Research Article

Hanjun Gao, Xin Li, Qiong Wu*, Wanhao Zhang, Guowen Dai, and Guohong Zhang

The optimization of friction disc gear-shaping process aiming at residual stress and machining deformation

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Abstract: Friction disc is the key part of the frictional clutch. But there is a lack of in-depth studies on the effect of the cutting parameters on residual stress and machining deformation. In this study, the simulation model for friction disc gear shaping was established and the effect of the typical cutting parameters on surface residual stress and machining deformation was studied. Based on the study's results, the optimization experiment of friction disc gear shaping was carried out and a method was proposed to reduce machining deformation and to improve the fatigue life. Applying the proposed method, the residual stress on the tooth bottom increased from -122.50 to -371.33 MPa, an increase of 203.13% that increases the fatigue life greatly. Meanwhile, the front and bottom face deformation of the outer ring as well as the deformation of the front and bottom tooth tip can be decreased effectively. This study can provide technical support for improving the comprehensive performance of the friction disc and transmission system.

Keywords: friction disc, machining deformation, residual stress

1 Introduction

The frictional clutch transmits torque depending on the friction between the multiple friction discs within it. As core components, the friction disc plays an irreplaceable role in the process of power transmission due to its characteristic high relative speed, compact structure, and large transmission power. However, the high impact load, high temperature, and other harsh working conditions make the friction disc prone to erosion, wear, deformation, and even fracture, which significantly affect the reliability and stability of the transmission device.

The large amount of friction heat generated by the relative motion between friction discs will significantly affect the temperature and stress field of the system, which is the key factor leading to the increase of material wear rate, local burning, surface warping, hot cracking, and even failure [1]. Jen and Nemecek [2] analyzed the temperature rise caused by the relative motion between the friction disc and solved the total energy of the system. Based on the expression of the temperature and stress fields as modal expansions, Li and Barber [3] applied the fast speed expansion method to solve the transient thermo-elastic contact problem.

The surface morphology and characteristics of the material significantly affect its service life and dynamic performance, and its parameters have a strong nonlinear effect on the wear of the friction material. Zou et al. [4] studied the surface characteristics under different contact loads as well as the effects of load and sliding speed on the friction coefficient, and discussed the relationship between the surface characteristics of clutch disc materials and friction performance. Based on the contact model and sliding friction work model, Zhu et al. [5] established the wear mathematical model of the friction disc respectively, and used the model to predict the fatigue life of the friction disc. It has a certain guiding significance on the effective use of the friction disc.

* **Corresponding author: Qiong Wu**, State Key Laboratory of Virtual Reality Technology and Systems, School of Mechanical Engineering and Automation, Beihang University, Beijing, 100191,

People's Republic of China, e-mail: wuqiong@buaa.edu.cn

Hanjun Gao, Xin Li: State Key Laboratory of Virtual Reality Technology and Systems, School of Mechanical Engineering and Automation, Beihang University, Beijing, 100191, People's Republic of China

Wanhao Zhang: Science and Technology on Vehicle Transmission Laboratory, China North Vehicle Research Institute, Beijing, 100072, People's Republic of China

Guowen Dai, Guohong Zhang: Powder Metallurgy Plant, Hangzhou Advance Gearbox Group Co., Ltd., Hangzhou, 311203, People's Republic of China

The temperature rise and wear discussed above are the two most common problems in the working process of the friction disc, to which researchers attach great importance. In addition, researchers have also conducted a lot of research on the design, manufacture, and performance of the friction disc. In design, the choice of material is the first consideration. 30CrMnSiA alloy steel emerges due to its superior comprehensive mechanical and technological properties, such as the high strength, toughness, hardenability, and good fatigue resistance. In terms of structure, Ning *et al.* [6] proposed a variable damping design method to reduce the impact load and improve fatigue life. Some scholars studied the oil groove on the surface of the friction disc [7], which has the function of increasing the friction coefficient and heat dissipation.

Common gear machining methods include gear milling, gear hobbing, gear shaping, gear grinding, and so on *refs* [8–11]. Considering the applicable scope of each processing method, the structural characteristics, and machining efficiency, the gear-shaping process was selected to machine the friction disc. In the aspect of gear shaping, Datta *et al.* [12] calculated the instant stress value of the gear-shaping cutter at different cutting strokes under different load conditions, and analyzed the stress distribution of the cutter edge. Li *et al.* [13] proposed a high-efficient gear-shaping method. In this method, the cutting area of each stroke of the gear-shaping cutter is kept approximately equal by changing the circumferential feed, which can improve machining efficiency by 40%.

