Study on the influencing factors of the deformation in the process of gear shaping

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Abstract
Ring gear is an important part of high-power transmission system. Because of its thin wall and low stiffness, it is easy to cause deformation in the process of gear shaping, which affects its accuracy. Therefore, how to ensure the quality of gear ring gear insertion is an urgent research topic. In this paper, the influence of cutting parameters of gear shaper on the deformation of gear ring is studied by finite element simulation and practical test. The results show that the influence of main cutting parameters on the deformation of 42CrMo ring gear is radial feed, circumferential feed, stroke speed, and cutting depth. In the actual gear shaping process, the cutting parameters can be adjusted according to this deformation law, so as to control the deformation of the ring gear.

Keywords 42CrMo gear steel · Gear shaping · Finite element simulation · Cutting deformation

1 Introduction
Ring gear is an important part of high-power transmission system. Its typical feature is that the wall thickness is very small compared with the radial and axial dimensions, and it is a very typical weak stiffness component. Therefore, the material selection and processing technology of the gear ring have put forward very high requirements.

In the process of gear shaping, gear shaper cutter and workpiece are usually matched according to modulus and pressure angle. In the process of reciprocating movement of gear shaper cutter, they are fully meshed without clearance. The schematic diagram of gear shaping process of ring gear is shown in Fig. 1. It mainly includes the gear shaper cutter moving up and down along the spindle to cut the chips from the workpiece; in order to avoid scratching the machined surface, damaging the tool tip of the gear shaper cutter and reducing the wear of the gear shaper cutter, the workpiece or the gear shaper cutter needs to do cutter relieving motion; The circumferential feed motion of the gear shaper cutter means that when the gear shaper cutter is cutting, it rotates around the axis of the cutter axis and continuously processes the new metal layer on the workpiece. When the shaper cutter moves back and forth every time, it needs to move a certain distance to the root until the whole tooth height is cut out. In order to process all the teeth on the gear blank, after the gear shaper cutter completes a reciprocating cutting movement, the worktable must drive the processed gear workpiece to rotate along the axis, so as to complete the involute tooth profile generating movement or other common gradient curve processing.

In the process of gear shaping, due to the thin wall thickness and low stiffness of the ring gear, under the influence of cutting force, cutting heat, residual stress, clamping force, machine vibration, and other factors, it is easy to cause the deformation and even scrap of the ring gear parts [1]. To solve this problem, the current research mainly focuses on the influence of cutting force, clamping deformation, residual stress, and the coupling of cutting force and cutting heat on the machining deformation of weak stiffness structural parts. For example, Liu Xuejie established the cutting force model based on the cutting layer area by analyzing and processing the cutting test data of ZL114A aluminum alloy, and studied the cutting force modeling and deformation prediction [2]. In order to solve the problem that thin-walled parts have low tolerance to cutting force and cutting heat, and are easy to produce machining deformation, Cao Boran established the
mathematical model between cutting parameters and cutting force and cutting heat, and obtained the optimal processing parameter combination scheme through the optimization of multi-step cutting parameters [3]. In reference [4], the influence of cutting speed, feed rate, and cutting depth on cutting temperature was analyzed by thermal mechanical coupling model, and the deformation of ring gear with and without temperature field was compared. It is found that the cutting heat will increase the deformation of the ring gear, but when the temperature rises to a certain range, the deformation of the ring gear will decrease, and the influence of the shape is limited.

According to the tooth profile error and deformation results in the gear profile inspection report after ring gear processing, Wang Jing found that the main error factor was improper clamping mode. The deformation caused by the existing clamping mode was analyzed by using caskilyano theorem, virtual displacement principle, and unit load method, and the fixture was redesigned accordingly [5]. The effect of forging and different heat treatments (normalizing, quenching, and tempering) on the final residual stress state, microstructure, and hardness of aisi4140 steel was studied in reference [6]. The results show that the banded ferrite pearlite structure, as well as the general chemical non-uniform structure, has non-uniform reaction to high temperature during forging and/or subsequent heat treatment, which affects the final stress state (plastic deformation is required to adapt to different thermal expansion behaviors at each stage), resulting in deformation. These unpredictable deformations are one of the main reasons for rejected parts and parts that need to be reworked. Qiang Kang analyzed the influence of tool flank wear on cutting force, cutting heat, and residual stress on the machined surface of 20Cr2Ni4 alloy steel ring gear by numerical model solving, finite element simulation, and experimental research. The results show that the tool wear will change the force and heat in the cutting process, thus affecting the distribution of residual stress on the machined surface [7].

