Structural and Fatigue Analysis of Aluminium A356 Alloy Automotive Wheel Using Finite Element Method

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Abstract

Automobile wheels are essential structural elements that transmit forces produced during braking, acceleration, and cornering as well as sustain vehicle loads. Lightweight components are becoming more and more necessary in contemporary automotive engineering to enhance vehicle performance, fuel economy, and pollution reduction. Because of their high strength-to-weight ratio, strong resistance to corrosion, and superior thermal conductivity, aluminium alloys are now commonly employed in the production of wheels. Because of its excellent cast ability, mechanical strength, and fatigue resistance, A356 aluminium alloy is frequently utilized for vehicle wheels.

The structural analysis of an automobile wheel composed of A356 aluminium alloy is the main topic of this work. The main goal is to assess the wheel's overall structural performance, deformation characteristics, and stress distribution under various loading scenarios. Using computer-aided design (CAD) software, a three-dimensional model of the wheel is created, and finite element analysis (FEA) is used for analysis. In order to evaluate the wheel's structural integrity, the simulation takes into account actual loading scenarios as impact and radial loads.

The analysis's findings shed light on the aluminium alloy wheel's deformation behaviour and areas of stress concentration. In order to increase strength and durability, the study assists in identifying crucial areas that need design modification. The results show that, when compared to traditional steel wheels, A356 aluminium alloy wheels provide notable benefits in terms of weight reduction and structural performance. Thus, in contemporary automotive applications, the use of A356 alloy wheels enhances vehicle performance, safety, and efficiency.

Keywords: Aluminium A356 alloy, Automotive wheel, Finite element analysis (FEA), Stress analysis, Lightweight materials, Structural performance.

1.Introduction

Because they support the weight of the vehicle and transfer forces produced during acceleration, braking, and cornering, automotive wheels are among the most important structural elements of a car. During service circumstances, the wheel is exposed to a variety of loads, including as radial loads, lateral loads, bending stresses, and cyclic fatigue stresses. To enable safe vehicle operation, wheels must have great strength, stiffness, durability, and fatigue resistance due to these complicated loading circumstances. Automotive wheel development requires careful material selection and structural design because a wheel component failure can result in serious accidents (Shigley et al., 2015; Budynas & Nisbett, 2014).Due to growing concerns about fuel efficiency, emission reduction, and environmental sustainability, lightweight design has become a primary engineering focus in the modern automotive industry. Improved fuel economy and reduced carbon dioxide emissions are directly correlated with vehicle weight reduction. According to studies, a 10% reduction in vehicle mass might result in a 6–8% increase in fuel efficiency. Because of this, automakers are replacing traditional steel parts with lighter materials including aluminium alloys, magnesium alloys, and composite materials (Ashby, 2011; Mallick, 2010; Cole et al., 2016).

Because they are a component of the vehicle's unsprung mass, wheels offer a substantial possibility for weight reduction among various automobile components. Reduced unsprung mass enhances braking, acceleration, handling, and ride comfort. Additionally, lightweight wheels improve vehicle dynamic performance by lowering rotational inertia. In order to create wheels that are both lightweight and structurally sound, a lot of research has been done employing cutting-edge materials and optimized geometry (Mohan & Babu, 2017; Yang & Wang, 2013).

In view of its advantageous mechanical and physical characteristics, aluminium alloy wheels are now widely used in passenger cars. Aluminium alloy wheels offer superior strength-to-weight ratios, superior corrosion resistance, good thermal conductivity, and enhanced visual appeal as compared to traditional steel wheels. Aluminium's enhanced thermal conductivity aids in greater heat dissipation from braking systems, increasing braking effectiveness and lowering thermal loads. Better vibration dampening qualities are another benefit of aluminium alloy wheels, which enhances driving comfort (Davis, 1993; Totten & MacKenzie, 2003).

A356 aluminium alloy is one of the most popular casting alloys for making automobile wheels among the different aluminium alloys used in automotive applications. Silicon and magnesium are the main alloying constituents of A356 alloy, which offers superior corrosion resistance, high strength, and outstanding cast ability. Additionally, the alloy performs well under fatigue, which is crucial for wheel components that are subjected to cyclic loading when a vehicle is in motion. Because of these benefits, A356 alloy is frequently utilized in low-pressure die casting and gravity casting procedures to create premium car wheels (Kaufman, 2000; Campbell, 2015).

