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Design and comparative strength analysis of wheel rims of a lightweight electric vehicle using Al6063 T6 and Al5083 aluminium alloys

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ABSTRACT

Purpose: Use of aluminium alloys in critical parts of a vehicle is common since they can combine the two important properties of a material those are being strength and lightweight. The aim in this research is to guide to design process of a wheel with taking example of an electric race vehicle implementation.

Design/methodology/approach: In this study, the fatigue strengths of wheels produced for a two-person racing electric vehicle (Demobil09) are evaluated by calculating maximum distortion energy criterion (Von Mises) with Finite Element Analysis.

Findings: Aluminium alloy wheels are crucial safety related components and are subjected to static and dynamic loads directly. Using FEA results, the weight and equivalent stress of the wheel are both reduced. So, the energy consumption is also decreased. Modal frequencies of the wheel models are determined.

Research limitations/implications: In this paper, the materials analysed are AL6063 T6 and Al5083 aluminium alloys. Different materials can be analysed in future works.

Practical implications: This paper is focusing on how to reduce the energy consumption of a two-person electric vehicle concentrating on reducing the weight of vehicle wheels. The vehicle is more technological than mass production cars since it is an electric race car which uses a hub motor, the body and chassis are produced using carbon polymer composites and all electronic units are designed and produced. Although its specialities it has homologated safety equipment like seats and safety belts.

Originality/value: All boundary conditions must be analysed in details and a strength analysis must be conducted during design of the wheels for different load cases to ensure the strength of a wheel while keeping the weight as low as possible. In this complex process, this paper can give some clues to designers for strengths and weights of the designs since three different wheel forms are evaluated for reducing energy consumption of the vehicle.

Keywords: Aluminium alloy wheel, Electric vehicle, Stress analysis, Energy consumption

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ANALYSIS AND MODELLING

1. Introduction

In recent years, the importance of lightweight materials in automotive industry is increasing dramatically due to strict fuel saving and emission control requirements. Aluminium alloy materials are widely used in automobile wheel industry due to their high specific strength, corrosion resistance and low weight. For these reasons, aluminium alloy wheel production and researches on aluminium alloy rims are increasing worldwide [1-4].

Jinhua Hu et al. developed a software called DWheel based on C# and ANSYS. They focused on rim and flange thickness as the design parameters. The weight of wheel was taken as the objective function to carry out the optimization. Consequently, the weight of the rim was decreased about 5.42% [5].

Zhijun Zhang et al. focused on topological optimization of automobile aluminium alloy wheel designs. First, they determined that a %40 weight reduction is possible by using a topologically optimized geometry. Then, they determined strength and stiffness values of that new wheel design. As a result, the weight of wheel was reduced to 7.6 kg [6].

Hobeika and Sebben investigated the wheel rotation and modeling using computational fluid dynamics (CFD) analysis programs and compared with wind tunnel experimental test [7]. Reduction of weight and improving aerodynamical characteristics are two important targets for decreased energy consumption of an electric vehicle [7].

In this study, mechanical properties of wheels designed and produced for an electric vehicle have been compared to find a design with sufficient fatigue strength and low weight. Various wheel designs have been examined with FEA Software.

2. Material and method

In this study, Al6063 and Al5083 materials were analysed to be used as the rim material on an electrical vehicle. Al6063 mainly consists of 0.2-0.6% Si, 0.45-0.90% Mg and the rest is aluminium whereas Al5083 aluminium alloy mainly consists of 0.0-0.4% Si, 4.0-4.9% Mg, 0.05-0.25% Cr, 0.05-0.25% Ti, 0.4% Fe, 0.1% Cu and 0.4-1% Mn. Both alloys were heat treated (T6). The properties of these alloys are shown in Table 1.