Currently, there are many researches on the optimization of hobbing parameters, but few on the optimization of gear shaping parameters. In a recently published research paper [8], the problem of tooth profile accuracy in bevel gear machining is selected, and the material of the workpiece in this study is 20Cr2Ni4A. The process of gear shaping with different machining parameters was simulated by ABAQUS, and the cutting force distribution cloud diagram during the process of gear shaping was obtained. The simulation results show that when the cutting speed of gear shaper is low, the influence of cutting speed on cutting force is great; when the cutting speed is increased, the influence of cutting speed on cutting force is small. In the process of machining, the feed rate has more influence on the cutting force. Under the same processing parameters, the cutting force increases with the increase of the back feed, and the increase range is larger; when the circumferential feed increases, the cutting force decreases relatively; the influence of the circumferential feed on the cutting force is smaller than that of the back feed. According to the simulation analysis of the ring gear shaping processing parameters, the actual processing experiment is carried out, the measured error of the right tooth surface of the ring gear is 9.3 μm, and the detection result of the right tooth surface of the ring gear according to the previous processing parameters is 21.1 μm.

Based on the above analysis results, it can be seen that although there are many researches on the machining deformation of thin-walled and weak stiffness structural parts, there are few researches on the special materials in the automotive transmission system, especially some special materials (such as 42CrMo) used in the automotive transmission ring gear. At present, there is still a lack of a complete set of process parameter selection principles for deformation control to guide the actual production of this kind of material ring gear.

Compared with the traditional gear steel 20CrMnTi, 42CrMo steel has the characteristics of high yield strength, good impact resistance, good hardenability, small deformation during quenching and tempering, but low hardness. Due to its good properties, 42CrMo steel is widely used in automobile gearbox ring gear. However, 42CrMo has low plasticity, high shear strength, and slightly poor thermal conductivity. Therefore, in the process of gear shaping of 42CrMo ring gear, there are some problems such as large cutting force, high cutting temperature, and tool wear [9], which will adversely affect the machined surface roughness and machining accuracy of the parts. Therefore, it is of great significance to study the influence of cutting parameters on the processing deformation and surface roughness of 42CrMo gear ring in gear shaping process for controlling the processing quality.
improving efficiency, and reducing production cost of 42CrMo gear ring.

Therefore, this research focuses on the internal gear shaping of 42CrMo steel. The manufacturing process of experimental gear ring is as follows: forging of gear ring blank → turning → quenching and tempering → turning → internal gear shaper → hobbing of external gear → nitriding heat treatment. After quenching and tempering, the hardness of the workpiece is about 35HRC. In the second part, the finite element simulation of chip deformation, cutting force, and cutting temperature in the gear shaping process of 42CrMo ring gear is introduced. The third part will introduce the actual cutting test of 42CrMo ring gear, and discuss the influence of cutting parameters on forming deformation and surface roughness. The fourth part is the conclusion of this study.

2 Simulation analysis of gear shaping process

2.1 The establishment of simulation model

The gear shaping process of gear ring is a typical discontinuous cutting process. Because the gear shaping cutter not only has its own rotation movement, the reciprocating movement in the axis direction and the radial movement, but also the workpiece continues to rotate, the relative position and movement relationship between them are more complex than the general turning process. On the other hand, the shape of tooth corresponding to each stroke gear shaper cutter is different, and the cross-section shape of each tooth is not the same, resulting in different shapes of new teeth shape. In order to be more consistent with the actual process of gear shaping, it is necessary to establish the cutter tooth model and workpiece model which are consistent with the actual processing in gear ring gear shaping simulation.

Gear shaper cutter can be regarded as a series of single cutter teeth with the same shape rotating around the spindle. When establishing the simulation model of gear shaper cutter machining process, because all gear shapers have the same geometry, it can be simplified to take a tooth of a gear shaper cutter as the cutter model. According to the drawing of gear shaper cutter matched with the actual workpiece, the model of gear shaper cutter is established in the ProE software, and the tool material selected is "coated TiAlN." Then, a single gear shaper cutter is cut based on the model of gear shaper cutter. Finally, it is imported into the finite element simulation software to complete the establishment of the gear model, as shown in Fig. 2. The modulus of the ring gear is \( m=2.25 \), the number of teeth \( z=95 \), the tooth width \( B=20\text{mm} \), the displacement coefficient \( x=1.405 \), the base circle diameter is \( 193.723\text{mm} \), and the pressure angle \( a=25^\circ \). The base material of the gear shaper cutter is powder metallurgy S390, the coating is TiAlN, the modulus is 2.25, the number of teeth is 56, the base circle diameter is 113.927mm, the pressure angle is 25\(^\circ\), and the hardness is 66–67HRC.

In the process of gear shaping, because of the difference of cutting materials in each stroke, it is very important to establish the tooth slot model of the previous stroke and the current stroke. When the radial cutting depth is 4mm, the radial feed is 0.02mm/str, and the circumferential feed is 0.2mm/str, the relationship between the number of strokes and the cutting cros-sectional area is shown in Fig. 3.

