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Innovative Design of Automobile Wheel Rim Based on Honeycomb Features

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Abstract: Lightweight is one of the primary design goals for the innovative development of wheel hubs. A new type of automobile wheel rim is proposed in this paper. The wheel rim is divided into wheel rim face and rib. The thickness of the wheel rim surface is studied by parameter optimization. The rib layout is designed based on honeycomb features by considering processing technology and load-bearing performance of wheel hub. A novel wheel rim named "honeycomb wheel rim" is given. The mechanical performances are analyzed and the results show that the weight of new wheel rim was reduced by 12.61%, and the stiffness and strength can meet the design requirements.

Keywords: Lightweight; Innovative design; Wheel rims; Honeycomb

1. Introduction

In the era of energy saving and emission reduction, the innovative design of wheel hub not only pays attention to safety, but also pays more attention to lightweight and aesthetics. Both lightweight and beautiful wheel hub will have a greater competitiveness in the market, and also good mechanical performance directly affect the economy, dynamics, maneuverability, comfort, braking, and driving safety of the automobile [1, 2].

Wheel hub can be divided into wheel rim, wheel spoke and wheel flange. The innovative design of wheel hub is widely concerned by mechanical engineers. Zhang et al. [3] adopted the variable density topology optimization method to optimize the wheel spoke design of aluminum alloy wheels. Xiao et al. [4] adopted the compromise programming method to establish a multi-objective topology optimization mathematical model, and the wheel spoke was optimized based on the bending fatigue test. Wang et al. [5] proposed a shape optimization method based on load path analysis to evaluate and optimize the structure of wheel rim, and the optimal size combination performance-oriented is obtained by parameter optimization. Pang et al. [6] optimized parameters of several sizes on wheel spokes and wheel rims by establishing a response surface model. Hu et al. [7] optimized the parameters of aluminum alloy wheels by taking the thickness of wheel rims and wheel flange as design variables and aiming at the minimum wheel mass.

The above researches mainly focus on the topology optimization of wheel spoke and the size optimization of wheel spoke, wheel rim and wheel flange, without giving the innovative design scheme of wheel rim. The main reason is that the wheel rim belongs to the ring thin-wall structures. There are many functional requirements and process restrictions, bearing complex load and size parameters. And it is difficult to use the structural optimization method based on an iterative search to give the innovative design of the wheel rim. As a result, the design and optimization of the wheel rim are obtained through continuous trial and error with the help of finite element analysis combined with engineering experience.

In recent years, many achievements have been made in applying biological structure characteristics to engineering equipment with the goal of lightweight [8]. Wang et al. [9] designed an automobile crash-avoidance beam structure with functional gradient characteristics according to the good bearing performance and impact resistance of the porous characteristics of human tibia, effectively improving the crash-avoidance and energy absorption performance. Zhao et al. [10] analyzed the distribution law of trunk and branch of vein according to the high bearing characteristics of cactus, a beam of gantry processing center was designed and the advantages of bionic model in mechanical performance was verified by simulation and experiment. Kim et al. [11] applied the sandwich structure in the design optimization of a micro-EDM machine, and the layout of the stiffened plates is improved. Wang et al. [12] proposed a lightweight design method based on load path for the skeleton structures. The automobile control arm was innovatively designed to achieve a better lightweight effect by combining the load-transferred path of the structure with the characteristics of fish bones.

According to the structure and functional characteristics of the wheel rim, an innovative design method based on “wheel rim surface & rib” is proposed in this paper. The thickness of the wheel rim surface is studied by parameter optimization. The rib layout is designed based on honeycomb features by considering processing technology and load-bearing performance of wheel hub. A novel wheel rim named “honeycomb wheel rim” is given and the mechanical performance is verified by simulation analysis.

2. The Structure of Wheel Rim

The structure of the aluminum alloy wheel hub studied in this paper is shown in Figure 1. The material is aluminum alloy A356, the specific material properties are shown in Table 1.

