Lightweight design and analysis of automobile wheel based on bending and radial loads

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Abstract. Lightweighting of automobile vehicle is a significant application trends, using magnesium alloy wheels is a valuable way. This article discusses design of a new model of automobile wheel. Then bending test and radial test finite element model were established. Considering three different materials namely magnesium alloy, aluminium alloy and steel, the stress and strain performances of each material can be obtained. Through evaluating and analyzing model in bending test and radial test, we obtained the reasonable and superior results for magnesium alloy wheel. The results of the equivalent stress and deformation were compared, the magnesium alloy wheel practicality has been confirmed. This research predicts the reliability of the structural design, some valuable references are provided for the design and development of magnesium alloy wheel.

1. Introduction
As the automotive industry is increasingly demanding on energy saving and environmental protection, people are taking more attention on the lightweight design of automobiles [1]. Wheel is one of the most important parts of a vehicle. It determines a number of parameters such as security, stability, performance and fuel economy. To ensure energy efficiency, the wheels must be as lightweight as possible. Magnesium alloys are considered one of the most promising materials in the 21st century, with low density, high specific strength and good casting properties [2].

In the modern design, it is important to improve the efficiency of development and reduce the number of tests. To achieve these goals, computer aided engineering (CAE) is a useful tool for the improvement and development of automotive wheels. B Anusha et al [3], introduced the results of the four-wheel strength analysis using four different wheel shapes, including straight, sloping, y-shaped and honeycombed shapes. The analysis variables include different materials and different models of the load. Recently, casting and forging techniques have been improved, and the corrosion resistance of magnesium has also been improved.

In this research, a kind of wheel structure is designed. The finite element model of wheels are established based on the radial test and bending test. Compared the finite element results of an aluminium alloy wheel, magnesium alloy wheel and steel wheel. The rationality and superiority of the designed magnesium alloy wheel are obtained.

2. Design of automobile wheel
When designing wheel, two major factors must be considered, such as safety and engineering standards. The wheel mainly consists of rim and spokes [4,5]. The shape and size of the wheel is
specified in standard according to JATMA. In this research, the market is the target to design a lightweight vehicle wheel. Therefore, the design is lightweight while satisfying the safety. The specifications of the wheel: rim diameter 355 mm, rim width is 165 mm, offset ET 45 mm, pitch centre diameter PCD 100 mm, hub centre diameter 59 mm.

Orthogonal experimental design is a common technique for optimization. It is based on probability theory, quantitative statistics and practical experience. The test scheme of the quasi-orthogonal table is arranged, and the results are calculated and analyzed. It is a design method to find the optimal test scheme quickly. The advantage of orthogonal design is that it greatly reduces the test. The frequency of inspection improves the working efficiency. Using orthogonal experimental design can be more efficient for wheel design and analysis. The three dimensional model of the wheel is shown in figure 1 below.

Figure 1. Wheel module.

The wheel optimization flowchart is shown in figure 2 below. Using optimization, we can achieve our target.

Figure 2. Optimization flowchart.

3. Numerical modelling of the wheel
In modern design, using finite element analysis can help us determine the strength of the wheel in advance and reduce the test times and cost [6]. Bending load while driving and static load while vehicle stops is two working conditions of the wheel, those two working conditions should be
considered seriously when designing wheel [7,8]. The mesh will be applied on the total surface of the wheel with equal element size.

In this research, the gross weight of the vehicle is about 1175 kg, load on each wheel is 2937.5 N. Three kinds of materials are used for the analysis and calculation of wheel as table 1 lists. According to the Mises yield condition, our Mises stress results can be considered and compared in the basic strength theory (mainly Mohr strength theory). On this basic, we can ensure the safety of the wheel in the elastic range.

| Table 1. The mechanical properties of Aluminum, Steel and Magnesium. |
|---------------------------------|----------------|----------------|
| Density (kg/m³)                 | SPFH540        | Aluminum 6061-T6 | Magnesium AZ91 |
| Modulus of Elasticity (GPa)     | 0.21           | 0.069           | 0.045          |
| Poisson ratio                   | 0.3            | 0.33            | 0.35           |
| Yield strength (GPa)            | 0.355          | 0.276           | 0.16           |

3.1. Bending endurance of the wheel

The bending endurance of the wheel can show the wheel strength under bending load. The bending moment $M$ is calculated by using below equation:

$$\bar{M} = (\mu R + d)\bar{F} \times S$$  \hspace{1cm} (1)

In the equation, $\bar{M}$ is bending moment ($N\cdot m$), $\mu$ is friction coefficient between tires and the road set as 0.7, $R$ is tire static load radius (m), $d$ is offset of wheel (m), $\bar{F}$ is maximum rated load ($N$), $S$ is strength coefficient set as 1.6. We can obtain bending moment is $1168.9 \, N \cdot m$.

3.2. Radial endurance of the wheel

The radial endurance is intended to detect the wheel performance when the total load of the vehicle compresses the wheel radially. The radial load $F_r$ shall be determined from the equation:

$$\bar{F}_r = K \times \bar{F}$$  \hspace{1cm} (2)

In the equation, $\bar{F}_r$ is radial load ($N$), $\bar{F}$ is maximum rated load ($N$), $K$ is coefficient according to the industrial standards set as 2.25. We can obtain radial load is $6609.4 \, N$.

