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***Research paper***

# Fatigue Life Simulation of an Alloy Wheel Design

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## Abstract

Finite element analysis (FEA) is extensively used in the engineering field, especially in structural engineering. FEA is a numerical method used for solving engineering problems that involve complicated geometries, various loading conditions and material properties. A fatigue life assessment of an engineering component is necessary to predict the life span of this component before failure. Automobile alloy wheel is an engineering component that is exposed to fatigue failure in services. Therefore, this study aims to determine the critical area for crack initiation on automobile alloy wheel and to simulate and analyse the fatigue life of an automobile alloy wheel design that is fabricated from different types of materials. The automobile alloy wheel design was modelled using computer-aided design and analysed using commercial finite element software. The automobile alloy wheel was modelled based on a 1200 cc national automobile. Three types of materials, namely, titanium, aluminium and magnesium alloys, were used in this study. A critical part of a steering knuckle could be identified by conducting a stress analysis, and the fatigue life of the automobile alloy wheel could be predicted on the basis of applied loads. Results showed that fatigue life is significantly influenced by the types of material used in a simulation.

***Keywords***: *Alloy wheel; Design; Fatigue Life; Finite element analysis; Simulation.*

## 1. Introduction

Wheels are an important component of vehicles. The strength of an automobile alloy wheel rim is crucial to engineering design, which plays an important role in determining the overall performance of a vehicle, the structural integrity of a rim and the life span of an alloy wheel rim [1]. The integrity of this alloy wheel also contributes to the safety of vehicles and passengers. A designer must ensure on the basis of strict reliability specifications that an alloy wheel can tolerate cyclic loading during an operation. Wheels must be sufficiently robust to with-stand force and variable loads from vehicles.

The major causes of automobile alloy wheel failure include manufacturing defect, crack initiation at welds, overtightening of bolts and corrosion. These failures can be detected by using various non-destructive methods, such as visual and ultrasonic inspections. Thus, a manufacturer must determine the root cause of a failure to prevent the occurrence of similar failures in the future [2]. Moreover, stress concentration must be avoided in the design stage and during the manufacturing process. Minimal imperfections and pre-cracks increase service loads and expand pre-cracks occasionally. Failures occur at the stress concentration point after a certain number of cycles.

The selection of materials for an alloy wheel is important. An appropriate selection must consider customers and design requirements, such as cost, performance, safety, risk and aesthetics. Few characteristics, such as mechanical properties, fatigue strength, fracture toughness and thermal properties, must also be recognised. Furthermore, these characteristics reflect the optimal performance for vehicles in terms of alternate fuel, alternate materials, power train enhancements and aerodynamic improvement. Many types of materials, that is, from wood to steel and alloys, are used in an alloy wheel design. The materials that are used currently in wheels are focused on light alloys, such as aluminium, magnesium, titanium and composite materials.

Aluminium alloy is lighter than steel. Thus, the performance of a car is increased. However, manufacturing aluminium alloy is costly because of technologies. Aluminium has been extensively applied to automobile components, such as automobile engine, transmission parts and wheels [3]. Aluminium alloy has been used in the automotive industry given its strength, light weight, recyclability, ductility, durability, corrosion resistance, formability and conductivity. The strength of aluminium alloys can be optimised by modifying the composition of its alloys depending on the application uses. Aluminium alloy can provide strength similar to that of steel when mixed with other metals without losing its ductility. In addition, aluminium alloys have a high corrosion resistance given their protective oxide coating [4]. However, aluminium alloys have lower fatigue strength than steel, and fatigue failure can occur even with minimal cyclic loadings.

Magnesium alloy is widely used given its high strength and low density. The vehicle performance improves, and fuel consumption decreases with the reduction in vehicle weight. The main advantages of magnesium alloys in engineering components are their lower mass and better strength than aluminium alloys and other materials. In addition, magnesium alloys are widely used in the automotive industry given its light weight, low density, high melting point and remarkable corrosive resistance. Magnesium alloys also have excellent strength, ductility, creep properties and low cost of production [5]. However, magnesium alloys have low strength and poor corrosion resistance at high temperature [6].