For manufacturers to guarantee safety, longevity, and optimal performance under actual operating conditions, structural analysis and performance evaluation of aluminium A356 alloy wheels are crucial.

Engineers can enhance wheel design and minimize weight without compromising structural integrity by using finite element analysis (FEA) to investigate stress distribution, deformation behaviour, and fatigue performance of wheels (Rao et al., 2019; Zhang et al., 2020).

2. Material Description

One of the most used casting alloys in the automobile sector is aluminium alloy A356, especially for parts like wheels, cylinder heads, and structural elements. The alloy is a member of the Al–Si–Mg family, where magnesium adds strength by precipitation hardening and silicon enhances cast ability and fluidity. A356 alloy is frequently used in gravity casting and low-pressure die casting procedures for the production of automobile wheels because of its superior cast ability, strong strength-to-weight ratio, and outstanding corrosion resistance. Because of these characteristics, A356 aluminium alloy is appropriate for parts like car wheels that are subjected to dynamic loads and cyclic loading (Davis, 1993; Kaufman, 2000).

Apart from being lightweight, A356 aluminium alloy has superior heat conductivity and exceptional fatigue resistance, all of which are crucial for automobile wheel applications. Additionally, the alloy is suitable for large-scale industrial production due to its good machinability and weldability. Precipitation strengthening mechanisms, which increase yield strength and tensile strength, greatly improve the mechanical characteristics of A356 alloy following heat treatment, especially T6 heat treatment (Campbell, 2015).

2.1 Chemical Composition of A356 Alloy

The key alloying elements in A356 aluminium alloy are silicon and magnesium, with aluminium serving as the base metal in table.1. To regulate casting behaviour and mechanical characteristics, minor elements including iron, copper, manganese, zinc, and titanium are also used in trace amounts. Silicon enhances the alloy's fluidity and casting properties, making it possible to produce intricate geometries like car wheels effectively. Through precipitation hardening during heat treatment procedures, magnesium boosts strength (ASM International, 2001).

Table 1: Chemical Composition of A356 Alloy

Element	Composition (%)
Aluminium (Al)	Balance
Silicon (Si)	6.5 – 7.5
Magnesium (Mg)	0.25 – 0.45
Iron (Fe)	≤ 0.20
Copper (Cu)	≤ 0.20
Manganese (Mn)	≤ 0.10
Zinc (Zn)	≤ 0.10
Titanium (Ti)	≤ 0.20

2.2 Key Properties of aluminium A356 Alloy

Aluminium A356 alloy possesses several properties that make it suitable for automotive wheel applications:

1. Lightweight: Because aluminium alloys have a density that is about one-third that of steel, they greatly reduce the weight of vehicles.
2. High strength-to-weight ratio: Maintains low bulk while offering structural integrity.
3. Excellent resistance to corrosion: Creates a naturally occurring oxide layer those guards against environmental deterioration.
4. Outstanding cast ability: During casting procedures, high silicon content enhances fluidity.
5. Good thermal conductivity: Aids in the braking systems' heat dissipation.
6. Good fatigue resistance is crucial for parts like wheels that are subjected to cyclic loads.

2.3 Mechanical Properties of A356 Alloy

The mechanical properties of A356 alloy depend on the casting process and heat treatment condition. In automotive wheel manufacturing, the alloy is commonly used in the T6 heat-treated condition to achieve higher strength and improved fatigue performances shown in table 2.

Table 2: Mechanical Properties of A356 Alloy

Property	Typical Value
Density	2.67 g/cm³
Yield Strength	170 – 230 MPa
Ultimate Tensile Strength	230 – 310 MPa
Elastic Modulus	70 GPa
Elongation	3 – 8 %
Hardness	75 HB
Poisson’s Ratio	0.33

A356 alloy's low density and comparatively high strength make it ideal for lightweight structural elements like car wheels. These characteristics minimize the total bulk of the vehicle while enabling the alloy to sustain operating loads (Kaufman, 2000).

