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Multi-objective Optimization Design of Magnesium Alloy Wheel Based on Topology Optimization

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Abstract: Lightweight of automatic vehicle is a significant application trend, using topology optimization and magnesium alloy materials is a valuable way. This article designs a new model of automobile wheel and optimizes the structure for lightweight. Through measuring and analyzing designed model under static force, clear and useful topology optimization results were obtained. Comparing wheel performance before and after optimization, the optimized wheel structure compliance with conditions such as strength can be obtained. Considering three different materials namely magnesium alloy, aluminum alloy and steel, the stress and strain performances of each materials can be obtained by finite element analysis. The reasonable and superior magnesium alloy wheels for lightweight design were obtained. This research predicts the reliability of the optimization design, some valuable references are provided for the development of magnesium alloy wheel.

Key words: Magnesium alloy wheel, structural design, topology optimization, lightweight, finite element.

1. Introduction

Environmental and resource issues have become the focus of attention around the world. As the automotive industry is increasingly demanding on energy saving and environmental protection, people are taking more attention on the lightweight design of automobiles. In the United States, the Environmental Protection Agency (EPA) and the National Highway Traffic Safety Administration (NHTSA) issued a joint regulation in August 2012 [1, 2]. This new regulation will be implemented on passenger cars to improve automobile consumption standard about greenhouse gases and fuels from 2017 to 2025. The emission for combined cars and trucks has to be reduced from 243g/mile in 2017 to 163 g/mile in 2025 according to new regulation. Moreover, the fuel economy must be improved from 36.6 mpg in 2017 to 54.5 mpg in 2025. When designing vehicle products, it needs not only to reduce energy consumption but also to remain in competition with peers [3, 4]. According to the data, the automotive own weight is reduced by 10%, and the fuel consumption is reduced by about 6%-8%. Magnesium alloys are considered one of the most promising materials in the 21st century. In the modern design, it is important to improve the efficiency of development and reduce the number of tests. The average use of magnesium in cars has increased from 0.1% (1.8 kg) in 1995 to 0.2% (4.5 kg) in 2007 in the United States according to Refs. [5, 6]. Using magnesium material in cars will increase by 15% (about 227 kg) by 2020 based on future vision for magnesium [7]. By understanding the efficiency of materials, engineers can gain benefits through magnesium materials when designing wheel [8-10]. Wheel is one of the most important parts of a vehicle.

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To ensure energy efficiency, the wheels must be as lightweight as possible [11-16].

Optimization design is a powerful tool for machinery design, and can produce the best layout of structural design. Topology optimization can provide the first optimized “design concept” of structure material distribution and achieve greater savings and design improvement in size and shape optimizations. Since Bendsoe introduces the homogenization method of topology optimization, topology optimization method has been deeply developed and applied in structural optimization design [17, 18]. Zhuang [19] carried out the topology optimization of aluminum alloy wheels, the strength and stiffness of the optimized wheels were simulated and analyzed. Hu [20] optimized the aluminum alloy wheel use the wheel rim and flange thickness as the design variables, the maximum stress of the wheel in bending fatigue and radial fatigue conditions as the constraint, and aiming at the smallest wheel quality, the aluminum alloy wheel optimized. Based on the bending fatigue test, Xiao [21, 22] carried out topology optimization on steel wheels, and designed the lightweight design of the wheels with flexibility and modal frequency as the target, and carried out stress analysis and experimental verification. Optimization design is beneficial to the improvement of global wheel performance and wheel lightweight.

Wheel disc and rim are two main parts of wheel. Some parameters of the vent holes such as number, position, and shape which are distributed in the wheel disc can be changed. In this research, a kind of wheel structure is designed, using topology optimization for wheel quality lightweight. The finite element models of wheels are established based on the static force. The rationality and superiority of the designed magnesium alloy wheel are obtained.

2. Structure Topology Optimization

In this paper, wheel structure topology optimization method is used to optimize the wheel, which satisfied the lightweight, strength and NVH requirements.

2.1 Optimization Method

The most common topology optimization is the variable density material interpolation method, which includes SIMP and RAMP [23-26]. The theory of variable density is to convert the discrete optimization problem into a continuous optimization problem by introducing an intermediate density unit.

The SIMP method uses discrete element density as an optimization variable and therefore tends to generate interlaced grayscale images of topological designs. In order to make it manufacturable, three processing steps are required: identify the topology design, smooth the structural boundary, and then realize the parameterization. The advantages of a slightly modified version of SIMP were discussed by Sigmund in 2007, a minimum stiffness (or other material parameter) that is independent of penalization is included.

