performance using the self-produced automobile rim. Zucchini and colleagues investigated the use of composite materials in designing wheel rims for a sports car [17]. They manufactured a composite material rim using resin transfer moulding, comparing it with a Ferrari 488 GTB wheel rim through experiments. Although the desired performance was not achieved in sharp bends, the reliability of the composite rim and its compliance with the standards were generally confirmed. Stearns and colleagues used finite element method calculations to measure the reaction of an A356-T6 aluminium alloy automobile rim under load. The results showed that under the influence of a radial load, the contact point of the rim became oval and started to deform. Despite frequently using aluminium rims in racing cars, they observed deficiencies [18].

Padmanabhan and colleagues conducted static analyses for automobile rims using different materials [19]. Using CFD, they performed calculations with magnesium, aluminium, and titanium alloys. They determined that magnesium alloy analyses yielded the best results when comparing equivalent stress and deformation measurements. In contrast, aluminium-based alloys produced the highest deformation, emphasizing the importance of material selection. Jaswin and colleagues investigated the use of graphene oxide nanoparticles in automobile rims [20]. They created three different alloys with varying graphene oxide and aluminium percentages. Manufacturing rims from these composite materials and subjecting them to static pressure, they found that the composite material with 3% graphene oxide and 1.5% aluminium exhibited the highest durability. Majumder and colleagues conducted studies to find a new composite material for wheel rims. They performed numerical analyses using aluminium (Al-Si-Mg) and titanium (Ti-Al) alloys to measure the static strength of rims made from different composite materials. Their CFD-based studies revealed that rims made from aluminium alloy deformed more than those made from titanium alloys, suggesting that titanium alloys are more suitable for high-performance vehicles [21]. Loganathan and Subramani conducted numerical calculations to optimize automobile rims using aluminium alloy Al6061-T4 and magnesium alloy AZ80 [22]. Using SolidWorks for design and Fluent for analysis, their studies aimed to measure static resistance to pressure. While acknowledging that aluminium alloy is an excellent alternative to traditional steel rims, it was found that magnesium rims did not have as high a resistance to pressure. Dhas and colleagues compared the strength of automobile rims made from different composite materials using experimental and analytical methods [23]. They measured the strength of the materials they produced using a Charpy Impact Test device. Their results indicated that the static performance of the hybrid fibre nano polymer composite was superior to other polymer composites, suggesting that this composite material is more suitable for use in automobile rims. Vijayakumar and colleagues designed and conducted numerical analyses for vehicle wheel rims using CAD software and CFD programs [24]. They used aluminium 6061 and 6066 as materials in their analyses. Their studies focused on measuring the deformation of structural parameters, such as bending and stress, during the load applied to the rims. Comparing the data obtained from their analyses, they concluded that aluminium 6061 was more suitable. This article aims to conduct a comparative analysis of the thermal investigation of wheel rims using different materials. Although many articles in the literature regarding the static strength of wheel rims using different materials, there needs to be more new studies concerning the thermal effects of material changes on rims. This study's originality is that materials not used in other articles in the literature were selected, and material behaviours were examined under extreme conditions such as 300 ^{o}C and 1 MPa. In this context, a wheel rim suitable for Formula 1 vehicles was designed, and numerical analyses were conducted using different materials for the designed part. The basis of the performed analyses will be to decide which material's usage conditions were better regarding static strength and thermal aspects.

2. Material and Methods

One of the market's most commonly used wheel rim models has been selected and drawn according to its original dimensions. The designed wheel rim has been subjected to the meshing process for CFD analyses. The materials used in this study were determined in the next step, and mechanical and thermal calculations were first made. The results obtained from the calculations have been compared and interpreted.

2.1. Desing

The design of vehicle wheels and rims is crucial due to their significant impact on aerodynamic performance. Particularly in racing vehicles, where the reduction of aerodynamic resistance is desired, it must be specially optimized [25]. The rims' shape, surface, and dimensions enhance aerodynamic efficiency by directing the airflow around the vehicle. This aspect is essential in racing cars and all vehicles with wheel and rim systems. Recently, new designs have been implemented in the rims of non-motorized vehicles to enhance aerodynamic efficiency [26].