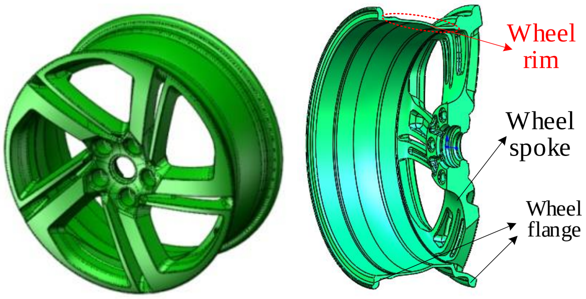


Figure 1. The structure of a wheel hub

Table 1. Material properties of the wheel hub

Materials	Young's modulus (GPa)	Poisson's ratio	Density (kg/m^3)	Yield strength (MPa)
A356	70	0.33	2680	150

According to international standards SAE J175 [13], SAE J267 [14], the bending fatigue test and radial fatigue test must be carried out before it is put into production. The load and boundary conditions of bending fatigue test and radial fatigue test are shown in Figure 2 and Figure 3.

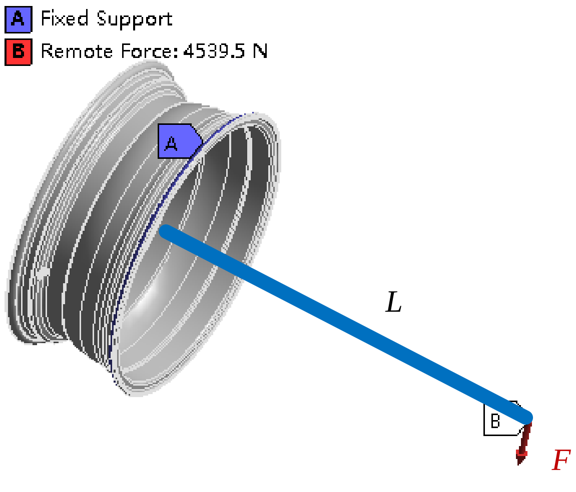


Figure 2. Finite element model of bending fatigue test

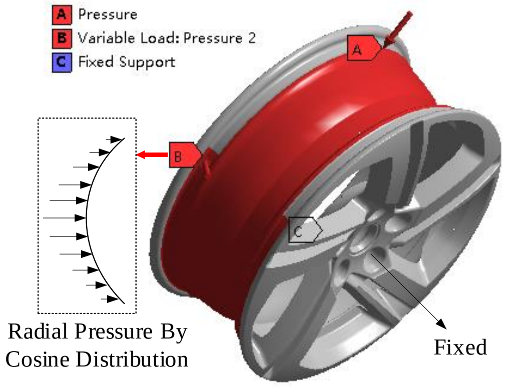
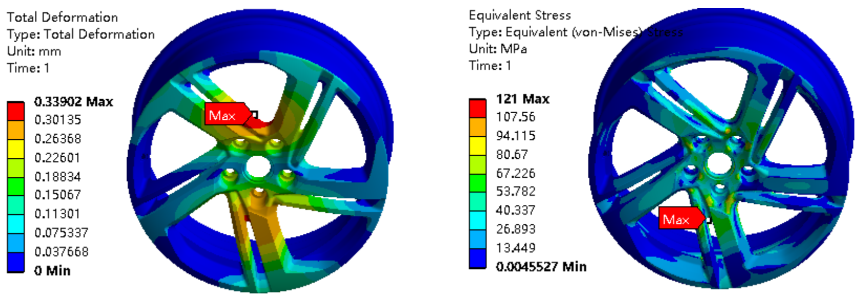


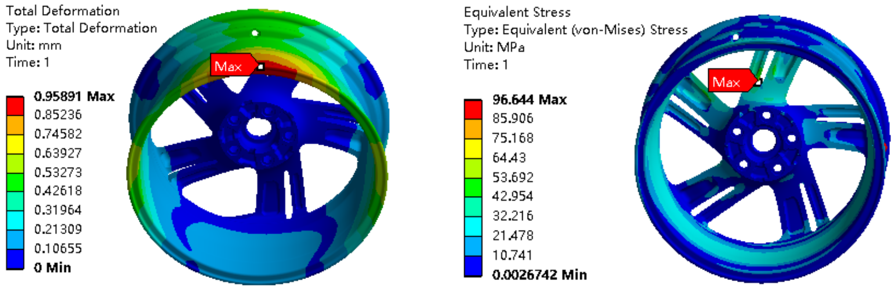
Figure 3. Finite element model of radical fatigue test