In terms of gear-shaping simulation, Zhu [14] proposed a new efficient machining method of gear shaping based on constant cutting force to reduce the variation range of the cutting force and to improve machining accuracy. Erkorkmaz *et al.* [15] proposed a new model to accurately predict the geometry shape of the chip as well as the cutting force during the gear-shaping process. Katz *et al.* established a comprehensive virtual model of gear shaping to study the influence of kinematics, cutter-workpiece engagement, and cutting force as well as tool deflection in gear shaping on the gear tooth profile error [16,17]. They conducted a systematic simulation study and summary on the gear-shaping process.

The machining process will inevitably produce machining deformation, and excessive machining deformation has an adverse impact on the assembly as well as the performance of parts. There are many factors influencing machining deformation, such as material properties, cutting force, cutting heat, clamping conditions, the initial residual stress, as well as machining induced residual stress. Scholars have conducted a series of research to study them, and to predict and control machining deformation [18].

The research on machining deformation control mainly covers the following aspects: machining parameter optimization, clamping layout optimization, residual stress homogenization, auxiliary support technology, numerical control compensation technology, high-speed machining, etc. [19].

Residual stress is an important factor of deformation. It is the key characterization parameter of internal quality, which directly affects fatigue strength and service life. In recent years, residual stress has attracted much attention. Huang *et al.* discussed the formation mechanism of residual stress, deduced the analytical model of surface stress field, analyzed the influence of tool parameters and cutting parameters on residual stress, and did a comprehensive study and summary of residual stress in the orthogonal cutting process [20–22]. The introduction of compressive residual stress can improve mechanical properties and prolong fatigue life. However, the formation of residual stress is an extremely complex multi field coupling process. Although some scholars have studied how to controllably introduce compressive residual stress [23], its application in engineering is not mature. Additional auxiliary processes are mostly applied to reduce residual stress, such as heat treatment [24], vibratory stress relief [25], and shot peening [26].

The mechanical, tribological, and thermal characteristics of the material significantly affect its fatigue life, and technology can be applied to improve the surface properties, such as nitriding, carburizing, boriding, coating, laser quenching, and high current pulsed electron beam [27–29]. Their basic principle is to improve wear resistance and fatigue life by changing the microstructure or stress state of the material surface. Besides, Nguyen *et al.* [30] applied the optimized non-Newtonian fluid polishing technology to machine the gear surface, which significantly reduced the concentrated stress at the tooth root, and improved the fatigue resistance of the material. In addition to the above methods, some researchers have adopted nano-additive [31] or hard anti-wear coatings to reduce the wear [32].

From the above analysis it can be seen that a large number of achievements have been made in studying the friction disc, such as the optimization of structure, the means of improving surface quality, the methods of reducing temperature rise and wear, as well as the gear-shaping process. However, the research on gear-shaping technology mostly focuses on the gear-shaping cutter, cutting force, tooth profile accuracy, kinematics, cutting efficiency, etc. The research on axial deformation and fatigue life of the friction disc is relatively inadequate, and further in-depth study is needed.

Therefore, this study establishes a numerical simulation model of the friction disc gear-shaping process,

studies the influence of typical cutting parameters on surface residual stress and machining deformation, optimizes the gear-shaping parameters and carries out corresponding experiments to verify it. Finally, a gear-shaping process method is proposed to reduce machining deformation and to improve fatigue life.

2 Theory

2.1 The calculation of the cutting area

The chip shape produced through the process of gear shaping is irregular, and the cutting area and cutting force vary periodically with the change in the machining position. Therefore, an analysis of the machining path of the gear-shaping cutter and the cutting area can provide the basis for selecting gear-shaping simulation parameters.

In order to facilitate understanding and to simplify simulation, the external meshing gear-shaping cutter single tooth model is established, in which the left and right edges as well as the top edge are mainly considered. As shown in Figure 1, $(O - x, y)$, $(O_1 - x_1, y_1)$, and $(O_2 - x_2, y_2)$ are the inertial coordinate system, gear-shaping cutter coordinate system, and workpiece coordinate system, respectively. Supposing that the involute profiles on both sides of a tooth are Involute 1 and Involute 2, and their coordinates are (x_{2L}, y_{2L}) and (x_{2R}, y_{2R}) , respectively, the involute equations of the gear can be obtained through the matrix change as follows [33]:

Figure 1: Coordinate system for solving the involute profile of the gear shaper cutter [33].