In summary, the design of rims is as crucial as their material. The wheel model used in this study was obtained from the catalogue of a well-known company in the market [27]. The rim model used in this study was drawn in three dimensions using Solidworks software. The solid model view of the rim, with an inner diameter of 360 mm and an outer diameter of 440 mm, is presented in Fig. 1.

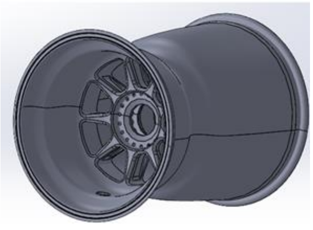

Figure 1. Drawing of the designed F1 wheel rim

2.2. Meshing

A mesh file was generated to prepare the geometry for numerical analysis by dividing the model into small grids. The accuracy of the solution depends significantly on the meshing process, necessitating the creation of tiny grids [28-29]. This study used hexagonal and triangular elements in the mesh, resulting in 4,266,540 grids using ANSYS Meshing. Typically, in finite element analysis, different files are prepared to measure the quality of the generated mesh file, and calculations are performed under the same conditions, comparing the results among themselves. Based on these results, the ideal grid count for the study is determined. However, such a procedure was optional in this study. Instead, the focus was on the ideal element quality value. Ideal element quality values should be as high as possible, preferably above 0.8 and close to 1.00 [30]. The average value of the element quality for the mesh structure created for analyzing the wheel rim model is very close to 1. This indicates that the mesh quality is suitable for analysis. The mesh structure created to analyze the wheel rim design used in Formula 1 vehicles is shown in Fig. 2.

Figure 2. The general view of the mesh

The main criterion in determining the quality of the solution mesh of the model is the skewness value. The high skewness value creates the risk of making wrong solutions. On the other hand, in CFD software, this value should not be greater than 0.90 for a solution to be made. As seen in Table 1, in this study, there were no cells with skewness in the range of 0.9-1.0, which is the maximum critical range. The highest skewness is 0.812 and is located in the wheel rim area. In this case, it can be said that the solution network is of good quality.

Table 1. Distribution of the number of elements according to the skewness value

Skewness Range	Number of Elements	Percent
0 ------ 0.1	1,303,888	30.85
0.1 ------ 0.2	473,795	11.21
0.2 ------ 0.3	659,341	15.6
0.3 ------ 0.4	825,020	19.52
0.4 ------ 0.5	425,190	10.06

0.5 ------ 0.6	369,823	8.75
0.6 ------ 0.7	143,702	3.4
0.7 ------ 0.8	17,328	0.41
0.8 ------ 0.9	8,453	0.20
0.9 ------ 1	0	0

After the mesh file created for this study is finished, a thorough assessment of orthogonal alignment has been carried out to confirm its accuracy. The precision and fluidity of the geometric relationships between the mesh network's parts are referred to as the orthogonal quality. An increased orthogonal quality indicates better element alignment and a more seamless connection. This, in turn, establishes a foundation for more exact and dependable analytical outcomes. Within the domain of finite element analysis, orthogonal quality is important since a poor mesh network can lead to erroneous conclusions and forecasts. To clarify, a mesh network with low orthogonal quality could ignore or distort important information like load distribution or stress concentration. Closeness to 1 in the maximum values denotes an excellent orthogonal quality, suggesting that the pieces connect at around 90-degree angles. This closeness to unity is a desired quality for accuracy in findings, highlighting the significance of well-connected element surfaces. Table 2 provides the orthogonal quality range values of the generated grids.

Table 2. Distribution of the number of elements according to the orthogonal quality value

Skewness Range	**Number of Elements**	**Percent**
0 ------ 0.1	1,303,888	30.85
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0.8 ------ 0.9	8,453	0.20
0.9 ------ 1	0	0

The mesh file created for the wheel rim model exhibits an appropriate orthogonal quality range of its grids when Table 2 is examined.