Table 1.
Mechanical properties of aluminium 6063 T6 and aluminium 5083

Material Properties	Magnitude with Units of Aluminium 6063 T6	Magnitude with Units of Aluminium 5083
Density, kg/cm^3	2.700	2.650
Tensile Strength, MPa	214	228
Poission's Ratio	0.33	0.33
Young Modulus, GPa	68.9	72
Elongation at Break, %	18-33	12-16

Technical specifications and the picture of the electric vehicle are shown in Table 2 and Figure 1. Wheel modelling process starts with the design of a wheel with a CAD Software. The design outputs are a 2D drawing and a 3D model. After design stage, the boundary conditions required for a finite element analysis (FEA) are determined. After this analysis, further product development activities such as strengthening, and weight reduction studies are conducted. Upon reaching an optimal geometry with enough fatigue strength and weight, the design process is concluded.

Fig. 1. Demobil 09 Electric Vehicle

Table 2.
Technical specifications of Demobil 09 electric vehicle

Dimensions, m	3.3 x 1.5 x 1
Body and Chassis	Carbon fibre
Number of Wheels	4
Weight, kg	250

As shown in Figures 2-4, three different models were investigated. The six leaf flower like pattern is selected as base pattern for designs (Model A). The main difference between the first and the rest is that the first pattern has smoother arm connections but not optimized in means of weight and strength. On the other hand, Model B has slot-like hollows on arms and Model C has not.

Fig. 2. Model A

Fig. 3. Model B

Fig. 4. Model C

2.1. Boundary conditions of fatigue simulations

Before starting the wheel cornering fatigue analysis, properties such as wheel load and tire dimensions shown in Table 3 were determined. The results were calculated under 400 Nm bending moment for each wheel. As shown in Figure 5, 400 N force was applied at the top of a 1-meter shaft to simulate the bending moment. This force was applied in a way to coincide with the spoke orientation to see the worst-case scenario since that is the critical load orientation.

Table 3.
Specifications

Wheel Load, kg	87.5
Tire Size	80/80 R16
Offset, mm	0
Rolling Radius, m	1.630
Dynamic Radius, m	0.259
%100 Moment, Nm	400

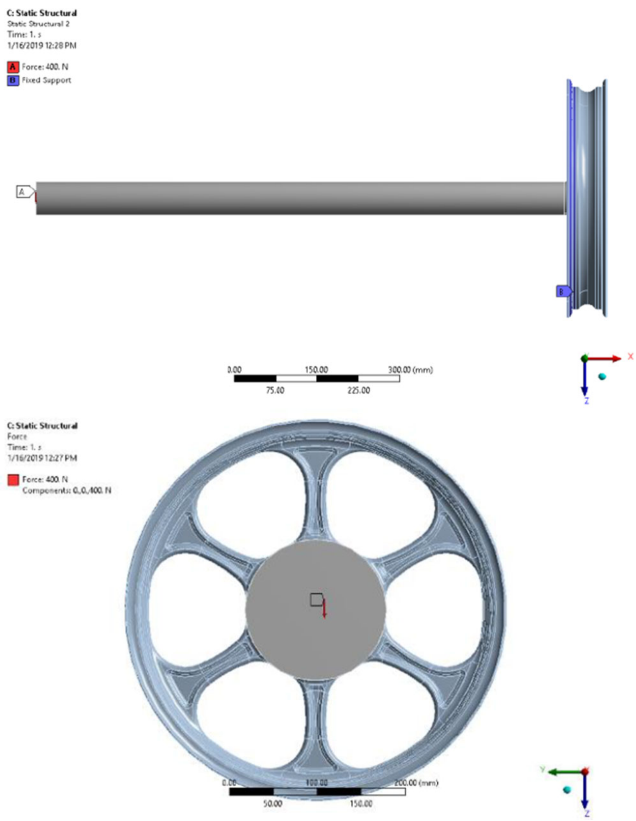


Fig. 5. Fixed support boundary condition and the direction of force

2.2. Modal analysis

Another aim of this study is to investigate free vibration and modal shape characteristics of designed rims as solid structures. Mode shape and mode frequencies were calculated by using finite element analysis calculation methods currently used in automotive industry for aluminium allow wheel verifications. The first step of the study is to model the vibration of the structure in terms of mass or inertia $[M]\ddot{x}(t)$, damping $[d]\dot{x}(t)$, stiffness $[K]x(t)$ and applied (or external) force $F(t)$ [8].