$$\text{Involute 1: } \begin{bmatrix} x_{2L} \\ y_{2L} \\ 1 \end{bmatrix} = \begin{bmatrix} \frac{r_{b2}}{\cos \alpha_k} \sin(\tan \alpha_k - \alpha_k) \\ \frac{r_{b2}}{\cos \alpha_k} \cos(\tan \alpha_k - \alpha_k) \\ 1 \end{bmatrix}, \quad (1)$$

$$\begin{aligned} &\text{Involute 2: } \begin{bmatrix} x_{2R} \\ y_{2R} \\ 1 \end{bmatrix} \\ &= \begin{bmatrix} \cos\left(2\pi - \beta + \frac{2\pi}{z_2}\right) & -\sin\left(2\pi - \beta + \frac{2\pi}{z_2}\right) & 0 \\ \sin\left(2\pi - \beta + \frac{2\pi}{z_2}\right) & -\sin\left(2\pi - \beta + \frac{2\pi}{z_2}\right) & 0 \\ 0 & 0 & 1 \end{bmatrix} \\ &\times \begin{bmatrix} -x_{2L} \\ y_{2L} \\ 1 \end{bmatrix}, \quad (2) \end{aligned}$$

where

$$\beta = 2 \left(\tan \left(a \cos \frac{r_{b2}}{r_{a2}} \right) - a \cos \frac{r_{b2}}{r_{a2}} \right) + \frac{S_{a2}}{r_{a2}}, \quad (3)$$

where r_{b2} is the radius of the base circle, α_k is the pressure angle, z_2 is the number of teeth, and r_{a2} and S_{a2} are the radius and tooth thickness of the addendum circle respectively, and a is the center distance between the gear and the gear-shaping cutter.

The involute tooth profile of the gear-shaping cutter is conjugate with that of the gear. Through coordinate transformation, the involute tooth profile of the gear-shaping cutter named Tool 1 and Tool 2 can be obtained, and their equations are as follows:

$$\begin{aligned} \text{Tool 1} &= \begin{bmatrix} \cos i\theta & -\sin i\theta & 0 \\ \sin i\theta & \cos i\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}^{-1} \\ &\cdot \begin{bmatrix} \cos \theta & \sin \theta & 0 \\ -\sin \theta & \cos \theta & -a \\ 0 & 0 & 1 \end{bmatrix} \cdot \text{Involute 1}, \quad (4) \end{aligned}$$

$$\begin{aligned} \text{Tool 2} &= \begin{bmatrix} \cos i\theta & -\sin i\theta & 0 \\ \sin i\theta & \cos i\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}^{-1} \\ &\cdot \begin{bmatrix} \cos \theta & \sin \theta & 0 \\ -\sin \theta & \cos \theta & -a \\ 0 & 0 & 1 \end{bmatrix} \cdot \text{Involute 2}, \quad (5) \end{aligned}$$

where i is the transmission ratio, and θ is the rotation angle of the gear.

Through the continuous contact condition, the relationship between θ and α_k can be established, so that formulas (1)–(5) have the same unique variable α_k , whose range is fixed and known. The curve equation of the top

edge is a simple arc equation. Thus the mathematical model of the external meshing gear-shaping cutter can be accurately established. Through coordinate transformation, the model of the external gear-shaping cutter is transformed to that of the internal gear-shaping cutter. The machining process of internal gear-shaping is calculated in MATLAB, and the machining path is shown in Figure 2.

The cutting area is the intersection of the two adjacent machining paths of the gear-shaping cutter and the workpiece blank. The obtained machining position trajectory is discretized into several points and imported into AutoCAD. The removal amount is calculated by the Boolean operation with VBA programming, and then it is equivalent to the regular rectangle. Figure 3 shows 29 groups of the area removal amount under 30 machining positions. Therefore, if the cutting thickness (width) is determined, the corresponding equivalent cutting width (thickness) could be calculated through the given cutting area.

2.2 The calculation of the cutting force

The calculation of the cutting force F_z (N) and cutting power P_m (kW) in the process of gear shaping is as follows:

$$F_z = \frac{0.475 m^2 f_c}{z^{0.09}} p, \quad (6)$$

$$P_m = \frac{F_z v_1}{6 \times 10^4}, \quad (7)$$

Figure 3: The cutting area under different machining positions.

where z is the number of gear teeth, m is the module, p is the unit cutting force (see Table 1), f_c is the circumferential feed rate ($\text{mm} \cdot \text{dst}^{-1}$), v_1 is the cutting speed, which is related to the number of stroke N_0 , and the stroke length l of the gear-shaping cutter. The computational expression is shown in formula (8):

$$v_1 = \frac{2N_0 l}{1,000}. \quad (8)$$

2.3 The calculation of roughness

Formula (9) is the calculation expressing turning surface roughness:

Figure 2: The machining position trajectory calculation by MATLAB.