3. CAD Modelling

The design and development of automobile components heavily relies on computer-aided design, or CAD. CAD modelling aids engineers in producing precise three-dimensional geometries that accurately depict the real wheel structure in the context of automobile wheels. These models are employed for dimensional verification, visualization, and additional engineering analysis, including finite element analysis (FEA). Additionally, the CAD model reduces development time and cost by identifying design modifications prior to manufacturing. Using CAD software, a three-dimensional model of an aluminium alloy wheel was created for the current investigation. The key geometric components of the wheel, including the rim, spokes, hub, and bolt holes, were created throughout the design phase. The wheel's dimensions as shown in fig.1 were chosen using the standard wheel specs seen in passenger cars.

Figure 1: CAD Model of aluminium Alloy Wheel

3.1 Wheel Design

The rim spokes, hub, and bolt circle are among the structural elements that make up an automobile wheel. The outer circular part that supports the weight of the car and retains the tire is called the rim. The spokes are in charge of transferring forces between the hub and the rim by joining the rim to the central hub. The hub is the central portion of the wheel that connects to the vehicle axle through bolt holes. To guarantee sufficient strength, stiffness, and longevity under a range of loading scenarios, these structural components must be carefully developed. Because multi-spoke designs offer better load distribution and structural stability, a multi-spoke aluminium alloy wheel design was chosen for this investigation. Standard modelling tools like extrusion revolve, fillet, and pattern operations were used to build the wheel geometry. In order to lower stress concentrations and enhance fatigue performance, appropriate fillet radii were placed at the spokes and rim connections as shown in fig 2.

Rim diameter, rim width, hub diameter, bolt circle diameter (BCD), and spoke thickness were among the exact dimensional data used in the development of the CAD model. To guarantee realistic structural behaviour during study, these dimensions were established using common automotive wheel standards (Mallick,2010).

The finished CAD model as shown in fig.1 was then integrated into finite element analysis software for structural analysis after being exported in a common format like STEP or IGES. The CAD model is the basis for assessing the aluminium A356 alloy wheel's overall performance, deformation properties, and stress distribution under various loading scenarios (Rao et al., 2019) shown in table 3.

Table.3: Wheel parameters

S.No	**Parameters**	**Value**
1	Area	196761.05 mm^2
2	DIAMETER	280MM
3	PERIMETER	1759.29mm
4	WEIGHT OF THE CAR	1.5 T
5	PASSEENGER 5 PEOPLE	400 KG
6	EXTRA LOAD	500KG
7	TOTAL	23520N
8	TYRES AND SUSPENSION REDUCED BY 30 %	16464N
9	WEIGHT ON INDIVIDUAL WHEEL	4116N
10	PRESURE	0.08N/mm^2

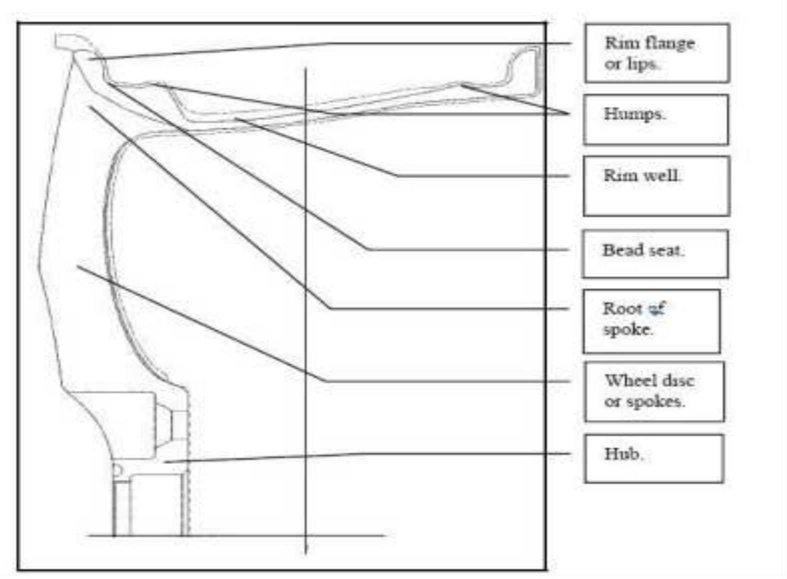

Figure 2: Wheel Components (Rim, Spokes, Hub)

4. Finite Element Analysis

In automobile engineering, finite element analysis (FEA) is frequently used to assess a component's structural performance under various loading scenarios. Before actual manufacturing, it enables engineers to forecast stress distribution, deformation, and possible failure areas. FEA is used in automotive wheel design to make sure that the wheel structure can sustain operating loads such impact loads, braking forces and radial forces without compromising structural integrity or safety. Designers can reduce weight and enhance mechanical performance by optimizing the wheel design using numerical simulation approaches .