An alternative interpolation scheme known as the Rational Approximation of Material Properties (RAMP) was proposed by Stolpe and Svanberg. RAMP model has nonzero sensitivity at zero density. Some numerical difficulties in problems related to very low density values in the presence of design dependent loading could be remedied by RAMP material model.

From Fig. 1, the FE model before optimization was showed by model (a) and optimal topology configuration was showed by model (b). The most commonly used material interpolation model method, SIMP formula is expressed as:

$$E(x_i) = E_{\min} + (x_i)^p (E_0 - E_{\min}) \tag{1}$$

where E_0 is the initial elastic modulus; p is the penalty factor, $p > 1$; $E(x_i)$ is the density value of the material at i.

The theory of variable density is to convert the discrete optimization problem into a continuous optimization problem by introducing an intermediate

(a) Before optimization (b) After optimization

Fig. 1 Element model.

density unit. In reality, the intermediate density unit is not exist and cannot be manufactured. Therefore, the intermediate density unit should be reduced as much as possible, the number of which needs to be penalized only for the intermediate density that appears in the design variables.

2.2 Topology Optimization for Wheel Structure

In topology optimization, add draft restraint, circum symmetry beam, minimum unit size and so on. In the wheel optimization, the lightest weight is the optimal design goal. Wheel spokes, disc and rim are main parts of wheel. Several vent holes are distributed in the wheel disc. When designing wheels, some parameters of the vent holes can be changed. These parameters include number, position, and shape. Many optimization approaches for wheel designs are concerned with size or shape optimizations. Based on topology optimization and the feature of the wheel, this research aims to identify wheel spokes. When doing topology optimization of wheels, optimize the wheel of structure by spokes for lightweight design.

According to the ICM (Independent Continuous Mapping) optimization method proposed by Yunkang Sui [27] and the topology theory, the topology optimization model is established. With wheel unit density as design variable, weight flexibility as constraints, the minimum quality is the objective function. Topology optimization objective function is the biggest structural stiffness or the minimum compliance for the topology optimization, constraint is to remove the volume percentage, the topology optimization mathematical model is in the following equation:

$$\begin{cases} \text{Find } \rho = (\rho_1,\ \rho_2,\ \rho_3, \cdots \rho_n)^T \\ \text{Min } C(u) = F^T U = U^T K U = \sum_{i=1}^{n} (\rho_i)^p u_i^T k_0 u_i \\ \quad Weight = \sum \rho_i v_i \le v_0 - \alpha v_0 \\ \quad \varepsilon \le \rho_i \le 1 \qquad (i = 1,2,3 \cdots n) \\ \quad \rho_i = 1 \qquad (i = J_1, J_2, \cdots J_n) \\ \quad F = KU \end{cases} \tag{2}$$

In the equation: ρ_i is unit density, P is penalty factor, ε is the lower material density, α is the percentage of the volume of material removal, k_0 is the initial matrix for the structure, k_i is optimized structure matrix, F is the load of unit structure, K is the overall stiffness matrix, U is the displacement vector of unit structure, V_0 is the initial value of volume of material, $C(u)$ is compliance function of structure, J_1, J_2,... J_n are the unit number of optimized unchanged density. Previous studies have shown that optimization wheel structure can be obtained. The optimization flowchart of the wheel is shown in Fig. 2.

3. Establishment of Wheel Model

In modern design, using finite element analysis can be established to determine the strength of the wheel in advance and reduce the test times and cost. Static load while vehicle stops is working conditions of the wheel that should be considered seriously [28-30]. Wheel model is shown in Fig. 3.

In this research, the gross weight of the vehicle is about 1,175 kg, load on each wheel is 2,937.5 N. Two alloy materials are used for the analysis and calculation of wheel as Table 1 lists.