$$[M]\ddot{x}(t) + [d]\dot{x}(t) + [K]x(t) = F(t) \quad (1)$$

At the second step, characteristic features of free vibration and modal frequencies of wheel models are determined with external force and damping force assumed to be zero (2). The eigen values and the eigenvectors are obtained by using related formulas (2 and 3). Thus, eigen frequencies and mode shapes may be obtained respectively [8].

$$[M]\ddot{x}(t) + [K]x(t) = 0 \quad (2)$$

$$x(t) = Ae^{i\omega t} \quad (3)$$

3. Results and discussions

3.1. Results of fatigue simulation

In this study, a product development study was carried out to reduce the weight of the aluminium alloy wheels. In first step of the study, model A was analysed with the pre-defined boundary conditions under static conditions.

According to the analysis results, the equivalent stress of model A is 101.61 MPa (Fig. 6), the total deformation of model A is ~ 0.28 mm and the weight of model A is 2.179 kg (Fig. 7).

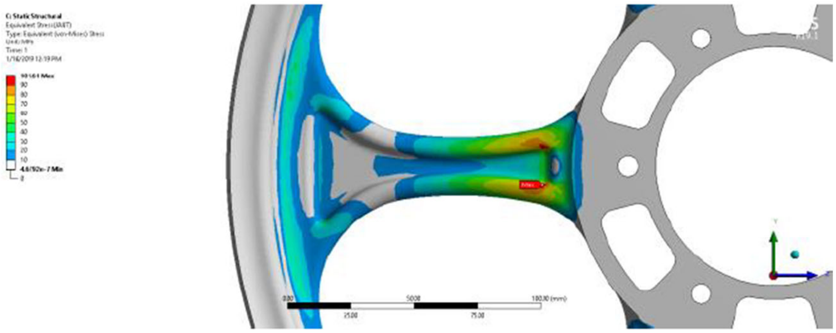


Fig. 6. The result of equivalent stress (Von-Mises) of Model A

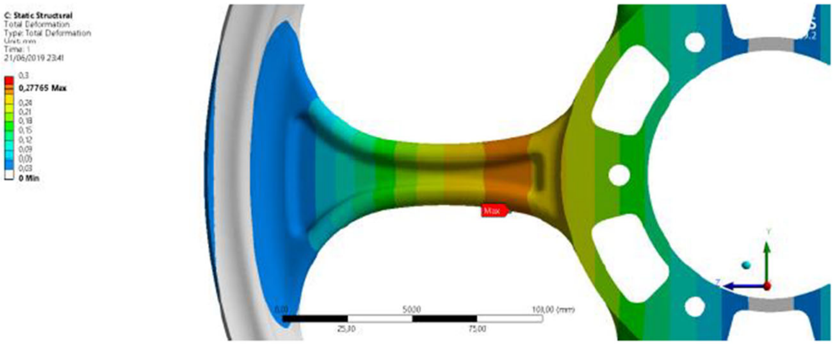


Fig. 7. The result of deformation of Model A

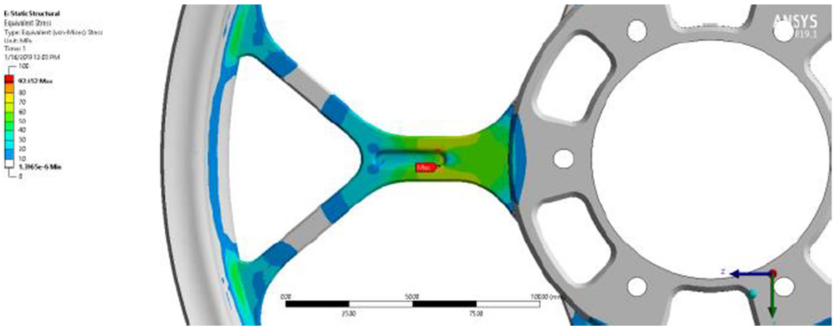


Fig. 8. The result of equivalent stress (Von-Mises) of Model B

In the second step of the study, static analysis results of model A were examined. The highest equivalent stress was observed close to hub side of spoke, and the equivalent stress was seen to very low at the flange side of spoke. For this reason, lightening studies have been carried out on these regions with low equivalent stress. As a result of these evaluation, second model (model B) is designed. Before the design of Model B, other studies on this subject were investigated. Checking the topology optimization study of Zhang et al., the optimized geometry found to be suitable and inspired the designs of Model B and C [5].

