Lightweight Design of Steel Wheel Introducing the Disc Spinning Process

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Abstract

The steel wheel consists of wheel disc and rim. The wheel disc is manufactured by using power spinning process. The spinning process does not guarantee that the design scheme can be realized accurately. In this paper, the simulation method of the disc spinning process is investigated, and introduced to the lightweight design of steel wheel. Firstly, the power spinning process is simulated, and the validity of the simulation method is verified by test. Then two optimization schemes of the disc are proposed. Finally, the forming quality of the products from the optimization schemes is analyzed by spinning process simulation. The results show that the product from the optimal scheme may not be optimal since the effect of the forming quality in the spinning process. To obtain the optimal performance of product, it is very necessary to evaluate the design scheme by introducing the disc spinning process in the design stage of wheel disc.

Introduction

As one of the most significant safety components, the steel wheel consists of the disc and rim. For the wheel of the commercial vehicle, the disc is mostly manufactured by power spinning process and the rim is formed by rolling process. As the rotating unsprung component of vehicle, the wheel has a greater contribution to the lightweight of the vehicle than the non-rotating sprung component[1]. The lightweight design of wheel involves the lightweight of disc and the lightweight of rim. The accurate realization of the disc lightweight design depends on the processing technology. The previous lightweight design of disc was only to minimize the weight on the premise of ensuring strength, while ignored the consideration of whether the spinning process can accurately realize the design parameters or not. This fact leads to the deviation between the product and the design, and affects the realization of optimization design. Therefore, it is necessary to introduce the spinning process in the optimization design stage of disc.

A lot of researches have been carried out on the spinning process and optimal design of wheel structure. Chen et al.[2] analyzed the two factors of the material and the spinning process related to the lateral cracking phenomenon of the spinning disc, and obtained that the main causes of cracking were original cracks, inclusions in the material and large spin forming ratio. Sangkharat et al.[3] combined the orthogonal test method with the finite element analysis (FEA), and studied the effects of eight parameters on the spinning pressure and forming quality of the steel sheet. Hsu et al.[4] described a weight reduction problem of aluminum disc wheels under cornering fatigue constraints and presented a sequential neural network approximation method to solve this type of discrete variable engineering optimization problems. Ahmad et al.[5] optimized the size of steel wheel rim based on the FEA and numerical method, and improved the mass and volume of the obtained wheel after two optimizations. Chen L et al.[6] performed stress analysis of the wheel based on FEA and compared the stress results and fatigue life results of the optimized position under different thickness. Finally, the weight of the rim is reduced by about 14% while ensuring the design requirements of the wheel. Li et al.[7] built a parametric model of the steel wheel, and optimized the disc’s shape and vent’s position. The maximum stress of the wheel under bending load is reduced by 11.52%.

The disc with variable thickness and approximately equal strength has been widely used. Although this method can meliorate the strength and rigidity of the wheel and meet the performance requirements of the wheel, it cannot truly realize the full utilization of the materials since most of the disc with variable thickness is designed on the basis of experience. The details in processing technology are rarely considered in the structural design of disc, which causes the design of disc to fail to be realized correctly. Moreover, so far as authors know, up to now, there is not a public report on the combination of parameter optimization and process analysis to evaluate the design scheme of disc.

Aiming at above-mentioned problems, in this paper, the spinning process of disc is introduced in the optimization design stage of disc. The power spinning process of the disc and the cornering fatigue test of a steel wheel are simulated. Taking the maximum stress of the disc under bending load as the constraint, the thickness of the disc is optimized, and two optimization schemes with different thickness distribution are proposed. The feasibility of spinning process related to the two schemes is analyzed by simulation, and the forming quality of the products from the optimization schemes is analyzed by spinning process simulation.

Simulation Of Power Spinning For The Wheel Disc

The thickness of the wheel disc manufactured by using the spinning process can be accurately predicted by using Simufact.forming software[8]. Considering the great effect of the residual stress in the wheel disc arising from the spinning process on the strength of the wheel, this software is also used to obtain the residual stress.