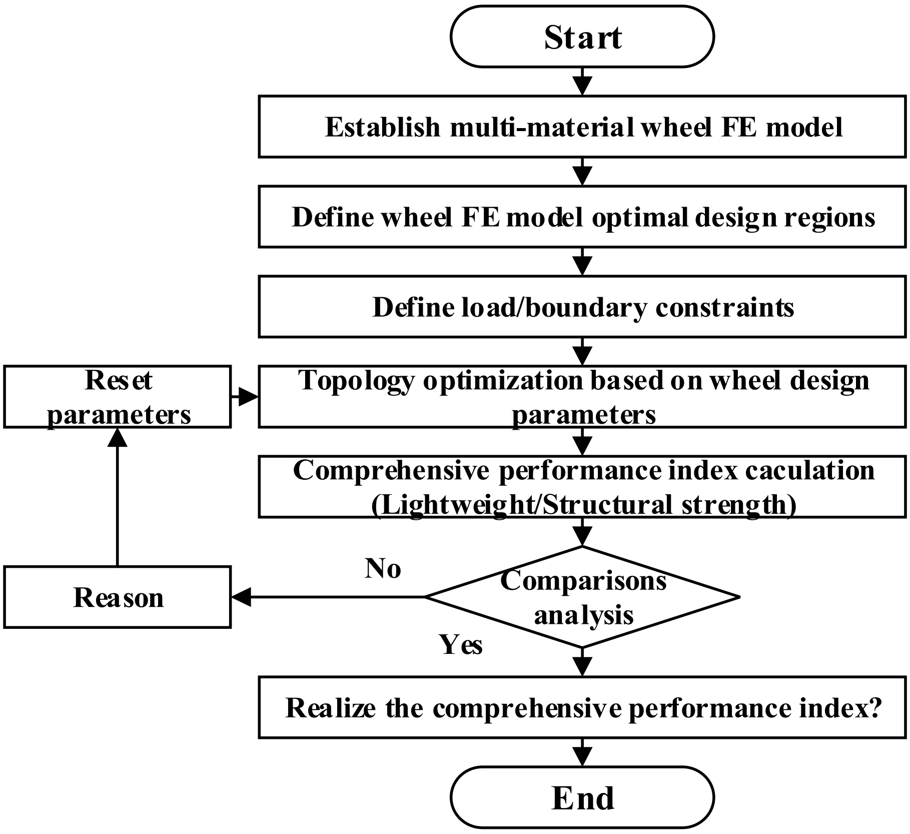
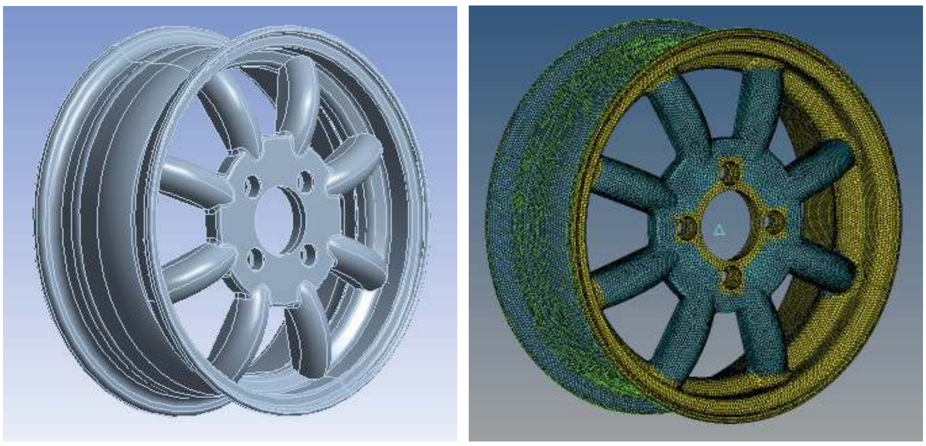


Fig. 2 Flow chart of the wheel optimization.



(a) 3D model (b) FE model

Fig. 3 Wheel model.

Table 1 Mechanical properties of 2 materials.

Mechanical properties	Aluminium alloy	Magnesium alloy
Density (kg/m³)	2,700	1,830
Coefficient of elasticity (Mpa)	69	45
Poisson ratio	0.33	0.35
Yield strength (Mpa)	276	160

3.1 Verification of Finite Element Model

Model verification is necessary for finite element analysis. The modal analysis result is to analyze the natural frequency, mode shape and other related parameters of the object, these parameters are the essential properties of any object with invariance and stability. Therefore, the finite element model is verified by modal experimental analysis.

By comparing the simulation frequency of the FE analysis and modal test frequency, experimentally measured modal parameters and FE analysis results of wheel basic agreement. Wheel finite element model is accurate, and can be applied to subsequent in depth finite element analysis.

3.2 Structural Strength Analysis

The static force 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:

$$\vec{F}_r = K \times \vec{F} \tag{3}$$

In the equation, $\vec{F}_r$ is radial load (N), $\vec{F}$ is maximum rated load (N), K is coefficient according to the industrial standards set as 2.25. Radial load is obtained by 6,609.4 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 calculation formulas W_r, W and W_0 are given by the following equation:

$$W = b\int_{-\theta_0}^{\theta_0} W_r r_b d\theta \tag{4}$$

$$W_r = W_0 \cos\left(\frac{\pi\theta}{2\theta_0}\right) \tag{5}$$

$$W_0 = \frac{\pi \cdot b\int_{-\theta_0}^{\theta_0} W_r r_b d\theta}{4br_b\theta_0} \tag{6}$$

In the equation, W is radial load on the wheel, b is width of the bead seat, r_b is radius of the bead seat, θ_0 is the maximum deflection angle of radial load. In this way, 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 Fig. 5.