Fatigue failure occurs under cyclic or fluctuating loading [7,8]. Structural or engineering components are prone to fatigue when subjected to a certain number of cyclic loading, which normally occurs below the ultimate strength of a material. Fatigue also typically occurs without warning after a progressive degradation of the material subjected to cyclic loadings [9,10]. Fatigue is consid-

ered a major failure mechanism in structural and engineering components; furthermore, fatigue comprises approximately 90% of all mechanical failures [11]. Fatigue failure may ensue in a wide range of application, from simple objects to complex structures, such as automotive, marine and aircraft components. Therefore, a fatigue life assessment of engineering applications is crucial [12].
However, fatigue tests are costly because they require considerable time for a single experiment. Thus, a simulation using finite element analysis (FEA) can reduce the cost and time of an experiment. Therefore, the fatigue life simulation of an alloy wheel design is presented in this study, and the critical area of a steering knuckle is determined using the FEA. Three types of materials, namely, titanium, aluminium and magnesium alloys, are used for the simulation. The fatigue life of alloy wheels that are designed using different materials can be predicted and simulated.

## 2. Methodology

In this study, an automobile alloy wheel was modelled using computer-aided design software. The dimensions of the alloy wheel model were based on a sample of a 1200 cc national automobile with a cracked outer rim surface (Figure 1). The main alloy wheel specifications are summarised in Table 1, and their three-dimensional (3D) model is illustrated in Figure 2.


**Fig. 1**: Alloy wheel of a 1200 cc national automobile with a small crack on the outer surface of the rim

**Table 1**: Main dimension of an alloy wheel 1200 cc national automobile

| Specifications | Measurements (mm) |
|---|---|
| Rim diameter | 420 |
| Rim width | 203 |
| Inner design | 300 |
| Hub diameter | 132 |

**Fig. 2**: Isometric view of a 3D model design of an automobile alloy wheel

A static FEA was performed on the alloy wheel design to determine their critical areas. This analysis was performed by using a commercial finite element package. The elements were applied to the model through meshing method and body sizing (Figure 3). The model was meshed with a tetrahedral element because this element is suitable for a complex shape with curves and holes. The tetrahedral element that had been used generated a triangle mesh around the model.
The mesh size in the analysis should be considered because it will influence the accuracy of the result. Five sets of element sizes, that is, 14, 12, 10, 8 and 6 mm, were used during meshing to obtain the optimal element quality. The mesh size affects the value of equivalent stress. The accuracy of the result increased with the decrease in the number of element size. However, a small number of element size increased computational time. Therefore, a 6 mm element was selected in the analysis and was adequate for producing a favourable convergent result

**Fig. 3**: Finite element model with mesh

The finite element model was constrained at their holes by a degree of freedom where the bolts must be placed (Figure 4). This constraint is based on the previous study of Singh and Saha [13]. A static force of 3102.4 N and moment of 104 N.m were applied to the model. The magnitude of this force was calculated in accordance with the weight of the 1200 cc car and was applied to each side of the wheel, and the moment produced by the engine was delivered to the wheel during service.

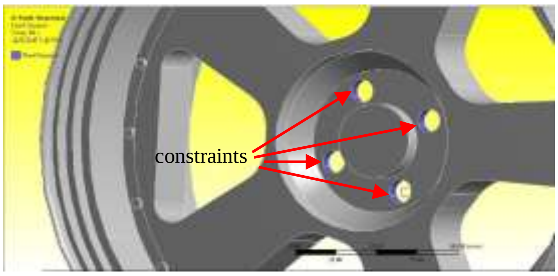



**Fig. 4**: Constraint applied to bolt holes

Three types of lightweight alloy materials, namely, aluminium alloy AA6061, magnesium alloy AZ91D and titanium alloy Ti-6A-4V, were used in the analysis. These types of alloys are commonly used in a modern alloy wheel. Table 2 lists the mechanical properties used for the static analysis.

**Table 2**: Mechanical properties of the alloys used in the analysis

| Alloy | Properties | | |
|---|---|---|---|
| | Density (kg/m) | Modulus elastic (GPa) | Poisson ratio |
| Aluminium | 2770 | 71 | 0.33 |
| Magnesium | 1800 | 45 | 0.35 |
| Titanium | 4620 | 96 | 0.36 |

In fatigue life assessment, the basic concept of stress-life is based on the number of cycles to failure. The stress-life curve is developed by using tabular data that follow the Basquin equation [14], which is written as follows,

$$\sigma_a = A(N_f)^b \quad (1)$$

where $\sigma_a$ is the stress amplitude, $A$ and $b$ are the material constants, and $N_f$ is the number of cycles to failure.
The geometry models, materials and loading histories were mapped collectively and analysed using DesignLife® software to predict the fatigue life of the automobile alloy wheel. The geometry model was imported from the FEA result in an *.rst format. The result of equivalent stress was selected to calculate the life cycle. The material map was set to aluminium, magnesium and

titanium alloys, and their properties were selected from a software database. In addition, fatigue loading was set using a time series generator. Loading cycles were set to 5 Hz because most experimental fatigue tests were conducted from 5 to 10 Hz. Figure 5 shows the interface of FEA-based fatigue analysis.