The wheel disc is made of the special steel plate (SW400) for wheel with original thickness of 11 mm. The hardening characteristic curve of SW400 is obtained through test (Fig. 1), and the key mechanical parameters affecting the forming results including density, elastic modulus, Poisson’s ratio, yield stress are shown in Table 1. According to the actual processing experience of the relevant enterprises, the spinning process parameters of the disc are: the feed rate of the rollers (2 mm/r), and the rotating speed of the mandrel (450r/min). And the friction coefficient between the rollers and the workpiece is appropriately set to be 0.13.

Table 1
Material parameters of SW400

Density (kg/m^3)	Elastic modulus (MPa)	Poisson's ratio	Yield stress (MPa)
7800	2.0×10^5	0.3	400

The machining residual stress needs to be considered in the design stage since its great effect on the strength of the wheel[4]. In this paper, the residual stress of the disc arising from the spinning process after unloading and rebounding is simulated, and the stress distribution is shown in Fig. 2.

To validate the effectiveness of the method, the measurement of the residual stress is performed. In this paper, the hole-drilling method is used since its convenience and low cost. In this method, the small blind hole is with the diameter of 1.5 mm and the depth of 2.0 mm[9]. The installation of strain gauge is shown in Fig. 3. Considering the disc shape and the feasibility of the residual stress test, three measure points on the outer surface of the disc are selected. The distance between measure points is great, and the angle between the radii where the measure points is located is about 90° (Fig. 4 (a)). This distribution may avoid the interaction of the stress fields at different measure points. The axial distance from the three measure points (Fig. 4 (b)) to the installation surface is 41.5 mm, 53.5 mm and 74.0 mm, respectively.

For each of the three selected measure points, the strain values along the directions of 0°, 45°, 90° and temperature compensation sheets are measured respectively. The results are shown in Table 2.

Table 2
Strain of measure points

Measure point	**0° direction**	**45° direction**	**90° direction**	**Compensation**	$\varepsilon_{0°}$	$\varepsilon_{45°}$	$\varepsilon_{90°}$
Point 1	-20.54	-28.94	-140.59	0.85	-19.96	-28.09	-139.74
Point 2	22.80	-8.06	-186.29	0.52	23.32	-7.54	-185.77
Point 3	-103.89	-28.52	-120.83	3.22	-100.67	-25.30	-117.61

Since the stress distribution obtained by the spinning simulation is nonuniform (Fig. 2), 7 positions are selected on the same circumference where each measure point is located. The average value of stresses at 7 positions is recognized as the residual stress of the point. Table 3 indicates the comparison of the residual stress measured from the test with ones from the simulation. We may see that the deviations of the residual stress at the three measure points are from − 1.53–11.26%. So the simulation results are in good agreement with the test ones. Therefore, the residual stress in the wheel disc after spinning may be predicted appropriately, and in the design stage of disc, the residual stress may be introduced to obtain the reliable optimization results.

Table 3
Test results of measure points

Measure point	σ_1 (MPa)	σ_2 (MPa)	θ (°)	Simulation results (MPa)	Test results (MPa)	Deviation
Point 1	172.14	61.12	0.36	151.15	151.15	-1.53%
Point 2	208.33	28.95	0.31	195.47	195.47	-0.63%
Point 3	218.49	100.32	0.73	189.43	189.43	11.26%

Optimization Of The Disc

The steel wheel disc of commercial vehicle is usually designed as a variable cross-sectional structure to achieve equal strength. In this paper, two optimization schemes of the disc cross-section dimension are given through the automatic optimization process[10]. Furthermore, the forming results of two schemes are analyzed through the spinning process simulation.

3.1 Simulation of wheel strength under bending load

The cornering fatigue test is used to simulate the stress state of the wheel when the vehicle turns under certain load condition. And the performance of the wheel disc is mainly evaluated in the cornering fatigue test. According to the standard ISO 3006 – 2015[11], the finite element analysis model of the cornering fatigue test of above-mentioned steel wheel is established. The model is composed of the wheel disc, rim and loading arm, as shown in Fig. 5. All parameters in simulation are from ISO 3006 – 2015: the moment of 23656 N·m, the moment arm with 1266 mm length, and the concentrated force (18685.6 N) applied on the end of the loading arm.