The displacement and stress distribution of the wheel hub under the bending fatigue test and radial fatigue test is calculated by Finite Element Analysis (FEA) and the results are shown in Figure 4 and Figure 5. The maximum displacement of the wheel hub is 0.3390 mm and the maximum stress is 121.0 MPa in the bending fatigue test. The maximum displacement is 0.9589 mm and the maximum stress is 96.64 MPa in the radial fatigue test. The stress is less than the yield strength of the material, and the maximum stresses are mainly concentrated at the spokes and less at the wheel rim. Therefore, the wheel rim has a certain lightweight space.



(a) (b)

Figure 4. FEA of bending fatigue test (a) Displacement distribution; (b) Stress distribution



(a) (b)

Figure 5. FEA of radical fatigue test (a) Displacement distribution; (b) Stress distribution

3. Innovative Design

3.1 Design Method

Based on the structural type and load-bearing features of the wheel rim, an innovative design idea of "wheel rim surface & rib" is proposed, as shown in Figure 6. The wheel rim surface is used to support the wheel hub, while the rib is used to reinforce the wheel rim surface. The thickness sum of the wheel rim surface and rib is the same as the original wheel rim. For this structural type, there are two problems to be solved: One is how to distribute the thickness of the wheel rim surface and rib, the other is what kind of rib layout is more appropriate.

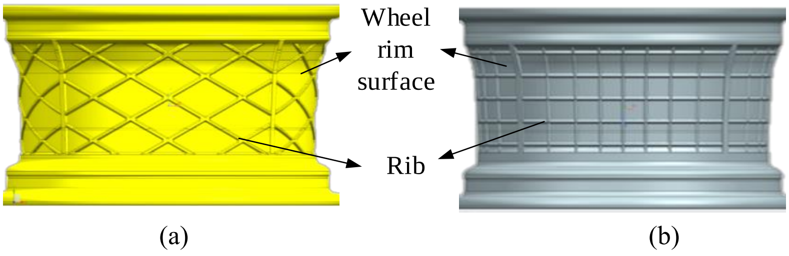


Figure 6. New structural type of wheel rim (a) ribs at 60º; (b) ribs at 90º

For the first problem, the thickness ratio of the wheel rim surface and rib can be studied by size optimization according to the requirements of the casting process of the wheel hub. For the rib layout, the conventional rib layout is usually designed with 45º, 60º, or 90º ribs arranged regularly in many engineering structures, as shown in Figure 6. But the layout does not take into account the actual load-bearing conditions in the local region of the structure, so there is space for further to design. An inspiration obtained from nature is to carries on the bionic design of rib layout.

3.2 Thickness Distribution

The minimum wall thickness of the wheel rim surface directly affects the stability of tire air pressure. So the wheel rim surface must be able to maintain sufficient mechanical performance under the maximum air pressure inside the tire from the perspective of safety in the design process. In this paper, the wheel rim surface is subjected to an ultimate load of 550 KPa. As shown in Figure 7, the thickness t of the wheel rim is taken as the design variable, and the thickness range of t is set to 1.5~4.5 mm considering the casting process constraint.

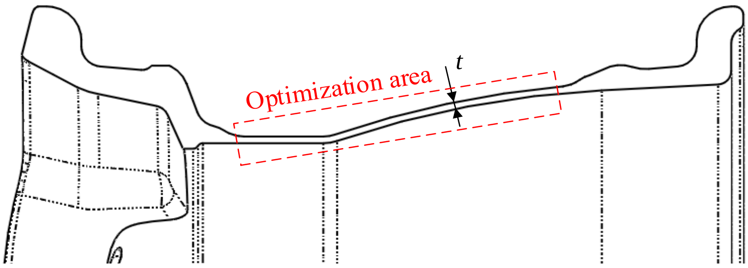


Figure 7. Design variable t of the wheel rim

Because the mapping relationship between the thickness of wheel rim surface and the mechanical performance of wheel hub is difficult to express analytically, the finite element model is established and the size optimization is carried out by numerical simulation in Figure 8. A pressure load of 550 KPa is applied to the wheel rim surface, and the mounting surface of the wheel hub is fixed as the constraints.