Table 1: Unit cutting force in the gear-shaping process

Material	Mechanical property (GPa)	Unit cutting force p (N·mm ⁻²)
Structural steel	$\sigma_b = 0.59 - 0.69$ $\sigma_b = 0.78 - 0.98$	1,668 – 1,766 3,139 – 3,433

$$R_a = \frac{1,000f^2}{8r}, \quad (9)$$

where R_a is the surface roughness and its unit is μm ; f is the feed rate per revolution, and r is the arc radius of the tool tip.

Like the formula for the calculation of turning surface roughness, the formula for friction disc tooth root surface roughness in the gear-shaping process can be expressed in the form shown in formula (10):

$$R_a = \frac{1,000f_c^2}{8r}, \quad (10)$$

where R_a is the surface roughness (μm); f_c is the circumferential feed rate in single stroke ($\text{mm}\cdot\text{dst}^{-1}$); and r is the addendum circle radius of the gear-shaping cutter (mm).

3 Simulation and experiment

3.1 The simulation and experiment under original process

3.1.1 The simulation of cutting force and residual stress

3.1.1.1 Simulation environment settings

Due to the same relative motion, AdvantEdge's two-dimensional broaching model is used to simulate the

gear-shaping process under single stroke. The constitutive parameters and physical parameters of the friction disc material 30CrMnSiA are assigned to the selected Johnson-Cook model, and HSS-Co-M35 high speed steel in the material library is selected as the cutting tool material. The bottom area of the workpiece is fixed, the immersion cooling medium is used, the cutting tool and workpiece are meshing with the default mesh size, and their initial temperature field is set at 20°C.

The actual and simulation cutting parameters are shown in Table 2. In actual processing, several friction discs are clamped together for machining to increase efficiency. But in the simulation model, only the finish machining of one friction disc is solved to explore the relationship between cutting parameters and machining quality.

3.1.1.2 The analysis of simulation results

The results of the cutting force, cutting temperature, strain, stress, etc. can be obtained in the post-processing. This study focuses on the analysis of the cutting force in the cutting process and the machining induced residual stress on the workpiece surface. The results of the cutting force and residual stress are shown in Figure 4, respectively. The analysis results are as follows.

In the cutting process of gear shaping, the cutting force increases sharply in the beginning, then it rapidly enters the stable cutting stage, and its value tends to be steady. The average values of the main cutting force (Force-X) and feed resistance (Force-Y) are about 1471.37 and 1129.51 N, respectively. After cutting, the residual stress on the workpiece surface is compressive stress, with a value of -83 MPa . The maximum compressive stress reaches about -150 MPa at 0.02 mm from the surface. With the increase in the distance from workpiece surface, the residual stress changes to tensile stress

Table 2: Analysis of actual and simulation cutting parameters

Actual parameters		Simulation parameters		Explanation
The number of stroke	80	Cutting speed	20	Calculated by formula (8)
The stroke length (mm)	125	($\text{m}\cdot\text{min}^{-1}$)		
Circumferential feed rate ($\text{mm}\cdot\text{dst}^{-1}$)	0.26	Cutting thickness (mm)	0.26	According to the relative movement relationship between gear shaping and broaching, the cutting thickness equals the circumferential feed rate
Radial feed rate ($\text{mm}\cdot\text{dst}^{-1}$)	0.02	Cutting width (mm)	0.91	Calculated by the maximum cutting area (0.237052 mm^2)
—	—	Cutting length (mm)	5	Tooth thickness of the friction disc plus certain allowance ($3.9 + 1.1$)

Figure 4: The simulation of cutting force and residual stress.

rapidly and then gradually decreases to 0 or so at a depth of about 0.4 mm.

3.1.2 The simulation of machining deformation

In ANSYS software, the SOLID278 element is defined for the model of the friction disc and the material properties of 30CrMnSiA are assigned. The inner diameter and outer diameter of the friction disc are 363 and 428.5 mm, respectively, and its thickness is 3.9 mm. The heat treatment process of the model is simulated, and the results of stress field are read as the initial state for the cutting process. The nodes around the outer diameter of the friction disc are fully constrained to simulate the clamping conditions in the actual gear-shaping process. On this basis, the cutting force calculated by AdvantEdge software is applied to the model, and the Birth and Death Element Method is utilized to simulate the full gear-shaping process and to solve the machining deformation of the friction disc.

The following information can be obtained from the results of the deformation nephogram (Figure 5): the distribution of axial deformation is basically symmetrical after the gear-shaping process. The axial deformation value decreases gradually from the outer ring to the inner ring, from the front to the bottom. The maximum positive deformation is 0.0233 mm, which is located near the front outer edge, while the maximum negative deformation is 0.0476 mm, located at the bottom tooth tip.