Only the stress distribution of the disc is given below since the stress of the rim induced by the bending load is much smaller than that of the disc. When the bending load is directed to the ventilation hole, the stress distribution of the wheel disc is as shown in Fig. 6. The stress in the left and right sides of the ventilation hole is larger than that in other areas of the disc, and Mises stress at the point P of the maximum stress is 272.3 MPa. The wheel needs to stand for 30,000 revolutions during the cornering fatigue test according to the ISO 3006 2015. But in the actual fatigue test of this wheel, it fails after 263200 revolutions. According to the test results provided by the enterprise, the crack occurs at the edge of the ventilation hole (Fig. 7). It can be seen that the position of crack is exact at point P (the most dangerous point shown in bending fatigue simulation), which validate the simulation method used here.

3.2 Establishment of optimization model

Since the brake of vehicle is installed inside the rim, the inner profile of the disc and the installation surface cannot be arbitrarily adjusted. Moreover, to ensure the quality of the combination welding of disc and rim, the thickness of the assembling surfaces of the disc and the rim keeps constant. Therefore, the outer contour of the disc is optimized here. In the parametric modeling of the disc, the inner profile of the disc (the solid line in Fig. 8) remain constant, but the outer contour (the dotted line in Fig. 8) varies with the design parameters[12]. The shape of the disc is mainly determined by the design variables of the six sections (D1, D2, D3, D4, D5, D6).

Since the selected steel wheel meets the bending fatigue test standard very well, the maximum stress of original disc under bending load is taken as the stress constraint of the disc in the optimization. Therefore, in the parametric modeling of the disc, the disc thickness parameters at different sections are set as optimization variables, and the maximum stress of 272.3 MPa is set as the constraint, and the disc's weight serves as the objective function. The flow chart of the optimization is shown in Fig. 9. The Solidworks is automatically driven by Excel to update the disc geometry modeling, and the disc weight is obtained. The updated disc model is imported into Abaqus. The analysis results (stress, deformation, etc.) obtained by Abaqus and disc weight are input to Isight. The Isight software determines new disc design parameters based on the specified optimization algorithm. The disc structure parameters are automatically optimized. Finally, the model strength simulation is automatically calculated and the required results are output.

3.3 The first set of optimal design variables and the analysis of optimization results

The first set of the disc cross-section optimization parameters is shown in Fig. 10. The design variables D1, D2, D3, D4 and D5 are optimized, and their value ranges are shown in Table 4. Considering the machining accuracy, the increment of each design variable is set to be 0.1.

Table 4
Optimization design variables and their value range

Design variables	Initial value	Lower bound	Upper bound	Increment of variables
D1(mm)	8.1	7.1	8.1	0.1
D2(mm)	7.2	6.2	7.2	0.1
D3(mm)	8.7	7.6	8.7	0.1
D4(mm)	6.0	5.2	6.0	0.1
D5(mm)	6.9	5.8	6.9	0.1

The optimization results obtained after 300 iterations are shown in Table 5, and denoted as Scheme 1(S-1). The stress distributions of the disc before and after optimization under the bending load are shown in Fig. 11. The maximum stress value of the disc after optimization is 264.3 MPa, which is 8 MPa lower than that of the original disc. The disc weight reduces from 15.51 kg to 14.83 kg, so is 4.4% less than before.

Table 5
Optimization results of S-1

Design variables	Initial value	Optimal value	Deviation
D1(mm)	8.1	7.1	-12.3%
D2(mm)	7.2	6.4	-11.1%
D3(mm)	8.7	7.8	-10.3%
D4(mm)	6.0	5.9	-1.7%
D5(mm)	6.9	6.1	-11.6%
Maximum stress (MPa)	272.3	264.3	-2.9%
Weight (kg)	15.51	14.83	-4.4%

3.4 The second set of optimal design variables and the analysis of optimization results

The second set of the disc cross-section optimization parameters is shown in Fig. 12. The design variables D2, D3, D4, D5 and D6 are optimized, and their value ranges are shown in Table 6. Considering the machining accuracy, the increment of each design variable is set to be 0.1.