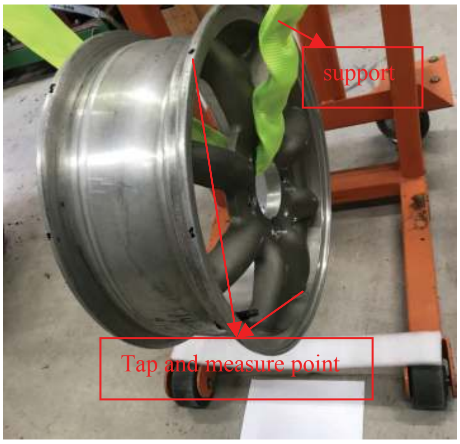


Fig. 4 Modal test.

Table 2 Comparison of simulation and experimental data.

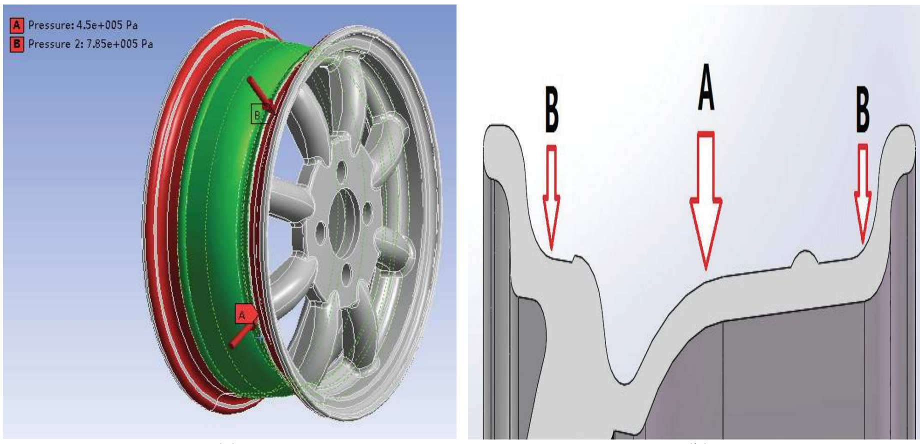
Modal	1	2	3
FE analysis frequency/Hz	474.51	480.42	948.03
Modal test frequency/Hz	466	494	954
Error	1.8%	2.75%	0.62%

3.3 Results of Structural Strength Analysis

From above loading conditions and finite element theory, in order to realize the lightweight of wheel, meanwhile ensure the strength safety, lightweight material replacement and static analysis are completed. The analysis results were determined and presented in Figs. 6 and 7.

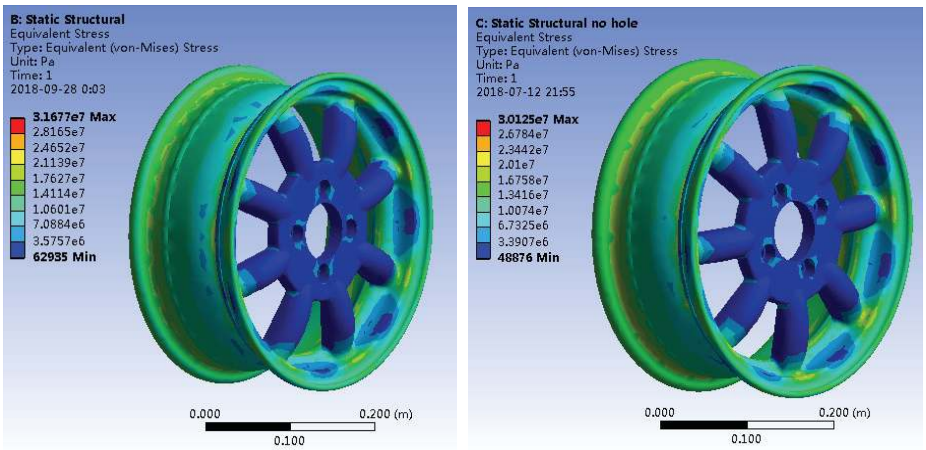
Fig. 6 is the analysis results of equivalent stress between aluminum alloy and magnesium alloy. Through the above comparison, magnesium alloy wheel and aluminum alloy wheel in the same size, magnesium alloy wheel equivalent stress is 31.67 Mpa while aluminum alloy equivalent stress is 30.13 Mpa, less than the material yield stress.