2.3. Material

Three different composite materials have been chosen for the mechanical and thermal analysis of F1 car wheel rims, including magnesium alloy, aluminium alloy, and carbon fibre, commonly used high-performance car wheel rim materials on the market. This study explicitly selects aluminium alloy 6061-T6, magnesium alloy AZ80, and carbon fibre to explore their deformation, stress, and temperature responses under extreme conditions. By comparing these materials under identical conditions, the study aims to identify the optimal material for F1 wheel rims. It provides new insights into their performance and potential improvements in material selection for high-stress applications. Each of these materials offers different advantages and disadvantages. The Al 6061-T6 material, a heat-treated form of aluminium, exhibits the best mechanical properties and better machinability [31-32]. However, its disadvantages include being heavier than other alloys and having lower fatigue resistance [33]. Magnesium alloys are the lightest among metals used in wheel rim manufacturing. They also possess superior shaping characteristics compared to other metals. However, magnesium alloys have lower corrosion resistance and static strength under load than aluminium alloys. The Mg AZ80 used in this study contains 8% aluminium and 0.5% zinc, providing higher strength and thermal resistance as a composite material [34]. Jants made from carbon fibre are lighter and more deformation-resistant than magnesium and aluminium brake discs. With its exceptionally high thermal conductivity, carbon fibre can maintain its shape even at high temperatures. Therefore, carbon fibre wheel rims can be comfortably used at higher operating temperatures and have a longer lifespan than other materials. However, the major drawback of using carbon fibre is its high cost [35]. Some physical properties of the used composite materials are provided in Table 3.

Table 3. Thermophysical properties of materials

	Mg AZ80	**Al 6061-T6**	**Carbon Fiber**
Density (g/cm³)	1.83	2.71	1.75
Thermal Conductivity (W/m.K)	76	155.3	70
Tensile Ultimate Strength (MPa)	380	310	3590
Compressive Yield Strength (MPa)	275	259.20	2250

2.4. Mechanical Analysis

Wheels and the rims connecting them to the vehicle are crucial components for vehicles, playing a vital role in driving safety and performance [17]. Wheel rims must be securely and robustly attached to the vehicle to provide grip at high speeds and challenging conditions, ensuring driving safety and protecting passengers. Therefore, mechanical analysis is crucial to measuring wheels' durability, safety, and performance. Mechanical analysis examines the rims' material properties, design, and dimensions [36]. This analysis helps to understand how the wheel rims behave under load, facilitating design changes. Additionally, it enables the anticipation of potential damage locations. This study will calculate stress conditions and deformation values in the F1 wheel rim using pressure and rotation speed parameters.

A total pressure of 1 MPa has been applied to the wheel rim from the surfaces indicated in Fig. 3. Formula 1 vehicles can reach very high speeds, especially at straight angles and curves. In some tracks, Formula 1 cars can reach speeds of up to 300 km/h; therefore, this value has been considered as the speed in the analyses conducted in this study.