Table 6
Optimization design variables and their value range

Design variables	Initial value	Lower bound	Upper bound	Increment of variables
D2(mm)	7.2	6.7	7.2	0.1
D3(mm)	8.7	7.0	8.7	0.1
D4(mm)	6.0	5.0	6.0	0.1
D5(mm)	6.9	5.9	6.9	0.1
D6(mm)	5.7	5.2	5.7	0.1

The maximum stress 272.3 MPa of the original disc under bending load is still set as the stress constraint. The optimization results obtained after 305 iterations are shown in Table 7, and denoted as Scheme 2(S-2). The stress distributions of the disc before and after optimization under the bending load are shown in Fig. 13. The maximum stress value of the disc after optimization is 266.16 MPa, which is 6.14 MPa lower than that of the original disc. The disc weight reduces from 15.51 kg to 14.89 kg, so is 4.0% less than before.

Table 7

Optimization results of S-2

Design variables	Initial value	Optimal value	Deviation
D2(mm)	7.2	7.0	-2.8%
D3(mm)	8.7	7.0	-19.5%
D4(mm)	6.0	5.7	-5.0%
D5(mm)	6.9	6.3	-8.7%
D6(mm)	5.7	5.4	-5.3%
Maximum stress (MPa)	272.3	266.16	-2.3%
Weight (kg)	15.51	14.89	-4.0%

Technological Feasibility Analysis Of Optimization Schemes

4.1 Analysis of first scheme

The spinning process simulation of the S-1 is carried out. The simulation results are shown in Fig. 14. It can be seen from Fig. 14(a) that the warpage at the corner of the disc's installation surface occurs, and the separation between the workpiece and the mold takes place, which arises from the excessive thickness reduction of D1. And by comparing Fig. 14(b) with Fig. 2, it can be seen that the residual stress of the disc is larger than the original one obviously.

Although the maximum stress in this optimization scheme meets the constraint conditions, and a certain lightweight of the disc is obtained, and a more reasonable scheme seems to be achieved, if the design scheme is analyzed from the aspect of spinning process, we may see that the reasonable poor machining performance and greater residual stress exist in so-called optimization scheme.

4.2 Analysis of second scheme

When selecting the second set of optimized design variables to avoid warping at the installation surface corner, the thickness of D1 remains constant. The spinning process simulation of the S-2 is carried out. Since the outer diameter of the disc after spinning needs to be turned before the assembly with the rim, 9 measure points of the disc without turning parts are selected (Fig. 15), and the disc thickness is compared. The comparison results are shown in Table 8. It can be seen that the maximum thickness deviation is 3.55%, that is, the simulation results are in reasonably good agreement with the design ones.

Although the reduction of maximum stress and weight in the S-1 is greater than those in the S-2, the effect of the spinning processing in the S-1 is not satisfactory. Obviously, the S-2 is a reasonable design scheme. The comparison of two schemes is shown in Table 9.

Table 8

Comparison of design thickness and thickness from simulation (unit: mm)

Number of Measure point	1	2	3	4	5	6	7	8	9
Design thickness	8.82	7.39	6.76	7.33	6.88	5.72	5.55	6.35	5.44
Thickness from simulation	8.60	7.19	7.00	7.33	7.12	5.92	5.67	6.15	5.61
Relative error (%)	-2.49	-2.71	3.55	0	3.49	3.50	2.16	-3.15	3.13

Table 9

Comparison of two schemes

Scheme	Maximum stress	Weight	Process forming effect
S-1	-2.9%	-4.4%	Warpage
S-2	-2.3%	-4.0%	Unwarpage

Conclusions

In this paper, the optimization of the disc's cross-sectional dimensions is performed. Two optimization schemes are proposed, and the spinning simulations are carried out to verify the machinability of the optimized results. The following conclusions are reached:

(1)
The two optimization schemes achieve the weight reduction effect of about 4% on the premise of satisfying the stress constraint. The optimization method can provide effective guidance for the research of wheel.