In order to conduct structural analysis, the CAD model of the aluminium A356 alloy wheel was imported into finite element analysis software. The analysis was done to ascertain the wheel's deformation behaviour and stress distribution under practical operating circumstances.

4.1 Meshing Strategy

As it directly impacts the accuracy of the simulation results, meshing is one of the most crucial phases in finite element analysis. The CAD model is split up into numerous little finite elements joined by nodes during the meshing process. Together, these components depict the structure's geometry and mechanical behaviour during study. To precisely capture the stress distribution for the current study, a fine mesh was created on the aluminium alloy wheel model. Critical areas where stress concentrations are anticipated to occur, such the hub area and spoke-rim junction, received particular attention. In order to reduce computational cost, a substantially coarser mesh was employed in areas with lesser stress gradients, whereas a relatively finer mesh was applied in these parts to increase solution accuracy. To guarantee correct element shape and convergence of findings, the mesh quality was checked.

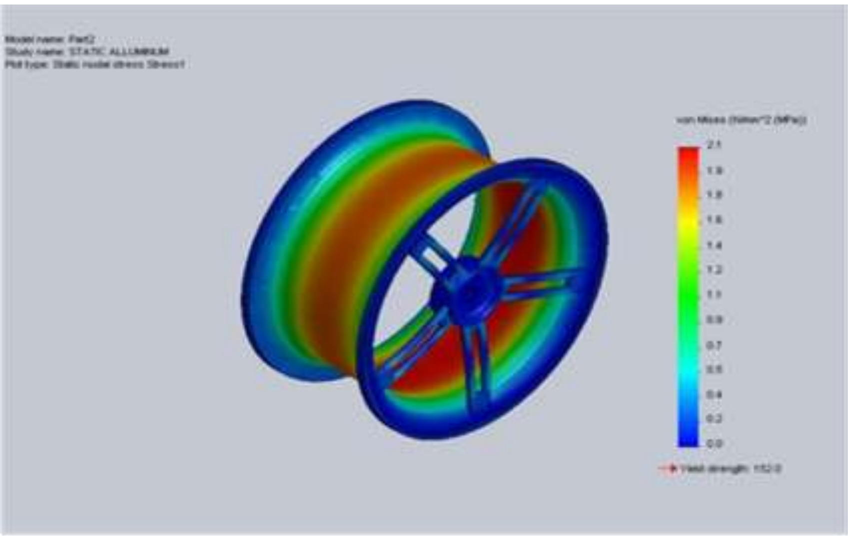

Figure 3: Finite Element Mesh Model

4.2 Element Types

The finite element modelling to accurately depict the geometry and mechanical behaviour of the structure, the right element type must be chosen. Three-dimensional solid elements were utilized for the structural study of the aluminium A356 alloy wheel due to its intricate geometry and variable thickness. Since solid tetrahedral components can properly represent complicated and curved surfaces, they are frequently employed for automotive wheel analysis. Under multi-axial loading circumstances, these elements can capture the behaviour of stress and deformation. The chosen element type yields accurate stress and displacement findings and enables the wheel structure to be examined successfully under actual loading circumstances.

4.3 Boundary Conditions and Loading

Boundary conditions and loading conditions are critical aspects of finite element analysis because they represent the actual working environment of the component. Proper boundary conditions ensure that the simulation closely resembles real operating conditions. In the present analysis, the central hub region of the wheel was constrained to simulate the connection between the wheel and the vehicle axle. The bolt hole areas were fixed to represent the mounting condition of the wheel on the vehicle hub.