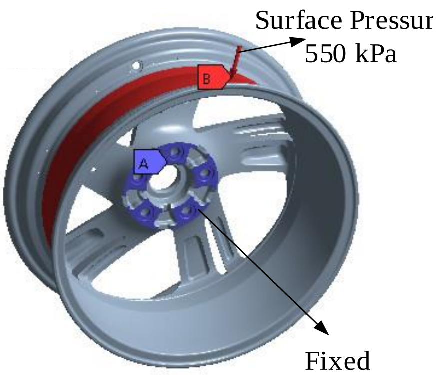


Figure 8. Finite element model of parameter optimization for the wheel rim

To meet the strength requirements of wheel hub, the safety factor is set to 2 and the maximum stress value is less than 75 MPa as the constraint. A mathematical model of size optimization is established as shown in Eq. (1). The genetic algorithm is selected for iterative optimization.

$$
\begin{cases}
\text{find} \quad t \\
\min \quad M = f(t) \\
\text{subject to} \quad t \in [1.5,\ 4.5] \\
\qquad\qquad\quad \sigma_p \le 75
\end{cases}
\tag{1}
$$

Three candidate solutions are obtained as shown in Table 2, which shows that when the thickness of the wheel rim surface is 1.925~2.025 mm, the maximum stress is about 75 MPa, which can meet the safety requirement.

Table 2. Results of size optimization

Candidate solutions	**1**	**2**	**3**
Wheel rim surface thickness /mm	1.925	1.975	2.025
Maximum stress /MPa	74.810	72.990	71.260

Therefore, 2 mm is set as the minimum wall thickness of the wheel rim surface in this paper, and the stress distribution is shown in Figure 9, the maximum stress is 71.79 MPa, which is located in the middle of the wheel rim surface.

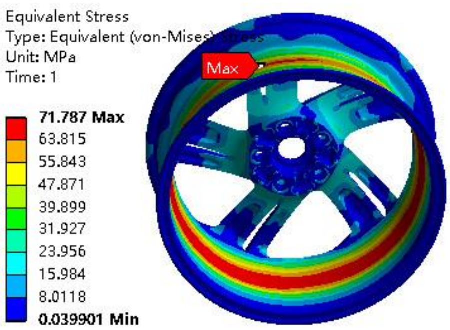


Figure 9. Stress distribution of wheel rim with 2 mm wall thickness

3.3 Rib Layout Based on Honeycomb Features

3.1.1 Design requirements

The innovative design of wheel hub should consider its manufacturing process at first. As shown in Figure 10, the mold is opened and closed in four directions of wheel hub respectively, and each side mold corresponds to 90º of the wheel rim. In addition, the rib layout should be symmetrically distributed circumferentially to ensure the dynamic performance of the wheel hub.

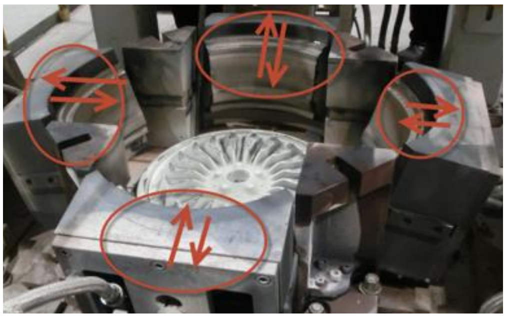


Figure 10. The casting process of wheel hub

For this purpose, four axial stiffening ribs are evenly distributed along the circumference of the 2 mm wheel rim surface. Every two ribs are set at 90º relative to the axis as shown in Figure 11. The rib layout of wheel rim is simplified into a plate or shell with an angle of 90º around the circumference as shown in Figure 12. The load is simplified to the surface load p and bending load F. The organisms with similar characteristics of load and constraint will be selected as the bionic prototype.