(2)
Spinning process simulation of the two optimization schemes is carried out respectively. The results show that the S-2 is a more reasonable optimization scheme although the disc designed according to S-1 is lighter in weight. The results of the disc spinning process simulation can provide a strong basis for the choice of disc design.

(3)
In the lightweight design of the wheel, the machining process should be considered to ensure the better forming effect of the wheel.

Declarations

Availability of data and materials section

The data used to support the findings of this study are included within the article.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests
We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.
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Authors' contributions
The manuscript was written through contributions of all authors. Bin Dang was a major contributor in writing the manuscript. Yingchun Shan and Xiandong Liu provided guidance for the research work in this manuscript. Lezheng Huan and Er Jiang helped with the experiments in this manuscript. All authors have given approval to the final version of the manuscript.
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Figures

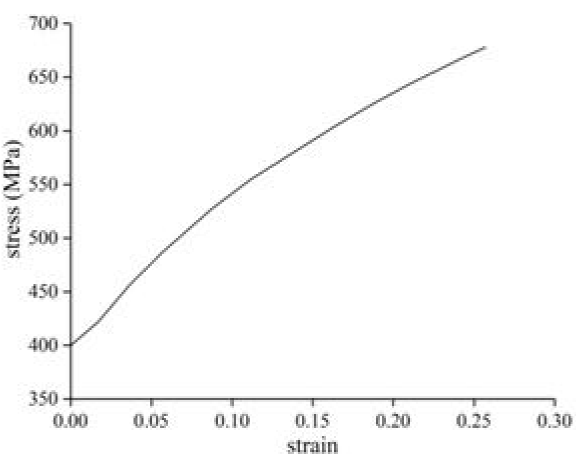


Figure 1

Material hardening characteristic curve of SW400

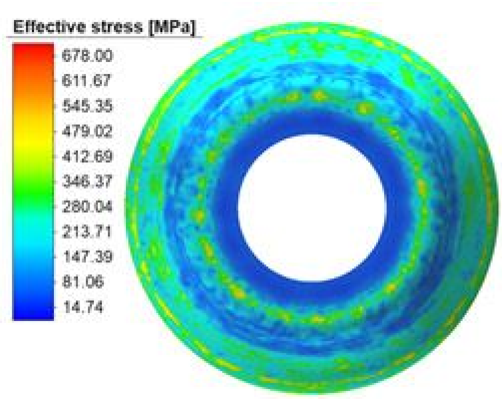


Figure 2

Residual stress of the wheel disc

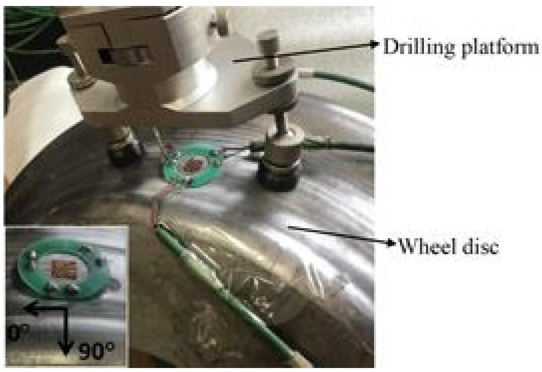
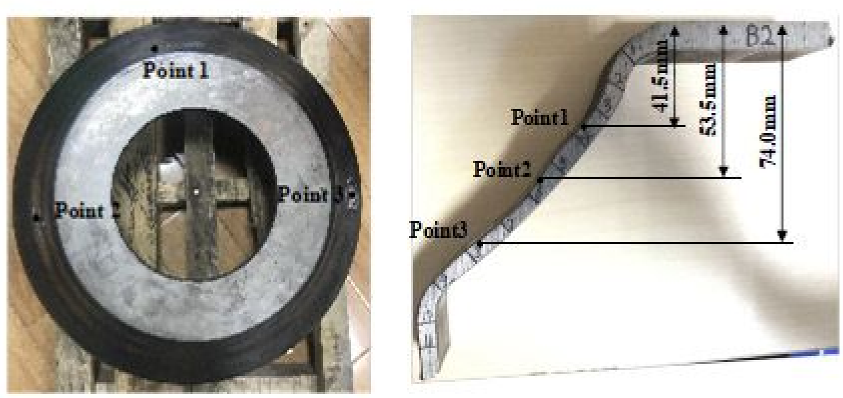