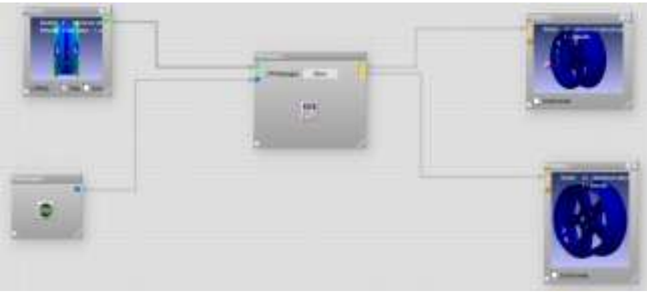
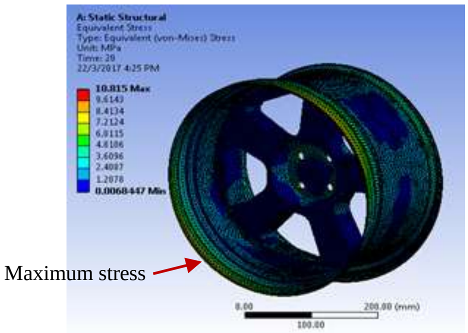


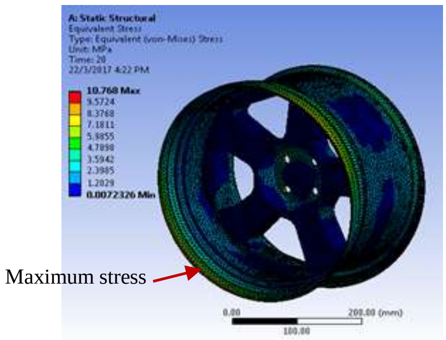
**Fig. 5**: FEA-based fatigue life simulation process

## 3. Result and discussion

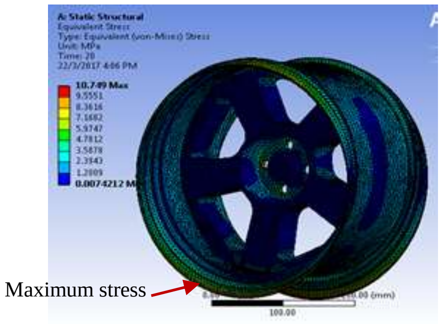
Figure 6 depicts the stress distribution on the automobile alloy wheel obtained from the FEA analysis. The results indicate that the maximum stress occurs at the circumference of the rim for all materials. Therefore, the circumferential area of the rim is identified as a critical area for the automobile alloy wheel, where fatigue failure may occur. The magnitudes of maximum stress for aluminium, magnesium and titanium alloys are 10.82, 10.77 and 10.75 MPa, respectively. The location of this critical area is similar to that in the study conducted by Singh and Saha [13]; these researchers found that the maximum stress occurs at the spoke corner and the circumferential area of the rim. Furthermore, the location of this critical area is similar to the actual cracked alloy wheel rim (Figure 1).




(a)




(b)




(c)

**Fig. 6**: Stress distribution on (a) aluminium alloy, (b) magnesium alloy and (c) titanium alloy wheels

To estimate the fatigue life, the simulation using software, such as FEA, is used to obtain the number of cycles to failure. In the automotive industry, predicting the fatigue life of a vehicle component is conducted through analytical methods in the early design process. The use of these methods can help improve fatigue life and reduce design, manufacturing, engineering tool and prototype costs [15].