According to the analysis results, the maximum equivalent stress of model B is 92.652 MPa (Fig. 8), the total deformation of model B is ~ 0.26 mm and the weight of model B is 1.976 kg (Fig. 9).

In the third step of the study, static analysis results of model B were examined. According to analysis, the maximum equivalent stress was calculated on the spoke cavity of the rim. Maximum equivalent stress value was calculated 92.652 MPa. For this reason, it was decided to omit the spoke cavity.

In the final step of the study, the cavity on the spoke on model B was removed. The model C was analysed with the boundary conditions for static analysis. According to the analysis results, the maximum equivalent stress of model C is 68.594 MPa (Fig. 10), the total deformation of model C is ~ 0.24 mm and the weight of model C is 1.992 kg (Fig. 11).

The limit value of maximum equivalent stress (Tab. 4) is determined to be 100 MPa, in a study conducted by C. Bosi et al. values over 100 MPa are identified as “high” stress [9]. In this study, a fatigue life of 1 million cycles is targeted.

Results of total deformation and modal analysis of model A and C were examined. Minimum deformation and maximum frequency were observed on Model C. Consequently, the design and material of Model C suitable for use.

Table 4.
Results of Fatigue Simulation

Model Name	Equivalent Stress, MPa
A	101.61
B	92.652
C	68.594

3.2. Results of modal analysis

As shown in Table 5, the lowest frequency value is 334.74 Hz which is obtained by modal analysis of Model A. Similarly, Model C gives min. 338.91 Hz values after modal analysis (Tab. 6). As known, 300 Hz frequency is highly recommended as vehicle interion noise limit [10]. Kindt et al. established the finite element model of wheel-tire above 300 Hz limit. This FE model is also validated by experimental approach. The authors noted the established FE model is suitable vehicle interior noise estimation [11]. As a result of modal analysis, vehicle interior noise is increasing in vehicle cabin under 300 Hz frequency limit.