The reasons for the above results are as follows: during the gear-shaping process, the surface of the friction disc is clamped and fixed. The negative deformation occurs at the cutting position due to the extrusion action of the gear-shaping cutter, while the positive deformation arises near the outer edge due to the warping action. The closer to the edge, the greater the moment, and greater the deformation.

3.1.3 The verification of the simulation model

3.1.3.1 The machining and detection of friction disc

The residual stress on the friction disc blank after heat treatment was measured by X-ray diffractometer and electrochemical corrosion technology. The results showed that the values of the circumferential and radial residual stresses are very small, which can be explained by the fact that the residual stress on the friction disc after gear shaping is mainly induced by the machining process.

The YK5180BX3 CNC gear-shaping machine (located in the powder metallurgy plant of Hangzhou Qianjin Gearbox Group Co., Ltd.) was used to carry out the gear-shaping experiment on the friction disc blank using the cutting parameters in Table 2. After testing its M value to be qualified, the GLOBAL S coordinate measuring machine (located in the Jiangsu Institute of Information Technology), the SmartSite RS X-ray diffractometer (located in the Beijing Xiangbo Technology Co., Ltd.), and the MicroXAM 3D optical profiler (located in the Youerhongxin Testing Technology (Shenzhen) Co., Ltd.) were used to detect the machining deformation, residual stress, and surface roughness, respectively, and to verify the accuracy of the simulation model. Figure 6 shows the machining and detection worksite of the friction disc.

3.1.3.2 The accuracy verification of the simulation model

3.1.3.2.1 The cutting force

The experiment demonstrated that the tensile strength of the friction disc is 1.042 GPa. According to Table 1, the unit cutting force value 3,524 ($\text{N} \cdot \text{mm}^{-2}$) is calculated by the linear interpolation method. The parameters of the

Figure 5: The nephogram results of machining deformation: (a) the front face and (b) the bottom face.

friction disc and machining process are brought into formula (6) to obtain the cutting force:

$$F_z = \frac{0.475m^2f_c}{z^{0.09}}p = \frac{0.475 \times 3^2 \times 0.26}{122^{0.09}} \times 3,524 = 2542.08 \text{ N}.$$

The simulation average values of Force-X and Force-Y are 1471.37 and 1129.51 N, respectively. So their resultant force is 1854.91 N. Compared to F_z , the relative error is 27.03%. Since the simulation model is a simplified two-dimensional model without considering the radial force, the relative error of 27.03% is acceptable. Under this condition, the cutting power can be calculated as follows:

$$P_m = \frac{F_z v_1}{6 \times 10^4} = \frac{2542.08 \times 20}{6 \times 10^4} = 0.85 \text{ kW}.$$

3.1.3.2.2 The machining deformation

The data and analysis of machining deformation are shown in Table 3: the average deformation errors of the

outer ring and inner ring are 19 and 28% respectively. Except for the A2 inner ring, the measured and simulation values are in good agreement. In view of the good consistency of the other test data, it is considered that the reason for the larger deformation of A2 inner ring is not only the difference between material properties and ideal values, but is also related to the position of clamping during the gear-shaping process.

In addition, the powder metallurgy layer would be bonded on the face of the friction disc after gear shaping, and then there will be a fine grinding process. So the deformation of the outer ring that happened during gear shaping will be compensated in the follow-up process.

3.1.3.2.3 The residual stress

The simulation results of Figure 4 show that the surface residual stress is -83 MPa, and the average residual stress measured by the X-ray diffractometer is -110.5 MPa, as is

Figure 6: The experimental and detection equipment: (a) the worksite of gear shaping, (b) MicroXAM 3D optical profiler, (c) the detection of residual stress, and (d) the detection of machining deformation (1, gear-shaping cutter; 2, annular pressing plate; 3, the friction disc to be machined; 4, the fixture; 5, the rotary table of the gear-shaping machine; 6, concentric stop block; 7, level indicator; 8, the friction disc to be detected; 9, RS X-ray diffractometer; 10, tiger bench clamp; 11, coordinate measuring machine; 12, the probe; 13, the friction disc to be detected; 14, workbench).

shown in Table 4, with a relative error of 24.89% compared to the simulation value.