Figure 3

Measure residual stress by hole-drilling method



(a) Radial distribution of measure points (b) Axial distribution of measure points

Figure 4

Measure point of residual stress

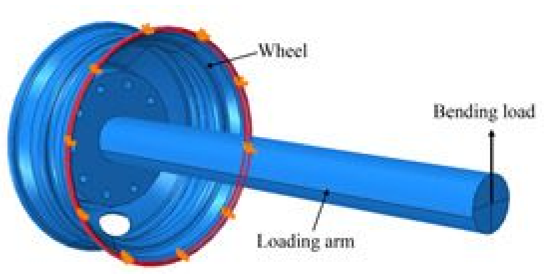


Figure 5

Constraint setting and application of bending load

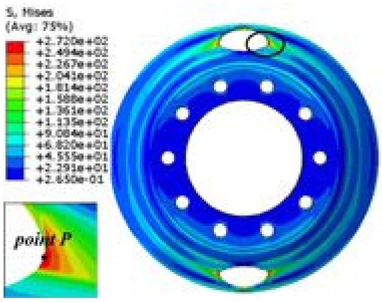


Figure 6

Stress distribution of the disc

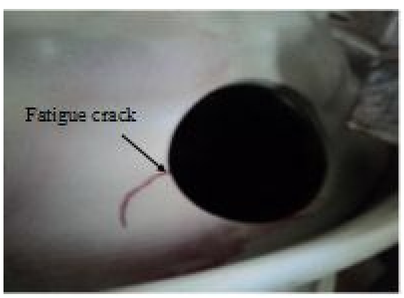


Figure 7

Result of the cornering fatigue test

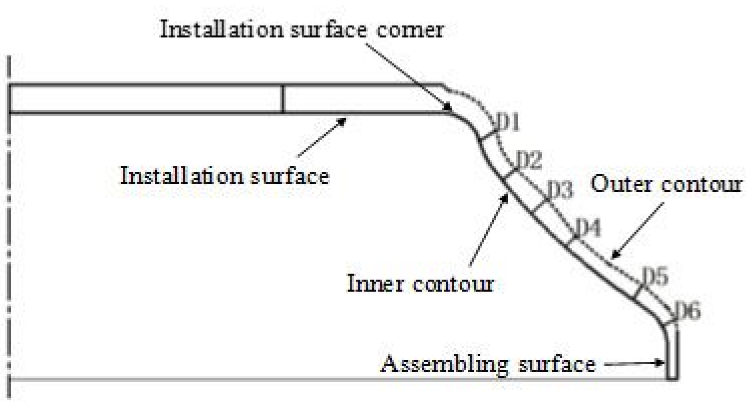


Figure 8

The disc cross-section parameters

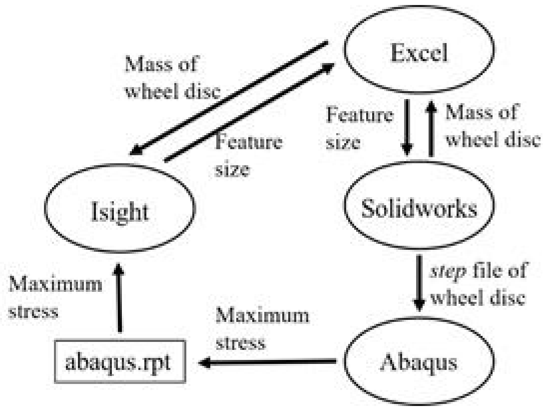


Figure 9

The flow of optimization design[12]