Fatigue failure can be described as a fracture of the material by progressive brittle cracking under repeated alternating or cyclic loading below the ultimate strength of the material. It depends on the applied load and the frequency of the stress cycles to propagate until a fracture occurs. In alloy metals, fatigue failure begins with microscopic cracking and propagates until a fracture occurs. It is the progressive and localised structural damage that occurs when a material is subjected to cyclic loading. In this case, fatigue damage may initiate at the critical area of the automobile alloy wheel before propagating sufficiently until failure. Figures 7, 8 and 9 demonstrate the fatigue life simulation results of the different types of automobile alloy wheel materials that are used in this study. The three alloy wheels exhibit the same location of the critical area, which is located at the circumferential area of the rim. The fatigue life simulation showed that the material with the highest fatigue life under a similar load is titanium alloy, followed by aluminium and magnesium alloys. The number of cycle to failure for aluminium alloy is 10 times higher than magnesium alloy; the former has generated $3.256 \times 10^6$ cycles, whilst the latter has produced $3.061 \times 10^5$ cycles. Furthermore, titanium alloy showed beyond cut-off results. This beyond-cut-off result occurs because the number of cycle to failure was set to $10^7$ cycles only in the FEA software, thereby indicating that no fatigue failure occurs for the titanium alloy wheel under the same magnitude of fatigue loading. The higher fatigue life of titanium alloy wheel is mainly contributed by their higher ultimate strength than aluminium and magnesium alloys. High yield and tensile strengths produce an improved fatigue life of alloy materials [16,17].

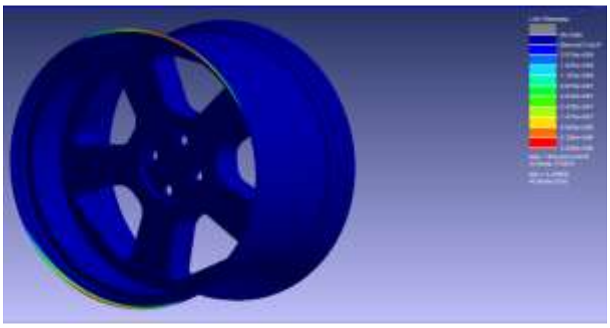


**Fig. 7**: Number of cycles to failure for aluminium alloy wheel

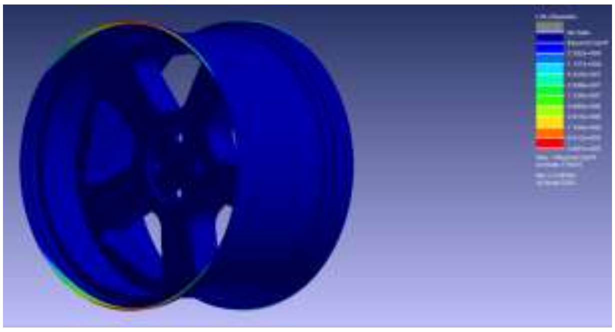


**Fig. 8**: Number of cycles to failure for magnesium alloy wheel

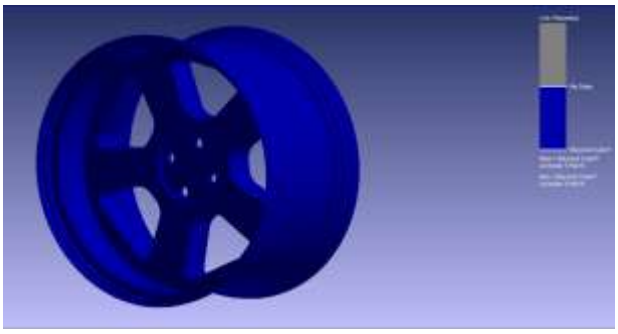


**Fig. 9**: Number of cycles to failure for titanium alloy wheel

## 4. Conclusion

An automobile alloy wheel was modelled using computer-aided design software, and FEA was performed to predict fatigue life. Three types of materials, namely, aluminium, magnesium and titanium alloys, were used in this study. The analysis indicated that the most critical part of an automobile alloy wheel is located at the circumferential area of the rim for all materials and is considered the potential area for crack initiation. The fatigue life simulation for the three types of common materials used for an automobile alloy wheel revealed that titanium alloy demonstrates the highest fatigue life, followed by aluminium and magnesium alloys. Titanium alloys have the longest cycles given their excellent mechanical properties and extensive fatigue strength. In particular, titanium alloy is the most suitable material to be used in the automotive industry but is more expensive than other materials in the market. Future studies can be conducted on the basis of this finding to optimise an automobile alloy wheel design. Furthermore, FEA-based fatigue life simulations can be performed using actual variable amplitude loading signals, which consider the load sequence effect in cycles.

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