A radial load was applied on the rim region to simulate the vertical load transmitted from the vehicle weight through the tire. This load represents the static load acting on the wheel during normal vehicle operation. The load was distributed uniformly along the rim surface to replicate realistic contact conditions between the tire and wheel. Under these loading conditions, the finite element analysis was performed to evaluate stress distribution, deformation patterns, and potential critical regions in the aluminium A356 alloy wheel. The results obtained from the simulation provide valuable insights into the structural behaviour of the wheel and help in improving design safety and performance.

5. Results and Discussion

Finite element analysis was used to assess the structural behaviour of the aluminium A356 alloy wheel in order to ascertain the deformation and stress distribution under applied loading conditions. The research helps establish whether the wheel design can safely bear operational loads and sheds light on crucial areas where stresses are concentrated. The Von-Mises stress distribution and maximum deformation, which are often used metrics for assessing structural integrity in engineering components, are the main emphasis of the simulation results.

5.1 Von-Mises Stress Distribution

In structural analysis, von-Mises stress is frequently used to assess how ductile materials, such aluminium alloys, yield. It is a representation of an equivalent stress value that integrates the impacts of various stressors on a material. Plastic deformation or failure may happen if the Von-Mises stress is higher than the material's yield strength. The findings of the finite element analysis demonstrate that the aluminium A356 alloy wheel's stress distribution is uneven. The spoke-rim interface and spoke-hub junction regions exhibit the highest amounts of stress. Because they transfer loads from the rim to the hub and are bent during wheel rotation and vehicle loading, these regions are more stressed.

The wheel construction can safely handle the applied radial loading conditions since the simulation's maximum Von-Mises stress stays within the A356 aluminium alloy's permissible stress limit. Optimized spoke shape and appropriate fillet design aid in lowering stress concentration and enhancing the wheel's structural performance. As shown in fig. 5

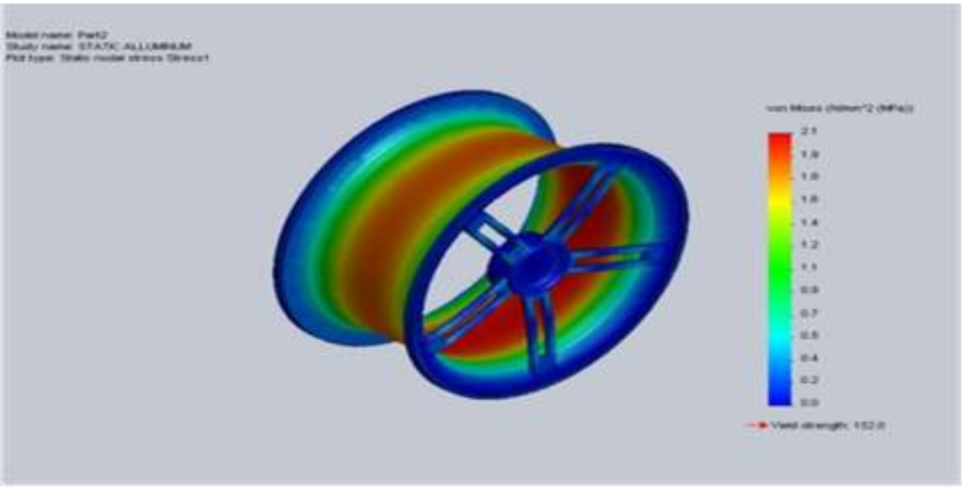

Figure 5: Von-Mises Stress Distribution

5.2 Maximum Displacement

The displacement distribution of the aluminium A356 alloy wheel obtained from the static structural analysis is illustrated in Fig. 6. The results indicate that the maximum displacement occurs mainly in the rim region where the radial load is applied. The maximum displacement obtained from the simulation is approximately 3.86 × 10^{-3} mm, while the minimum displacement is zero observed near the hub region, which is constrained by the boundary conditions representing the wheel–axle connection. The higher displacement in the rim area is expected because it directly receives the load transmitted from the tire and vehicle weight. However, the overall displacement values are extremely small due to the high stiffness and strength of the aluminium A356 alloy material. The results confirm that the wheel structure maintains adequate rigidity and structural stability under the applied loading conditions, indicating that the design is suitable for automotive applications.