Fig. 7 is the analysis results before and after wheel optimization. From the above analysis, under the premise of the strength of wheel, the structure optimization of magnesium alloy wheel is carried out. The magnesium alloy wheel deformation is 0.091 mm, aluminum alloy wheel deformation is 0.058 mm. Magnesium alloy wheel has good strength properties. The optimization effect comparisons were in Table 3. In radial load, designed wheel model meets strength and other characteristics. Designed wheel can be further optimized.



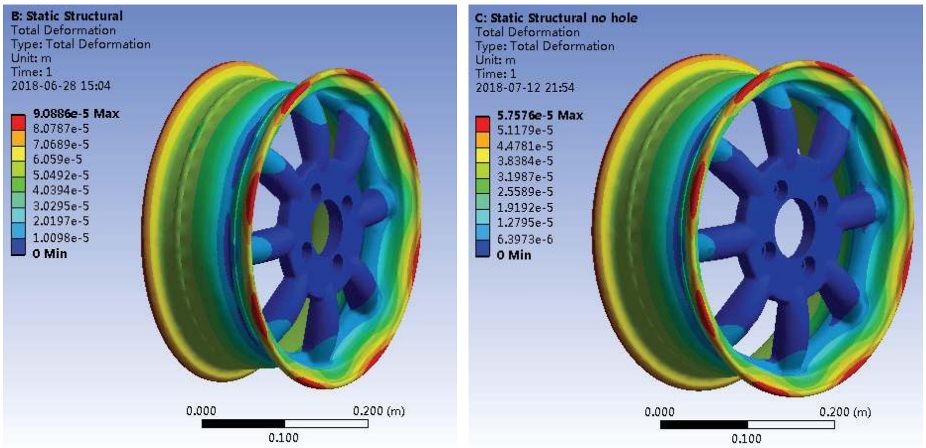
(a) (b)

Fig. 5 Wheel FE model load.



(a) Magnesium alloy (b) Aluminum alloy

Fig. 6 Equivalent stress of wheel.



(a) Magnesium alloy (b) Aluminum alloy

Fig. 7 Deformation of wheel.

4. Optimization of the Wheel and Results

Based on above optimization theory, structural optimizations of wheel were designed.

4.1 Optimization of the Wheel

Based on above optimization theory and steps, Combined with shape and practicality of structure, optimization results of the wheel can be done.

Under the premise of satisfying conditions such as strength, the most remove and optimal model was obtained.

From the FE simulation results concerning the four steps of wheel structure optimization in Figs. 8-10, comparisons among the wheel models can be shown:

(1) Comparisons among the wheel models shown in Figs. 8 and 9, step 1 and step 4.

By analyzing step 1 model and step 4 model, the stress values for critical locations of wheel under static load, we find that the stress level of the step 4 model is significantly higher than that of the step 1 model. Actual processing can be considered on the wheel basis of topology optimization.

(2) Comparisons among the wheel models shown in Figs. 8 and 9, step 2 and step 4.

By analyzing step 2 model and step 4 model, the stress values for critical locations of wheel under static load, we find that the stress of the step 2 is 32.52 Mpa at the same time, step 4 model is 32.35 Mpa. Step 2 stress is significantly higher than that of the step 4 model. Total deformation of step 2 model is 0.022 mm while step 4 model is 0.021 mm. Wheel mass of step 2 model is 4.179 kg, wheel mass of step 4 model is 4.05 kg. Under reasonable stress and strain conditions, wheel model of step 4 is better for optimization target.

(3) Comparisons among the wheel models shown in Figs. 8 and 9, step 3 and step 4.

By analyzing step 3 model and step 4 model, the stress values for critical locations of wheel under static load, we find that the stress of the step 2 were 32.52 Mpa at the same time, step 4 model is 32.35 Mpa. Step 2 stress is significantly higher than that of the step 4 model. Total deformation of step 2 model is 0.022 mm while step 4 model is 0.021 mm. Wheel mass of step 2 model is 4.097 kg, wheel mass of step 4 model is 4.05 kg. Under reasonable stress and strain conditions, wheel model of step 4 is better for optimization target.

According to the stress, total deformation analysis and optimization step, the most significance model is step 4 model, That is, the spoke reduction of 40% by volume is combined with the influence of vent holes shape on wheel performance and inner ring of wheel disc influence of wheel structure. The wheel structure after parameter optimization can be done.