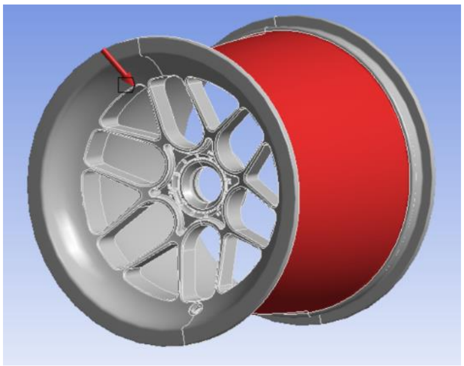

Figure 3. The pressure surfaces

2.5. Thermal Analysis

In Formula 1 races, vehicles often make sudden braking manoeuvres due to their high speeds. During braking, brake discs and pads convert kinetic energy into heat energy [33]. This heat is dissipated from the wheel and rim to the surroundings. Additionally, the friction of the vehicle wheel rims on the race track also generates heat. Furthermore, hot air from the engine and exhaust systems can heat the rims [37-38]. Although numerous reasons can increase the temperature of the rims, they can experience thermal fatigue above a specific temperature. The analyses aim to examine the thermal load distribution on the wheel rims. Since thermal fatigue can directly affect vehicle performance and the vital condition of the driver, it is essential to prefer materials with high heat resistance in wheel rim manufacturing. Composite materials used as wheel rim materials in F1 cars can be decided through various analyses or experimental studies in CFD programs. ANSYS Fluent was preferred because the CFD program gives the most accurate results while analyzing this study. Thus, it is possible to predict which material can withstand higher temperatures. The temperature of the inner surface of the wheel rim shown in Fig. 4 is assumed to be 300 °C. The ambient temperature with convective heat transfer is defined as 22 °C.

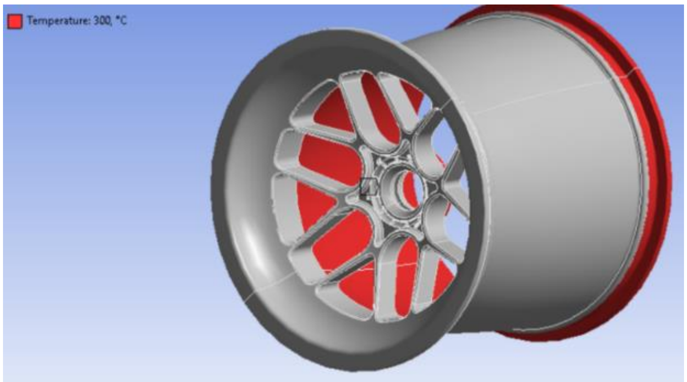

Figure 4. The temperature surfaces

3. Results

The wheel rim of the F1 car was modelled in three dimensions using Solidworks and subjected to mechanical and thermal analyses in ANSYS according to the specified boundary conditions. These boundary conditions include applying a uniform pressure of 1 MPa, a constant temperature of 300 °C, and a convective heat transfer coefficient reflecting ambient conditions at 22 °C. In the conducted mechanical analyses, total deformation values were calculated, while in the thermal analyses, the minimum temperature value representing the maximum cooling rate was obtained. Explaining these boundary conditions is crucial as they directly influence the accuracy and relevance of the simulation results.

3.1. Result of Mechanical Analysis

During the mechanical analysis, a pressure of 1 MPa was applied to the wheel rim rotating at a speed of 300 km/h, and the total deformation in millimetres and maximum stress values in MPa were calculated for each composite material. Contours illustrating the deformation conditions at the end of the analysis for Magnesium AZ80, Aluminum 6061-T6, and carbon fibre materials are presented in Fig. 5, 6, and 7, respectively.