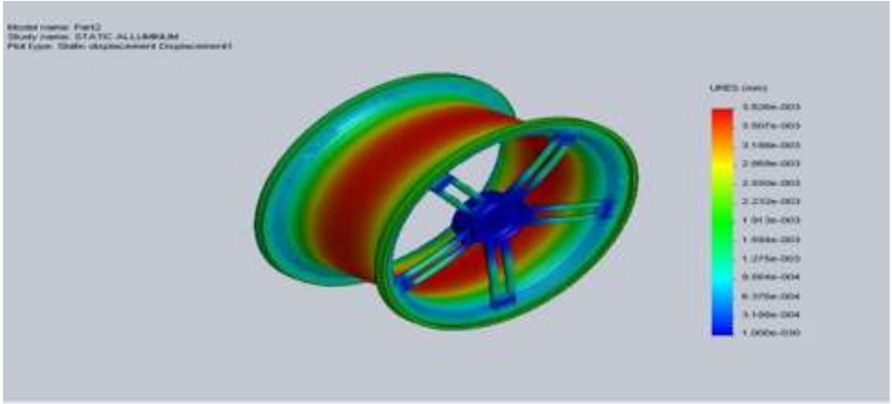

Figure 6: Total Displacement of Wheel

5.3 Fatigue Life Evaluation

Since wheels are constantly subjected to repetitive loading during vehicle operation, fatigue failure is one of the most important failure types in automotive wheels. Vehicle weight, imperfections in the road, braking forces, and cornering conditions all contribute to these cyclic loads. Repetitive loading over an extended period of time can cause fracture initiation and propagation, ultimately leading to fatigue failure, even when the applied stresses are below the material's yield strength. In order to guarantee long-term durability and safety, fatigue life evaluation is a crucial component of vehicle wheel design. Because aluminium alloys typically have lower fatigue strength than steel materials, aluminium alloy wheels—including those manufactured of A356 alloy—must be thoroughly examined for fatigue performance. Engineers can predict the fatigue life of wheel constructions under cyclic loading circumstances by combining fatigue analysis techniques with finite element analysis. S-N curves, which link stress amplitude to the number of cycles to failure, are commonly used to assess fatigue life.as shown in Fig.7 for minimum stress 0.00165150N/mm^2 and maximum is 2.11428 N/mm^2 .

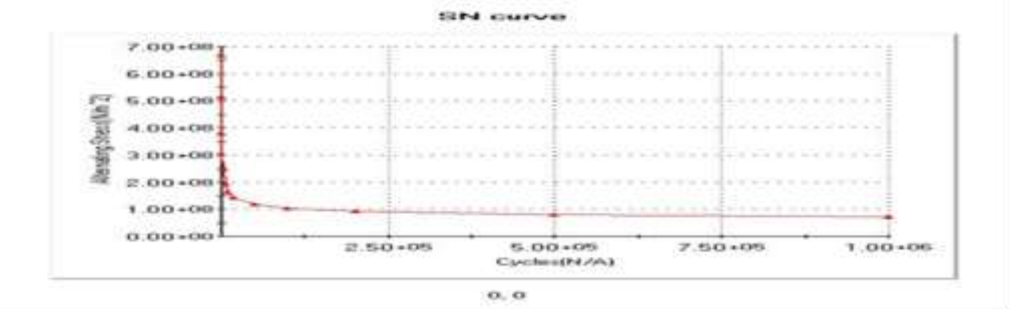

Figure 7: Stress–Life (S–N) Curve for Aluminium A356 Alloy

5.4 Radial Load Fatigue

Radial load fatigue analysis is performed to simulate the vertical load acting on the wheel due to the weight of the vehicle as shown in fig.8. During vehicle operation, the wheel continuously experiences radial forces transmitted from the road surface through the tire. These loads are cyclic in nature because the wheel rotates while supporting the vehicle weight.

In the radial fatigue test, the load is applied at the rim section while the hub region remains constrained to simulate the actual mounting condition of the wheel on the vehicle axle. The applied load causes cyclic stresses in different regions of the wheel structure, particularly at the spoke–rim junction and spoke–hub interface. These regions are considered critical because they experience higher stress concentrations during operation.