The more removal of material of optimal topology, the more complex shape of the structure, the smaller size of the spokes, Table 3 shows spokes' structure after

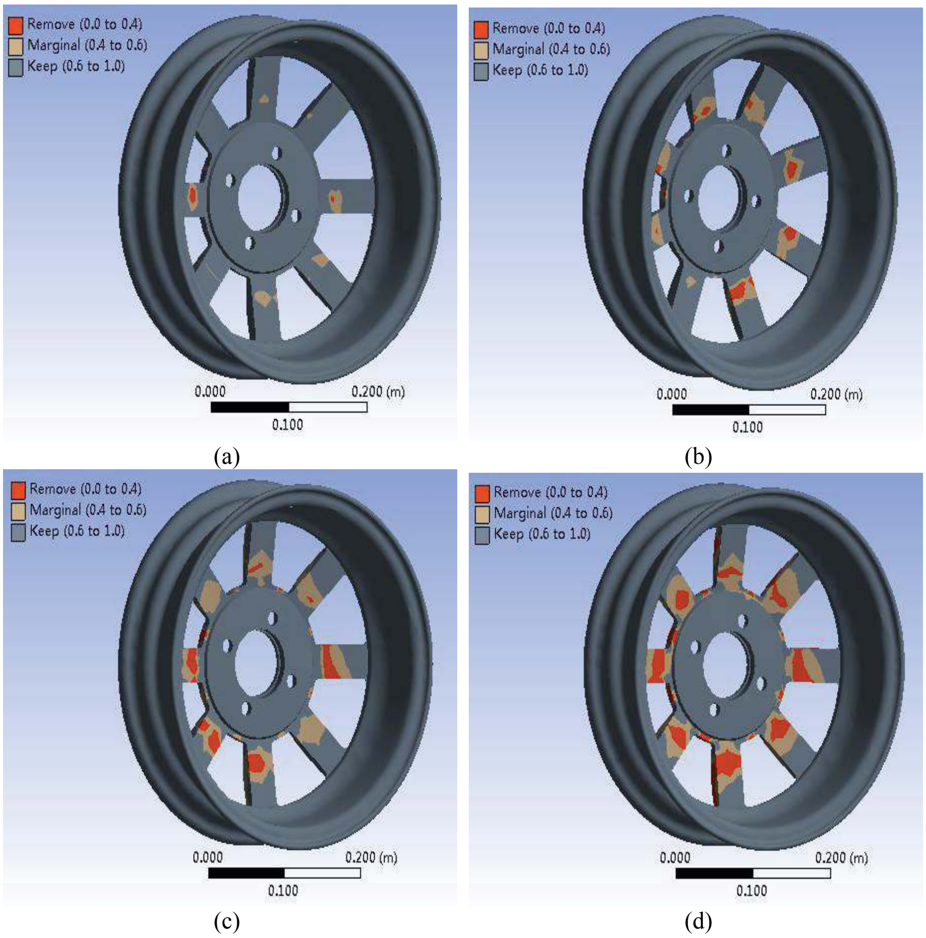


Fig. 8 The optimization process of wheel.