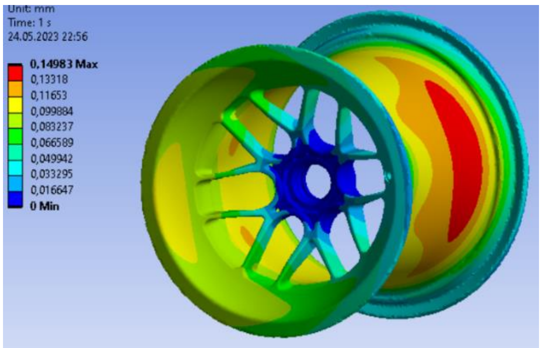

Figure 5. Total deformation result for Mg AZ80

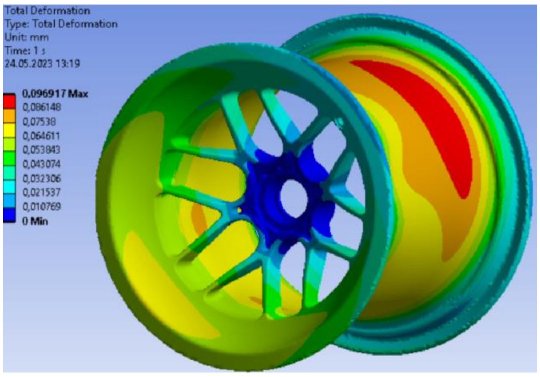

Figure 6. Total deformation result for Al 6061-T6

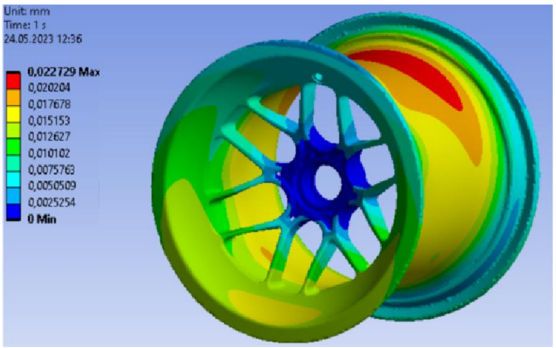

Figure 7. Total deformation result for carbon fibre

According to the total deformation data obtained from the mechanical pressure analysis, the highest deformation value at 300 km/s and 1 MPa pressure was observed in Mg AZ80, with a value of 0.14983 mm. This indicates that Mg AZ80 is the least deformation-resistant under the given conditions. On the other hand, the lowest deformation value, at 0.02000 mm, was observed in carbon fibre, demonstrating its superior resistance to mechanical stress. Al 6061-T6 provided a maximum total deformation value of 0.09600 mm, closer to Mg AZ80 but still significantly higher than carbon fibre. These results indicate that carbon fibre outperforms Mg AZ80 and Al 6061-T6 in terms of deformation resistance, making it the most suitable material for F1 wheel rims in high-stress environments. The significant difference in deformation values highlights the importance of material selection in optimizing performance and durability in high-speed racing applications.

3.2. Result of Thermal Analysis

The wheel rim of the F1 car was modelled in three dimensions using Solidworks and subjected to mechanical and thermal analyses in ANSYS according to specified boundary conditions. In the mechanical analysis, Mg AZ80 exhibited the highest deformation of 0.14983 mm, Al 6061-T6 showed 0.09600 mm, and carbon fibre had the lowest deformation at 0.02000 mm. In the thermal analysis, the minimum temperature values, representing the maximum cooling rates, were determined for each material. Temperature contours for Mg AZ80, Al 6061-T6, and carbon fibre are shown in Figures 8, 9, and 10, respectively. These results highlight carbon fibre's superior deformation resistance and thermal performance compared to Mg AZ80 and Al 6061-T6.