3.1.3.2.4 The roughness

Figure 7 and Table 5 are the detection and analysis results of roughness. It can be seen that the machined surface has a certain fluctuation in the circumferential direction,

while the consistency in the axial direction is very good. The measured average roughness is $1.712\ \mu\text{m}$. Bring f_c and r into formula (10), and the theoretical value of the tooth bottom surface roughness is calculated as follows:

$$R_a = \frac{1,000f_c^2}{8r} = \frac{1,000 \times 0.13^2}{8 \times 1} = 2.11\ \mu\text{m}.$$

The relative error between the theoretical value and simulation value is 18.86%, which indicates that this

Table 3: The comparison between measured and simulation maximum machining deformation (unit: mm)

Group		Simulation	Measured	Relative error (%)	Average relative error	
					Outer ring	Inner ring
A1	Outer ring	0.023	0.02	15	19%	28%
	Inner ring	0.048	0.05	4		
A2	Outer ring	0.023	0.03	23		
	Inner ring	0.048	0.10	52		

Table 4: The comparison and analysis of the measured and simulation residual stress (unit: MPa)

Group	Measured value	Average value	Simulation value	Relative error
A1	-91.6	-110.5	-83	24.89%
A2	-129.5			

formula has high accuracy and is suitable for the calculation of tooth bottom roughness.

To sum up, the established finite element model is reliable and can be further utilized for process optimization analysis.

3.2 Process optimization

3.2.1 Optimizing parameters to improve residual stress

The cutting parameters of the gear-shaping process include the stroke number, stroke length, circumferential feed rate, radial feed rate, etc. The stroke number can characterize the cutting speed due to the usually invariant stroke length. In

Table 5: The comparison and analysis of roughness (unit: μm)

Group	R_a	Average value	Theoretical value	Relative error
A1-1	1.905	1.712	2.11	18.86%
A1-2	1.627			
A1-3	1.779			
A2-1	1.522			
A2-2	1.876			
A2-3	1.596			

the actual gear-shaping process, the workpiece is fixed on the workbench for circumferential feed movement. After the gear-shaping cutter moves to the required position along the radial direction according to the set radial feed rate, it maintains its own rotation movement and axial cutting movement. The radial feed rate determines the distance of each radial feed. Therefore, the parameters of cutting speed and circumferential feed rate are the two factors that have a greater impact on the forming performance.

In AdvantEdge, the effect of cutting speed on residual stress is studied by changing the value of the cutting speed keeping the other parameters unchanged. Figure 8 demonstrates the results. With the increase in cutting speed, the

Figure 7: The surface profile image of roughness detection.

Figure 8: The effect of cutting speed and circumferential feed rate on residual stress.

maximum tensile stress first slightly decreases and then increases slowly, while the maximum compressive stress presents a very slowly decreasing trend. The cutting speed has little effect on the residual stress and $20\text{--}25\text{ m}\cdot\text{min}^{-1}$ is a better choice. The stroke number range is $80\text{--}100$ with the stroke distance of 125 mm remaining unchanged.

The circumferential feed rate is set as the parameter of cutting thickness in the finite element simulation. According to the reference manual, the circumferential feed rate is usually $0.2\text{--}0.5\text{ mm}\cdot\text{dst}^{-1}$. The cutting thickness is changed to study the effect of the circumferential feed rate on residual stress. As is shown in Figure 8: with the increase in the circumferential feed rate, the stress values of the surface and subsurface decrease first and then increase. Among the five levels studied, the stress state is the most ideal when the circumferential feed rate is $0.30\text{ mm}\cdot\text{dst}^{-1}$. Taking into account the levels not studied, its value can be taken in the range of $0.25\text{--}0.35\text{ mm}\cdot\text{dst}^{-1}$ during machining.

3.2.2 Adding circular gasket to reduce machining deformation

Different cutting parameters lead to different cutting forces and different degrees of machining deformation. Based on the parametric model, the cutting force is adjusted to study its influence on the machining deformation of friction disc in ANSYS software. The simulation result is shown in Figure 9: with the increase in cutting force, the maximum positive deformation gradually decreases, while the maximum negative deformation increases gradually, and the difference value is almost unchanged. That is to say, it

is not feasible to reduce machining deformation by changing the cutting force. It is necessary to find other ways to reduce deformation.

In the transmission system of mechanical equipment, a layer of high temperature resistant metallurgical powder is plated on the upper and lower surfaces of the friction disc to increase the friction coefficient and improve transmission efficiency. Therefore, there is a certain gap between the different friction discs in the gear-shaping process, resulting in the position to be machined suspended and forming a cantilever structure. Consequently, a circular gasket can be designed and placed in the gap to increase the rigidity of the friction disc and reduce machining deformation.

As shown in Figure 10, its thickness is slightly higher than twice the thickness of the metallurgical layer, so that

Figure 9: The influence of cutting force on machining deformation.