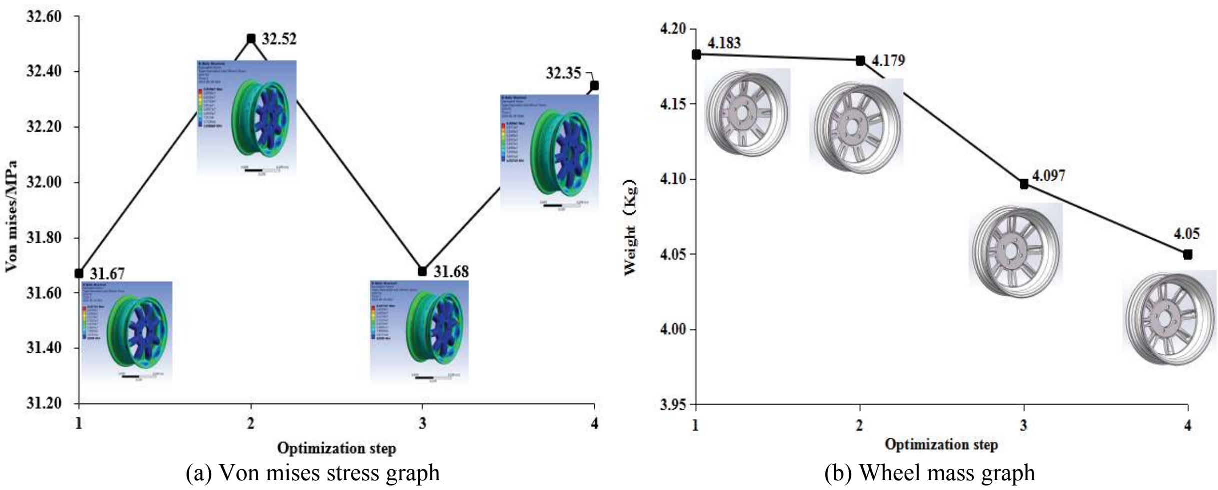
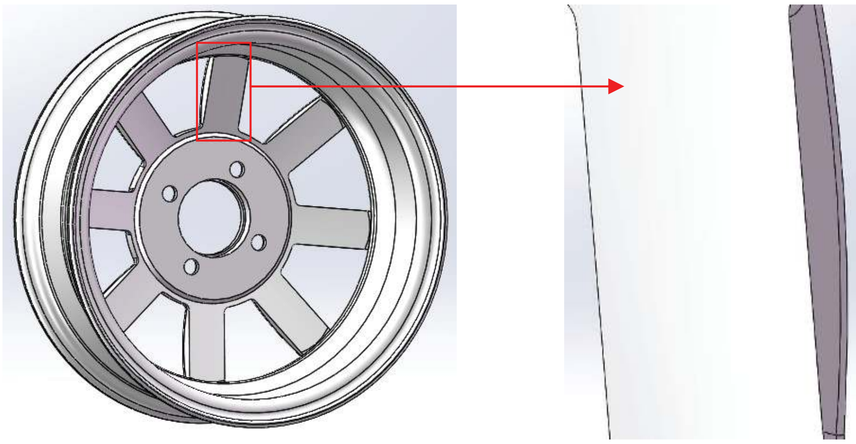
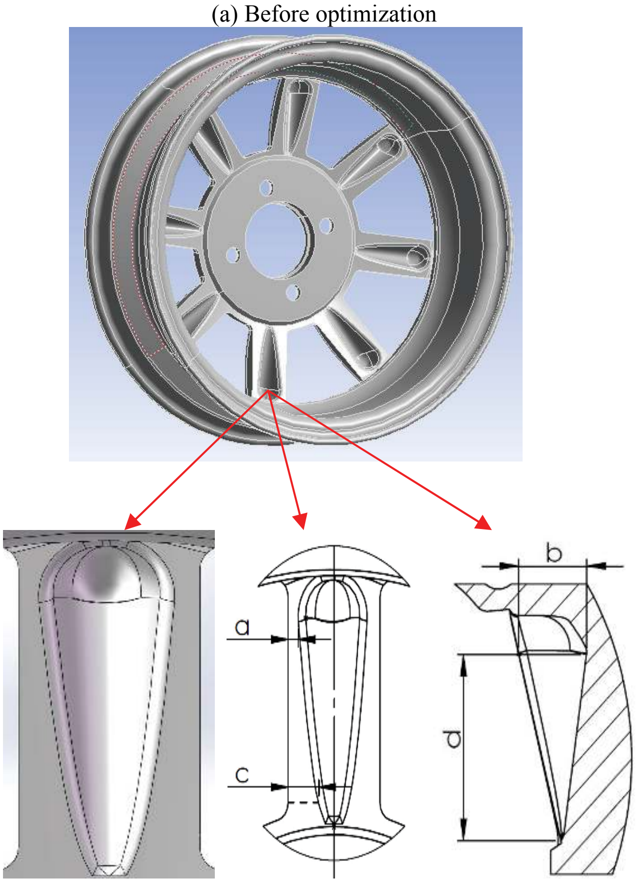


Fig. 9 Optimization of wheel.



(1) Wheel model (2) Spoke

(a) Before optimization



(b) After optimization

Fig. 10 Optimization parameters of wheel spokes.

Table 3 Before and after parameter optimization (mm).

Wheel optimization parameters	a	b	c	d
Before optimization	6.6	9	14	44
After optimization	4	25	12	55

Optimization, the percentage of material removal of the optimal topology was chosen based on the structure and optimization theory.

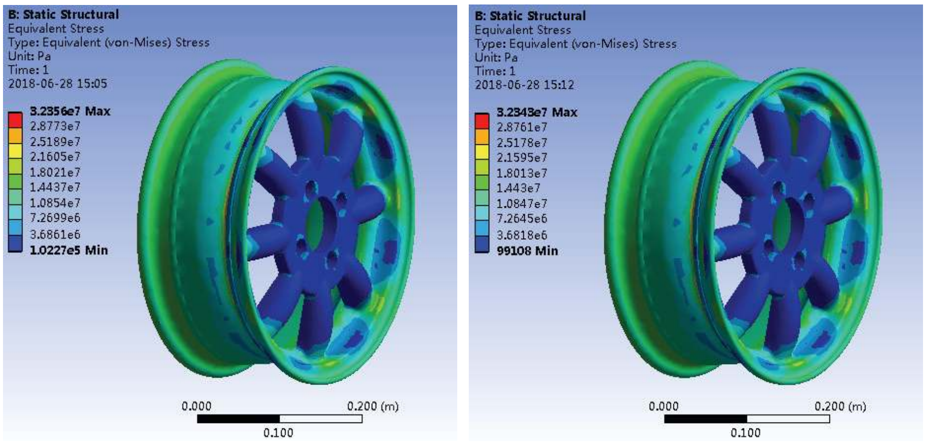
4.2 Results and Discussions after Optimization