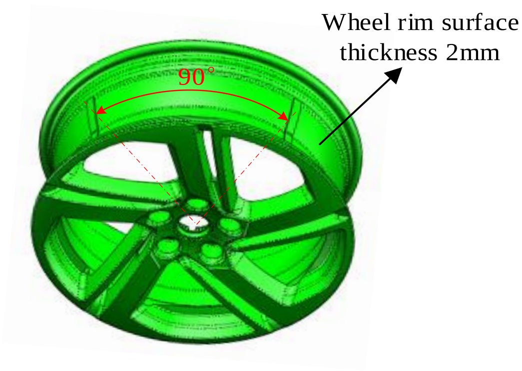


Figure 11. Diagram of main structure of wheel rim rib

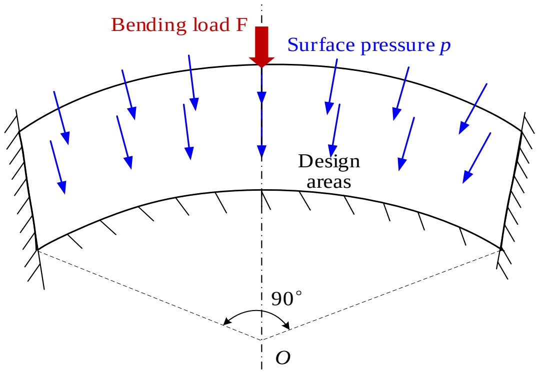


Figure 12. Bionic model of wheel rim

3.3.2 Honeycomb wheel rim

According to Figure 12, the bionic prototype of rib layout requires better compressive and flexural loads. It is found that the honeycomb has a good adaptability to surface load and has been applied in engineering structures [15, 16]. On the one hand, the honeycomb and wheel rim actually bear the same loads including surface load and bending load. The ribs studied in this paper are distributed on the wheel rim surface, similar to the staggered cells at the bottom of the honeycomb. On the other hand, the precise structure of the hive allows it to withstand tens of times more honey with a lighter structure, and the wheel rim is also designed to withstand greater tire pressure with the least amount of material. So, the honeycomb structure is selected for bionic design of the wheel rim in this paper.

Based on the similarity of load, structure and function between the honeycomb structure and the wheel rim, the honeycomb hexagon structure was directly applied to the rib layout as shown in Figure 13. The honeycomb wheel rim is established as shown in Figure 14.

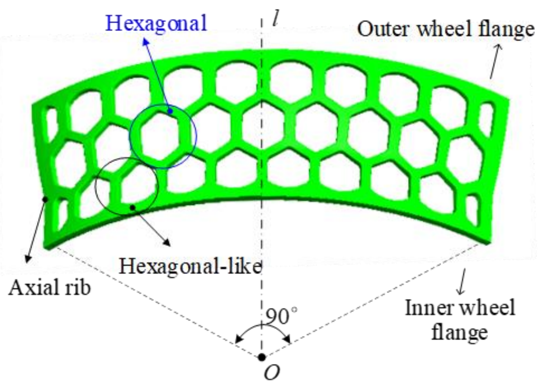


Figure 13. Rib layout of wheel rim

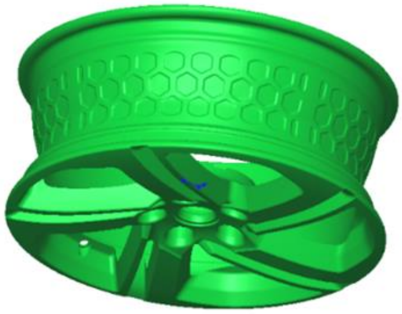
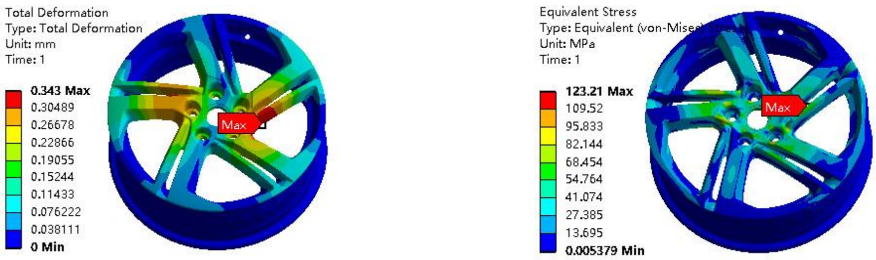