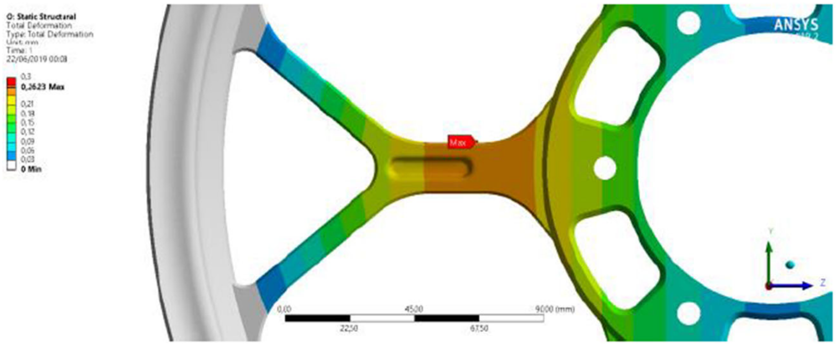


Fig. 9. The result of deformation of Model B

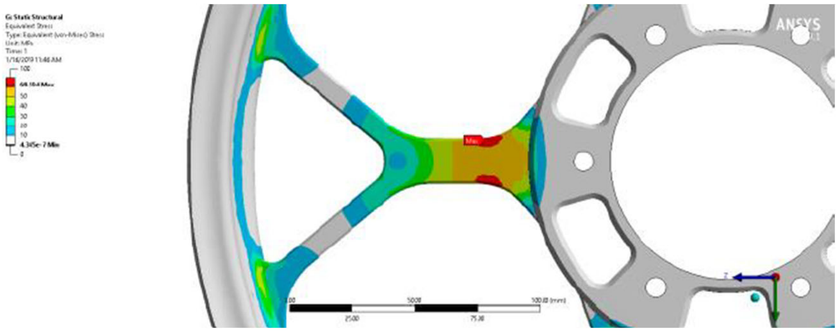


Fig. 10. The result of equivalent stress (Von-Mises) of Model C

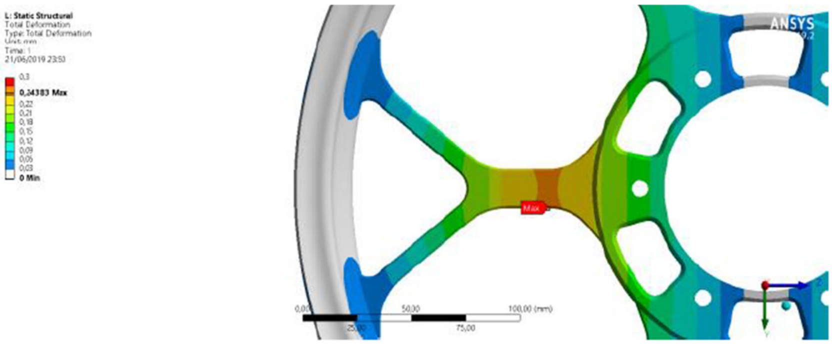
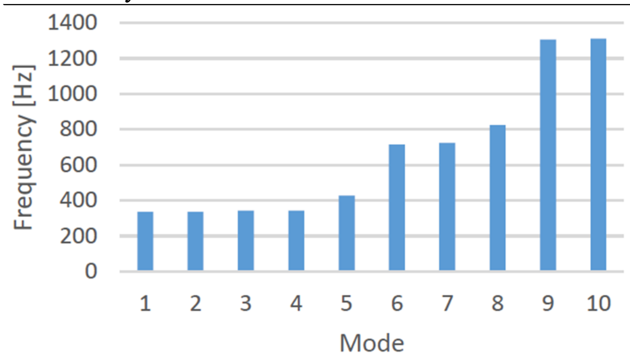


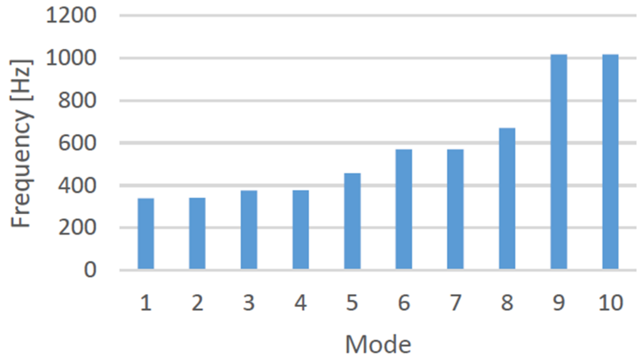
Fig. 11. The result of deformation of Model C

Table 5.
Modal analysis result of Model A



Mode	Frequency, Hz
1	334.74
2	334.83
3	341.96
4	342.51
5	427.30
6	714.90
7	723.06
8	824.63
9	1305.6
10	1311.3

Table 6.
Modal analysis result of Model C



Mode	Frequency, Hz
1	338.91
2	339.79
3	376.02
4	376.80
5	456.86
6	569.10
7	570.25
8	669.88
9	1016.9
10	1017.1

Thus, the natural frequency must be above 300 Hz frequency limit to avoid vehicle interior noise and roadway noise [10].

Optimization of the wheel is a significant step. However, design changes may cause an intolerable road noise in the vehicle cabin due to excessive vibrations. To reduce road noise the minimum natural frequency of the wheel must be above 300 Hz [10].

4. Conclusions

In this study, the static analysis of the aluminium alloy wheel produced for an electric car was carried out and strengthening and weigh reduction studies were conducted. It has been observed that weight and mechanical properties can be improved by different design approaches and material selections. The conclusions are given below:

1. According to FEA results, it was concluded that a weight reduction may be applied at regions where the low equivalent stresses are observed. The final design has an 8.58% (0.187 kg) weight reduction compared to the initial design (2.179 kg).
2. The maximum equivalent stress of the wheel was also reduced by 32.49%.

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