In order to realize the lightweight of wheel, meanwhile ensure the strength safety, lightweight material replacement and further structural optimization are completed. The analysis results of wheel after optimization are presented in Figs. 11 and 12.

Fig. 11 is the analysis results of equivalent stress between aluminum alloy and magnesium alloy. Through the above comparison, magnesium alloy wheel and aluminum alloy wheel in the same size, magnesium alloy wheel equivalent stress is 32.35 Mpa while aluminum alloy equivalent stress is 32.34 Mpa, less than the material yield stress. Magnesium alloy wheel has good strength properties.

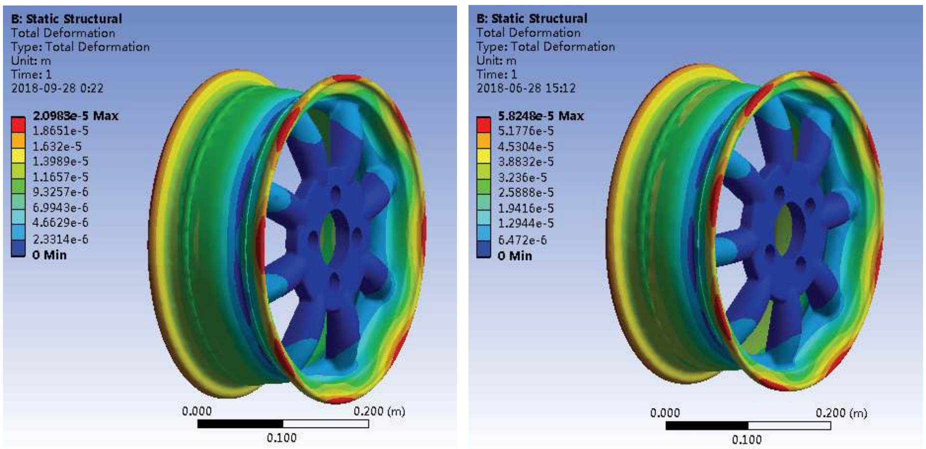
Fig. 12 is the analysis results before and after wheel optimization. From the above analysis, under the premise of the strength of wheel, the structure optimization of magnesium alloy wheel is carried out. The magnesium alloy wheel deformation is 0.021 mm, aluminum alloy wheel deformation is 0.058 mm. Magnesium alloy wheel has good strength properties. The optimization effect comparisons were shown in Table 4.

The optimized magnesium alloy wheel is much lighter than the steel wheel and aluminum wheel, compatible with wheel lightweight design. It makes sense to optimize the wheel with magnesium alloy materials.



(a) Magnesium alloy (b) Aluminum alloy

Fig. 11 Comparison of equivalent stress.



(a) Magnesium alloy (b) Aluminum alloy

Fig. 12 Comparison of deformation.

Table 4 Lightweight comparisons (kg).

Lightweight comparisons	Aluminium alloy	Magnesium alloy	Magnesium alloy (optimization)
Weight/kg	6.24	4.23	4.05
Improvement/%	_	35.1	4.4

The optimization results meet the design target value. Based on topology optimization theory, the wheel optimal structure and key dimensions are obtained while satisfying the performance of the wheel.

Topology optimization method was efficient and correct, significance for lightweight design of wheels.

5. Conclusion

The finite element analysis has been carried out on the wheel. Through the above profound analysis following research results can be acquired:

(1) Using topology optimization for wheel quality lightweight is a useful way. By optimizing wheel spokes to accurate wheel lightweight design, the optimization designed wheel meets the strength condition.

(2) By replacing lightweight materials, compared to aluminium alloy, the weighted reduction is 35.1%. After optimization, the weight of magnesium alloy has reduced by 4.4%. Magnesium alloy has a better weight reduction effect, and lightweight materials have effective lightweight means.

(3) According to the analysis results, comparison of wheel performance of different materials, after using the magnesium alloy material for replacement and analyzing of the wheel, the goal of reducing the weight of the automobile wheel can be achieved while satisfying the wheel strength requirements.

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