The fatigue analysis results indicate that the maximum stress regions correspond to the areas where fatigue cracks are most likely to initiate. However, the stress levels obtained in the analysis remain within the allowable fatigue strength limits of the A356 aluminium alloy. This indicates that the wheel design can withstand the applied radial loading conditions for a large number of loading cycles, ensuring reliable performance during service life as shown in fig.9.

Fig.8. Damage percentage on aluminium alloy

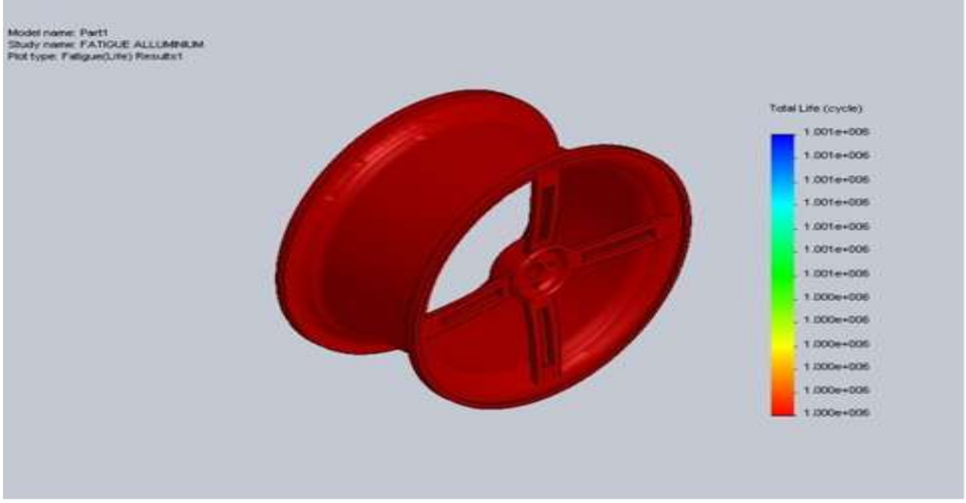

Fig. 9. Total life on aluminium alloy

Table.4: Fatigue analysis of alloy wheels

Material	**Total Life (Cycles) Min**	**Total Life (Cycles) Max**	**Load Factor Min**	**Load Factor Max**
Aluminium	1.0E+06	1.0E+06	92.7230	115533

5.5 Cyclic Loading Analysis

Cyclic loading analysis is performed to evaluate the response of the wheel under repeated stress variations over time. In real driving conditions, wheels experience complex loading patterns caused by road irregularities, acceleration, braking, and cornering forces. These loads produce alternating stress cycles that may lead to fatigue damage in structural components. In this study, cyclic loading conditions were applied to the finite element model of the aluminium A356 alloy wheel to simulate realistic operating conditions as shown in fig.10. The stress response of the wheel was analysed for multiple loading cycles to evaluate its fatigue performance. The results show that the stress amplitude remains within the endurance limits of the material for most regions of the wheel.

The fatigue life prediction indicates that the aluminium A356 alloy wheel is capable of sustaining a large number of stress cycles without structural failure. The spoke geometry and proper fillet design help in distributing stresses uniformly, thereby improving fatigue resistance and extending the service life of the wheel. Overall, the fatigue life evaluation confirms that the aluminium A356 alloy wheel possesses adequate durability under cyclic loading conditions. This analysis is essential for ensuring safe and reliable performance of automotive wheels under real-world operating environments.