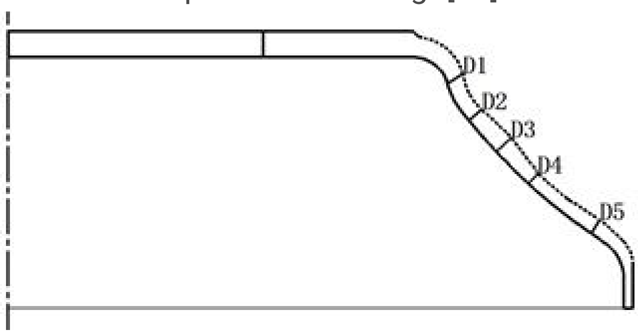


Figure 10

The first set of optimization parameters

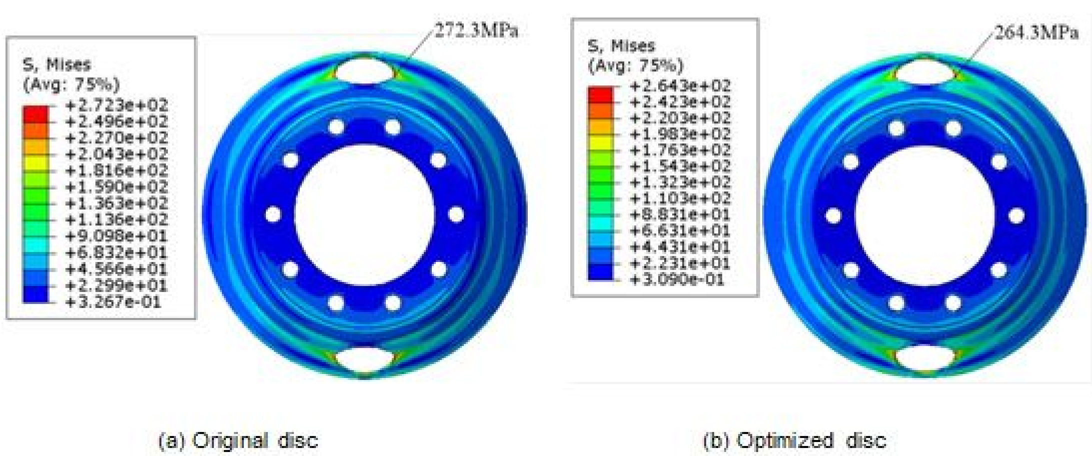


Figure 11

Distribution of the disc stress of S-1

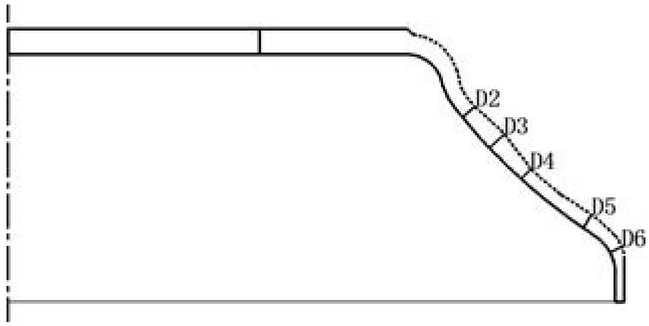


Figure 12

The second set of optimization parameters