In this research, using Stearns J wheel and tire contact research results, the force on the magnesium alloy wheel from the tire can be replaced by the radial force directly on the wheel to simplify the modeling. The pressure $W$, $W_r$ and $W_0$ is given by the following equation:

$$W = b \int_{\theta_0}^{\pi / 2} W_r \, r_0 \, d\theta \cdot W_r = W_0 \cos \left( \frac{\pi \theta}{2 \theta_0} \right) \cdot W_0 = \frac{W \pi}{4 b r_0 \theta_0}$$  \hspace{1cm} (3)

In the equation, $W$ is radial load on the wheel, $b$ is width of the bead seat, $r_0$ is radius of the bead seat, $\theta_0$ is the maximum deflection angle of radial load. In this way we can get the pressure loaded in the wheel inner ring is 0.45 MPa, the pressure loaded on the rim of the wheel is 0.785 MPa.

The load of test model is shown in figure 3 below. Setting the length of the loading axis as 1000mm and the force is 1168.9 N.
Figure 3. Bending endurance test and radial endurance test model. (a) Bending endurance test model, and (b) Radial endurance test model.

4. Results and discussions
Based on above loading conditions, the model of the wheel is analyzed and calculated. The equivalent stress and total deformation were determined in ANSYS and presented in figures 4-9.

Figure 4. Equivalent stress and deformation of AZ91 magnesium alloy wheel.

Figure 5. Equivalent stress and deformation of Aluminum alloy wheel.
Figure 6. Equivalent stress and deformation of Steel wheel.

Figure 7. Equivalent Stress and deformation of AZ91 magnesium alloy wheel.

Figure 8. Equivalent Stress and deformation of Aluminum alloy wheel.

Figure 9. Equivalent Stress and deformation of Steel wheel.
4.1. Bending endurance results of the wheel
From the above analysis, the results under bending endurance test such as equivalent stress and deformation are obtained.

For the magnesium alloy and aluminum alloy wheel maximum equivalent stress is concentrated on spokes shown in above figures, steel wheel maximum equivalent stress also concentrated on spokes, which is less than the yield stress of each material suggested. Strain of each material wheel is acceptable according to the principle of elastic-plastic deformation.

4.2. Radial endurance results of the wheel
From the above analysis, the results under radial endurance test such as equivalent stress and deformation are obtained.

The magnesium alloy wheel and aluminum alloy maximum equivalent stress is concentrated on rim shown in above figures, steel wheel maximum equivalent stress also concentrated on rim, which is less than the yield stress of each material suggested. Each material wheel with acceptable strain.

| Table 2. Comparison table. |
|---------------------------|
| Results                  | Parameters  | AZ91 | 6061-T6 | SPFH540 |
|                          | Weight(Kg) | 3.82 | 5.63    | 16.37   |
| Bending endurance results| Equivalent Stress(Mpa) | 58.57 | 58.76 | 58.71 |
|                          | Deformation(mm) | 4.28  | 3.24   | 1.85    |
| Radial endurance results | Weight(Kg)  | 3.82 | 5.63    | 16.37   |
|                          | Equivalent Stress(Mpa) | 46.46 | 46.96 | 47.69 |
|                          | Deformation(mm) | 0.20  | 0.13   | 0.04    |

After the finite element analysis and orthogonal experimental design. From the above table 2, after material optimization, contrast about different materials, considering the equivalent stress, deformation and weight, we can get the most suitable result. The quality of magnesium alloy is about 30% lighter than aluminum and 70% lighter than steel, meets the lightweight design concept. In this research, the wheel model was improved, magnesium alloy wheel has the least equivalent stress, which is less than the yield stress of the material suggested, the displacement is acceptable, satisfying lightweight wheel design.

5. Conclusion
The finite element analysis has been carried out on the wheel using ANSYS software. The design wheel meets the bending load and static load conditions and therefore the design is safe. By comparing results of different materials, az91 magnesium alloy wheel can be subjected to less stress value. In terms of stress, our new wheels have a better performance; in terms of strain, although the strain result is within an acceptable range, we will focus on improving it. Hence, magnesium alloy is more feasible to be used in wheel than other materials for the lightweight design.

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References
[1] Prem J, Raghupathi P and Kalaiyarasan A 2016 Analysis of magnesium alloy wheel for four wheeler IJRSR 7 13126-30
[2] Kumar D S, Sasanka C T, Ravindra K and Suman K N S 2015 Magnesium and its alloys in
automotive applications – A review AJMST 4 12-30
[3] Srikanta B A and Veeraraju P 2014 Geometrical and Material optimization of alloy wheel for four wheeler IIRI 1 1401-2
[4] Ganesh S and Periyasamy D P 2014 Design and analysis of spiral wheel rim for four wheeler IJES 3 29-37
[5] Theja M S and Krishna M V 2013 Structural and fatigue analysis of two wheeler lighter weight alloy wheel IOSR-JMCE 8 35-45
[6] Torgal S and Mishra S 2012 Stress Analysis of wheel rim IJMER 1 34-7
[7] Wang L M, Chen Y F, Wang C Z and Wang Q Z 2011 Fatigue life analysis of aluminum wheels by simulation of rotary fatigue test SV-JME 57 31-9
[8] Adigio E M and Nangi E O 2014 Computer aided design and simulation of radial fatigue test of automobile rim using ANSYS IOSR-JMCE 11 68-73