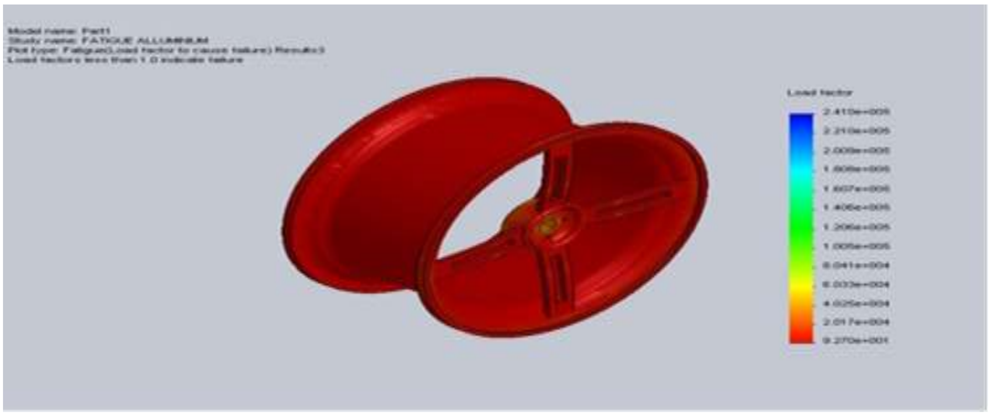

Fig.10. Load factor on aluminium alloy

5.6 Critical Stress Regions

The analysis results indicate that stress distribution across the aluminium alloy wheel is not uniform. The highest stress values are observed primarily in the spoke–hub junction and spoke–rim interface regions. These areas are subjected to higher stresses because they transfer loads from the rim, which supports the vehicle weight, to the hub that connects the wheel to the axle. The Von-Mises stress distribution obtained from the finite element simulation shows that these regions experience stress concentrations due to geometric transitions and load transfer mechanisms. However, the maximum stress values remain within the allowable yield strength limits of the A356 aluminium alloy, which typically ranges between 170 MPa and

230 MPa depending on heat treatment conditions. This indicates that the wheel structure maintains sufficient strength to withstand the applied radial and cyclic loading conditions.

The stress concentration areas identified in the simulation highlight the importance of proper spoke geometry and fillet design. By optimizing these design features, stress distribution can be improved and fatigue resistance can be enhanced. Similar observations have been reported in previous studies on aluminium alloy wheel analysis, where spoke–hub connections were identified as critical regions for structural performance.

5.7 Design Performance

The overall performance of the aluminium A356 alloy wheel design was evaluated based on the results obtained from stress, deformation, and fatigue analysis. The finite element results demonstrate that the wheel structure exhibits adequate stiffness and strength under the applied loading conditions. The deformation results show that the maximum displacement occurs at the rim region, where the radial load is applied. However, the magnitude of deformation remains relatively small due to the high stiffness of the aluminium alloy material. The hub region exhibits minimal deformation because it is constrained by boundary conditions representing the mounting configuration of the wheel.

The fatigue analysis further indicates that the wheel structure is capable of withstanding a large number of loading cycles without failure. The combination of aluminium A356 alloy material properties, optimized spoke design, and proper load distribution contributes to improved durability and long-term performance of the wheel. Overall, the results confirm that the aluminium A356 alloy wheel design satisfies structural safety requirements and provides reliable performance for automotive applications. The lightweight characteristics of aluminium alloy also contribute to improved vehicle efficiency and handling performance.

6. Conclusion

1. Finite element analysis of the aluminium A356 alloy wheel was successfully performed to evaluate the structural performance under radial and cyclic loading conditions. The simulation results provided detailed information on stress distribution, deformation behaviour, and fatigue characteristics of the wheel structure.
2. The maximum Von-Mises stress was observed at the spoke–hub junction and spoke–rim interface, which are identified as the most critical regions of the wheel. However, the obtained stress values were found to be lower than the yield strength of A356 aluminium alloy, indicating that the wheel structure operates within safe stress limits.
3. The maximum displacement obtained from the static structural analysis was approximately 3.86×10^{-3} mm, which occurred mainly in the rim region where the radial load was applied. The hub region experienced minimal displacement due to the applied boundary constraints.
4. Fatigue analysis results indicate that the wheel can sustain approximately 1×10^{6} loading cycles, demonstrating adequate fatigue strength for long-term automotive service conditions.

5. The fatigue damage factor obtained from the analysis remained within acceptable limits, confirming that the aluminium wheel structure can withstand repeated cyclic loading without premature failure.
6. Frequency analysis results show that the maximum displacement values for different materials were approximately 962.28 mm for aluminium, 612.85 mm for zinc, and 1208.22 mm for magnesium, indicating that aluminium provides a balanced performance between structural stiffness and weight reduction.
7. Overall, the analysis confirms that the aluminium A356 alloy wheel design satisfies structural safety requirements, providing high strength, good fatigue resistance, and reliable performance for automotive wheel applications.

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