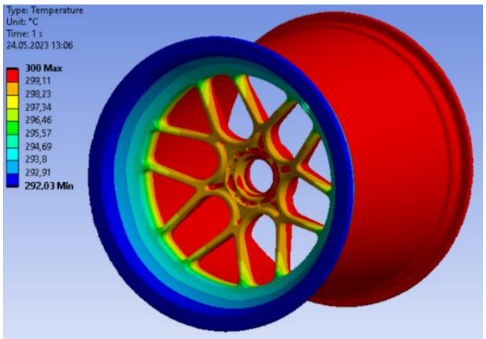

Figure 8. Thermal analysis result for Mg AZ80

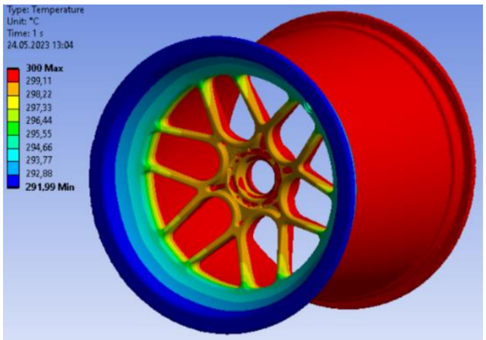

Figure 9. Thermal analysis result for Al 6061-T6

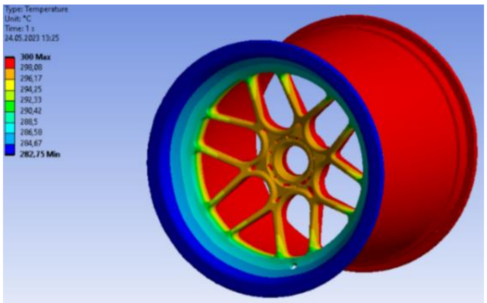

Figure 10. Thermal analysis results for carbon fibre

According to the data from thermal analyses, the highest wheel rim surface temperature was observed with Mg AZ80 material, reaching 292.03°C, while the lowest was found in carbon fibre, measuring 282.75°C. Al 6061-T6 material had a surface temperature of 291.99°C. These findings indicate that carbon fibre wheel rims have superior heat transfer characteristics and experience fewer heating issues than Mg AZ80 and Al 6061-T6. This result is significant as it demonstrates the potential for improved performance and durability of F1 car wheel rims using carbon fibre. Unlike previous studies that primarily focused on individual materials, this comprehensive comparison provides new insights into the thermal behaviour of these materials under identical conditions. By highlighting the advantages of carbon fibre in terms of heat dissipation, this study contributes to optimising material selection for high-performance applications, enhancing the overall efficiency and safety of F1 vehicles.

4. Conclusions

The wheel rim of the F1 car was modelled in three dimensions using Solidworks and subjected to mechanical and thermal analyses in ANSYS according to the specified boundary conditions. The mechanical analyses calculated total deformation values to assess the structural integrity under pressure. The minimum temperature value was obtained in the thermal analyses to determine the maximum cooling efficiency. These analyses were performed to understand how different materials behave under extreme conditions, aiming to optimize the wheel rim design for better performance and durability in high-speed racing environments.

In this study, three-dimensional modelling of the F1 wheel rim was performed using SolidWorks, and mechanical and thermal analyses were conducted using three different materials: Mg AZ80, Al 6061-T6, and carbon fibre. The results of the mechanical analyses indicated that the carbon fibre composite rim exhibited lower deformation than the other materials. Specifically, the carbon fibre rim deformed approximately seven times less than Mg AZ80 and about 4.5 times less than Al 6061-T6. The thermal analysis revealed that the carbon fibre rim experienced a temperature increase of approximately ten °C less than the other materials. In Formula 1, maintaining optimal cooling rates is crucial as it directly affects vehicle performance. A higher cooling rate reduces the thermal expansion and deformation of the wheel rim, enhancing its stability and durability under high-speed conditions. Consequently, the ability of carbon fibre to maintain lower temperatures and reduce deformation makes it the most suitable material for Formula 1 wheel rims.

In the thermal analyses conducted in this study, the highest temperature value was recorded at 292.03°C for the Mg AZ80 composite material, while the lowest was 282.75°C for the carbon fibre rim. The Al 6061-T6 material exhibited a temperature of 291.99°C. These results are significant as they highlight carbon fibre's superior heat dissipation properties compared to traditional materials like Mg AZ80 and Al 6061-T6. This finding is crucial for F1 car performance, as lower rim temperatures can enhance brake efficiency and overall vehicle functionality. Unlike previous studies that often focused on single-material analyses, this study provides a comprehensive comparison, offering new insights into optimising material selection for F1 wheel rims. The data presented in Table 2 underscore the potential for carbon fibre to improve the thermal management and durability of F1 wheel rims, contributing to advancements in high-performance automotive engineering.

In the mechanic analyses conducted in this study, carbon fibre showed the lowest total deformation of 0.022 mm, significantly less than Mg AZ80 (0.149 mm) and Al 6061-T6 (0.097 mm). This shows that the carbon fibre rim experienced the most minor deformation under the given conditions, indicating superior mechanical performance.

Regarding thermal performance, the carbon fibre rim reached the lowest temperature of 282.75 °C, compared to 292.03 °C for Mg AZ80 and 291.99 °C for Al 6061-T6. This shows that carbon fibre has better thermal management ability and reduces temperature more effectively than other materials. Considering all these obtained data, carbon fibre is the most suitable material for the F1 wheel rim.

Acknowledgements

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