Figure 10: The position of the circular gasket in the gear-shaping process.

it comes into close contact with the upper and lower friction discs, and its outer diameter is slightly smaller than the inner diameter of the metallurgical layer to achieve the clearance fit. The simulation results demonstrate that the axial maximum negative deformation of the friction disc's inner ring bottom face before and after adding the circular gasket decreases from 0.0195 to 0.00383 mm, that is, a reduction of 80.36%. The axial deformations of the other gear-shaping parts are also reduced by about 60%. Therefore, adding the circular gasket can significantly reduce machining deformation during the gear-shaping process.

3.2.3 Experimental verification of optimization effect

Based on previous research, gear-shaping experiments were carried out to optimize the cutting speed and circumferential feed rate. The setting of experimental cutting parameters is shown in Table 6. The cutting parameters in groups B3 and B4 are the same and there is a circular gasket between the bottom of B3 and the front of B4 to verify its inhibition effect on machining deformation. After the gear-shaping process, the machining deformation and residual stress of each friction disc are tested to verify the optimization effect. The experimental equipment is the same as the one used in Section 3.1.3 to ensure consistency of the other data as much as possible.

4 Results and discussion

4.1 Machining deformation

Figure 11 and Table 7 show the results of the analysis of machining deformation data detected by the coordinate measuring machine:

Table 6: The design scheme of the optimization experiment

Group	N_0	f_c	Gasket or not	Explanation
B1	80	0.26	No	The original process
B2	80	0.30	No	Change the circumferential feed rate compared to B1
B3	100	0.30	Yes	Change the cutting speed compared to B1, and verify the effect of the gasket
B4			No	

- 1) Compared to B1, the front and bottom face deformation of B2 outer ring decreased by 0.0279 mm (38.38%) and 0.0102 mm (19.62%), respectively, and the deformation of the front and bottom tooth tip increased by 0.005 mm (5.52%) and decreased by 0.0168 (14.18%), respectively. Although the deformation of the front tooth tip increased slightly, in general, the deformation of the B2 friction disc is significantly reduced when compared with the original process.
- 2) Compared with B1 and B2, the deformation of the friction discs in group B3 and B4 are significantly increased, which indicates that increasing the cutting speed will have an adverse effect. At the same time, it is worth noting that the deformation of the bottom tooth tip in group B3 and the front face deformation of B4 outer ring is reduced by 21.19 and 10.31%, respectively. And when compared with B3, the front face deformation of the B4 outer ring is reduced by 5.3%, which indicates that the existence of the circular gasket can significantly reduce machining deformation.

From the experimental results, it can be seen that in the selected cutting parameters, increasing the number of strokes will increase machining deformation, increasing the circumferential feed rate will reduce machining

Figure 11: The analysis of the friction disc machining deformation.

deformation, and adding the circular gasket can significantly reduce machining deformation. This is consistent with the previous simulation results.

In addition, the bottom face of the inner ring deformation of B4 is significantly larger than the other deformation, which may be caused by other unexpected reasons, such as insufficient heat treatment resulting in its small stiffness. However, from the overall experimental results, this value does not affect the above analysis on the influence of the law of cutting parameters on machining deformation.

4.2 Residual stress

Table 8 shows the detection results of residual stress: the stress value under original process is about -122.50 MPa. Compared to B1, the surface compressive stress of group B2 increases to -371.33 MPa, an increase of 203.13%. The stress values of B3 and B4 are -150.5 and -170 MPa, respectively, which are both improved to some extent.

Table 8: The residual stress data of friction disc (unit: MPa)

Group	The residual stress	Average value	Relative error (%)
B1	-128 ± 27	-122.50	0
	-117 ± 24		
B2	-313 ± 31	-371.33	203.13
	-471 ± 49		
	-330 ± 70		
B3	-141 ± 21	-150.5	22.86
	-160 ± 44		
B4	-179 ± 46	-170	38.78
	-161 ± 30		

However, the improvement in group B2 is the most significant.

The experimental result is consistent with the simulation results in Section 3.2.1. Therefore, selecting the parameters of the circumferential feed rate with $0.30 \text{ mm} \cdot \text{dst}^{-1}$ and maintaining other parameters at their original values are most effective in improving the residual stress on the machined surface.

4.3 The simulation of fatigue life

In order to efficiently study the influence of residual stress on fatigue life, the loading condition of the friction disc is simplified, and normal pressure is applied to the tooth profile surface to solve the stress field under this pressure, and then the FE-SAFE software is applied to solve the fatigue life under the load.