Figure 14. Honeycomb wheel rim

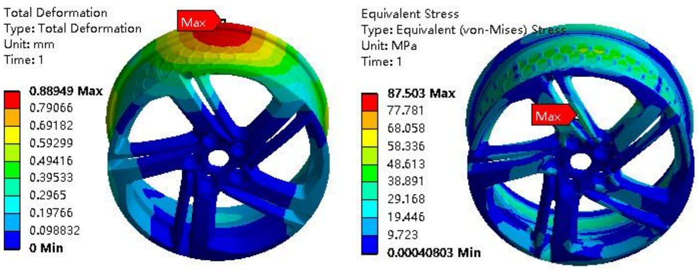
4. Simulation analysis and Discussion

The mechanical performances of honeycomb wheel rim are analyzed by FEA with the similar loads and constraints under the bending fatigue test and radial fatigue test. The displacement and stress distribution of the honeycomb wheel rim are calculated as shown in Figure 15 and Figure 16.



(a) (b)

Figure 15. FEA of honeycomb wheel rim under bending fatigue test (a) Displacement distribution; (b) Stress distribution



(a) (b)

Figure 16. FEA results of honeycomb wheel rim under radical fatigue test (a) Displacement distribution; (b) Stress distribution

Table 3. Comparison of mechanical performance

		Original model	Honeycomb wheel rim
Rim weight (kg)		2.673	2.336 (-12.61%)
Bending fatigue test	Maximum displacement (mm)	0.3390	0.3430 (+1.18%)
	Maximum stress (MPa)	121.00	123.21 (+1.83%)
Radial fatigue test	Maximum displacement (mm)	0.9589	0.8895 (-7.24%)
	Maximum stress (MPa)	96.64	87.50 (-9.46%)

The mechanical performances of the honeycomb wheel rim and the original model is compared in Table 3. The maximum stress of honeycomb wheel rim under bending fatigue test condition and radial fatigue test condition is 123.21 MPa and 87.50 MPa respectively, which is less than the yield strength of the material. The maximum displacement of the honeycomb wheel rim under two working conditions is 0.3430 mm and 0.8895 mm respectively, which is close to the deformation of the original structure. The stiffness and strength can meet the design requirements of wheel hub. Through the above analysis, it can be found that the honeycomb wheel rim has an excellent lightweight effect, and the weight reduces by 12.61%.

5. Conclusions

A new type of automobile wheel rim including wheel rim face and rib is proposed in this paper. The thickness radio of the wheel rim surface and rib is studied by parameter optimization. Setting the minimum wall thickness of the wheel rim surface to 2 mm can meet the basic strength requirements. The rib layout is designed based on honeycomb features by considering processing technology and load-bearing performance of wheel hub. A novel wheel rim named "honeycomb wheel rim" is designed. The mechanical performance of the honeycomb wheel rim is verified by simulation analysis, and the results show that the weight reduction of the honeycomb wheel rim was 12.62%. The maximum stress and maximum displacement of the honeycomb wheel rim under the bending fatigue test condition and radial fatigue test condition meet the design requirements. It shows that the design idea of "wheel rim surface & rib" can solve the lightweight problem of complex wheel rim structures.

Author Contributions

Conceptualization, Z.W. and F.W.; methodology, Z.W. and G.Y.; software, Z.W., G.Y. and C.W.; validation, C.W. and F.W.; writing—original draft preparation, C.W. and G.Y.; writing—review and editing, Z.W. and F.W.; visualization, C.W. and G.Y.; supervision, Z.W.; project administration, F.W.; funding acquisition, F.W. and Z.W. All author shave read and agreed to the published version of the manuscript.

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Data Availability

The data can be obtained from the first author or corresponding author by email.

Conflicts of Interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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