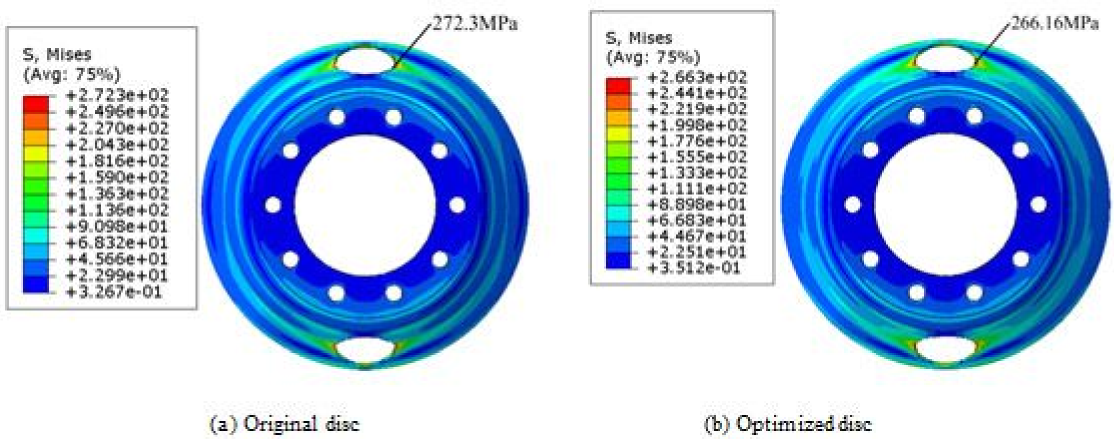


Figure 13

Distribution of the disc stress of S-2

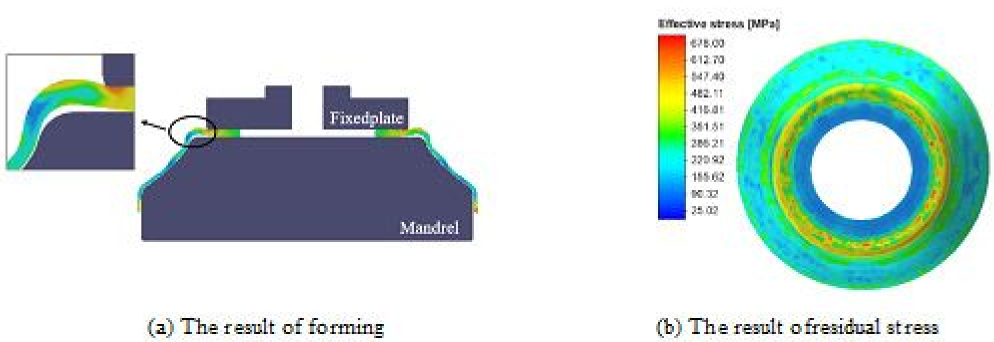


Figure 14

The result of S-1

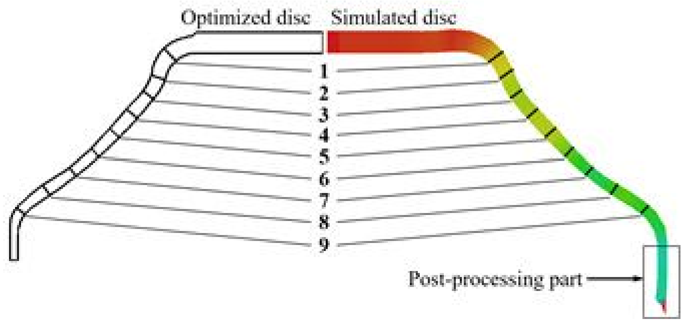


Figure 15

Measure point of disc

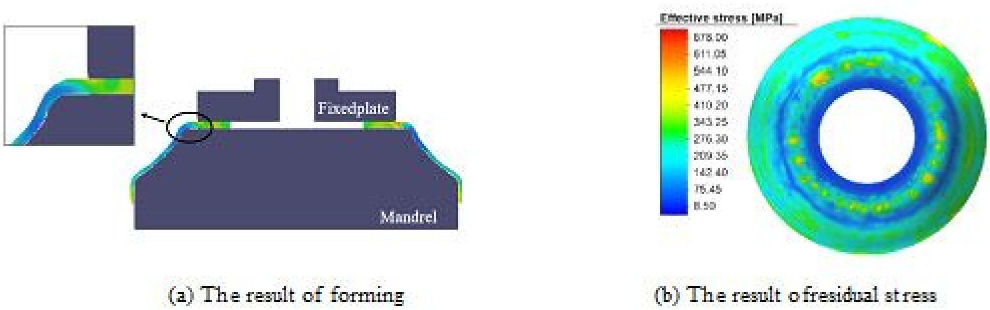


Figure 16

The result of S-2