First, complete the basic settings and read the result file calculated by ANSYS software. Second, the properties of 30CrMnSiA material are given to the friction disc. Then, set the periodically varying load, set different surface stress, select the stress correction algorithm, and let the other settings remain at default values. Finally, submit the calculation to solve the fatigue life.

Table 7: The detection data and analysis of the friction disc machining deformation (mm)

Group	Outer ring				Inner ring			
	Front face	Relative error (%)	Bottom face	Relative error (%)	Front face	Relative error (%)	Bottom face	Relative error (%)
B1	0.0727	0	0.052	0	0.0906	0	0.1185	0
B2	0.0448	-38.38	0.0418	-19.62	0.0956	5.52	0.1017	-14.18
B3	0.0773	6.33	0.0874	68.08	0.1012	11.70	0.0934	-21.19
B4	0.0652	-10.31	0.0947	82.12	0.0964	6.40	0.3297	178.28

Table 9: The fatigue life under different residual stress

Residual stress (MPa)	Fatigue life	Logarithmic fatigue life
-350	Unlimited life	Unlimited life
-330	522,170	5.717811917
-320	480,167	5.681392309
-300	405,201	5.607670508
-250	261,813	5.417991207
-200	165,996	5.220097623
-150	103,097	5.013246028
-122	78,197	4.893190092
-100	62,602	4.796588208
-50	37,081	4.569151438
0	21,370	4.329804522
50	11,946	4.07722251
100	6,454	3.809828961

Table 9 shows the values of fatigue life calculated under different surface stresses, and the curve in Figure 12 shows the relationship between logarithmic fatigue life and surface stress. Some results can be analyzed as follows:

- 1) The logarithmic fatigue life of the friction disc is basically negatively correlated with the surface stress, and the fatigue life decreases rapidly with the decrease in surface compressive stress.
- 2) Under the original process, the fatigue life of friction disc is 7.82×10^4 . When the compressive stress increases to -330 MPa, the fatigue life increases to 5.22×10^5 , an improvement of 567.76%. When the compressive stress reaches -350 Mpa, the fatigue life is high enough and the software has been thinking that it has no damage.

Figure 12: The curve of the logarithmic fatigue life versus the surface residual stress.

- 3) Under the cutting process of group B2, the compressive stress of the tooth bottom is as high as -371 MPa. Compared to the original process, the optimized process can remarkably improve the fatigue life of the friction disc.

The compressive stress distributed in a certain depth can partially offset the tensile stress produced by the alternating external load, and has a closure effect on microcracks to prevent its propagation. So it can significantly improve fatigue life.

There are still some shortcomings in this study that has to be improved. For example, the fatigue failure of the friction disc is a very complex process because the magnitude and position of the fatigue load are always changing. Simplifying the load as a constant value on the tooth profile could reflect the effect of the surface residual stress on fatigue life, but the results of the fatigue life are not very accurate. Therefore, the calculation method of fatigue life can be further studied in future studies.

5 Conclusion

In this study, the simulation model of the friction disc gear shaping is established and verified by the theoretical analysis and experimental detection of machining deformation, residual stress, and surface roughness. Then, based on the verified simulation model, the influence of the process parameters on machining introduced residual stress, the influence of the cutting force on machining deformation, as well as the inhibitory effect of the circular gasket on machining deformation are studied. Finally, a process optimization scheme of reducing machining deformation, increasing residual compressive stress, and improving fatigue life is summarized. The conclusions are as follows:

- 1) During the selected parameter range in the optimization experiment, the machining deformation can be reduced by reducing the number of strokes, increasing the circumferential feed rate, or by placing a circular gasket in the gap between adjacent friction discs.
- 2) According to the experimental results, the process parameter in group B2 is the best. Compared to the original process, the machining deformation decreases and the residual compressive stress on the tooth bottom surface increases significantly.
- 3) The logarithmic fatigue life of the friction disc is basically negatively correlated with the surface stress.

Compared to the original process, the optimized process of group B2 can remarkably improve the fatigue life of the friction disc.

- 4) A set of methods are summarized to reduce machining deformation and to improve the fatigue life of the friction disc, that is, placing a circular gasket in the gap between the different friction discs, and applying the cutting parameters of the circumferential feed rate with 0.30 mm-dst^{-1} and stroke number with 80. The other parameters are the same as in the original process.

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Authors contribution: Qiong Wu: Conceptualization; Hanjun Gao: methodology, simulation, review and editing; Xin Li: experiment, original draft and formal analysis; Wanhao Zhang: investigation; Guowen Dai: validation; Guohong Zhang: resources.

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Data availability statement: The data used to support the findings of this study are available from the corresponding author upon request.

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