In the first interval, before the radial feed is completed, the center distance between the tool and the workpiece continuously changes, and the cutting cross-sectional area increases in a fluctuating manner. In the second section, after one rotation of the workpiece, the teeth that have not reached the preset machining depth are machined to the set depth, at which time the maximum cutting cross-sectional area continues to decrease. The second section is for tooth machining to reach the set machining depth. The change of the cutting cross-sectional area is more stable, and the corresponding cutting force change rule is also more stable. Therefore, the simulation selects the gear forming process in the second section.

In the ProE software, the cogging model of the workpiece is established according to the workpiece size, the cutter geometry size, the set cutting depth, and the circular feed. The relevant expressions are shown in Table 1.

The formation process and cutting cross section of the \( m_{th} \) cogging model are shown in Fig. 4. When the center distance is \( O_1O_2 \), the gear slot shape of the \( m-1 \)th stroke is shown in the figure. When the tool rotates \( \omega_1 \) and the workpiece rotates \( \omega_2 \), the \( m_{th} \) machining position is reached, and the \( m_{th} \) gear slot shape is formed after cutting. In ProE software, by performing the Boolean intersection operation on the rotated model, the cutting cross-sectional shape and area of the \( m_{th} \) machining position can be obtained.

In order to reduce the mesh number of the model, a certain tooth groove of the ring gear is taken as an example when establishing the solid model, as shown in Fig. 5. The minimum mesh size of the workpiece mesh is 1/3 of the feed speed.

2.2 Relevant settings of shaper finite element simulation

The key parameter setting of finite element simulation of gear shaper is an important basis to ensure the accuracy and rationality of simulation results. It mainly includes material constitutive model, chip separation and fracture criterion, chip friction model, and mesh generation. The related options are shown in Table 2.
2.3 Simulation results

2.3.1 Analysis of chip deformation in gear shaping

In the actual production of gear shaper, Zheng Pantuo found that the actual chip thickness should be observed in time. When there are very thick or very thin chips, the tool should be polished or the cutting parameters should be adjusted in time to avoid unnecessary wear when the tool enters the rapid wear stage, which can effectively improve the processing efficiency of the product and prolong the service life of the gear shaper tool [11]. Therefore, this study collected and observed the chips produced in the process of gear shaping by visual inspection.

By comparing the chip obtained by finite element simulation with the chip collected by actual gear shaping, it is found that its shape and deformation law are very similar (as shown in Fig. 6).

In the process of 42CrMo gear ring gear shaping, due to the influence of processing environment, coolant, and other factors, compared with the simulation model, the chip shape obtained by actual gear shaping is more diverse and the chip deformation is more complex, as shown in Fig. 7.

When the contact area between the gear shaper tool and the workpiece is narrow and the cutting thickness is large, the chip deformation is small and thicker, mostly in an arc shape. This is because the too long chip is broken, which is similar to the simulation result, as shown in Fig. 7a. When the gear shaper cutter contacts the workpiece too wide and the chip thickness is thin, the chips are bent and the chip surface is large, as shown in Fig. 7b. When the cutting width is too wide or too narrow, the chips are easy to break and the degree of curl is small, as shown in Fig. 7a, b, c. When the material to be removed is relatively slender, the chips will completely curl toward the machined surface, as shown in Fig. 7d and e, and the chips are not prone to breakage, mostly band-shaped chips.

Although the stroke speed and feed rate remain constant, the chip shape produced in the process of gear shaping is still diverse. Due to the formation movement, the meshing conditions of the tool and the workpiece change, and the cutting tool will produce chips with different cross-sectional shapes. It is...
not difficult to find from the collected chips, although the shape of the chips is diverse, there are many similar chips. For a single cutter tooth, during the processing of a single tooth slot, the shape of the tooth slot corresponding to each stroke is different. However, when cutting different grooves, because of the same processing technology and similar cutting shape, many chips with similar shape will be produced. It reflects that although the process of gear shaping is complex, the chip deformation has certain rules. Therefore, the process of multiple gear shapers can be simulated through the cutting simulation of a single gear shaper cutter.

### 2.3.2 Analysis of cutting force and temperature in gear shaping

The specific parameters of gear shaping process simulation include as follows: stroke speed of 200str/min, circular feed of 2mm/str, cutting depth of 4mm. The simulation results show that in the feed direction of the gear shaper cutter, the force on the cutter is the largest, so it is taken as the main cutting force. Through the simulation, the results of the main cutting force changing with time in the process of gear shaping are obtained, as shown in Figure 8.

It can be found from Fig. 8 that the main cutting force rises rapidly firstly, and gradually rises to near the peak as the strain rate strengthens. It is mainly because the main cutting force increases sharply when the tool just cuts into the workpiece. Afterwards, the stable fluctuations, rather than smooth curves, are mainly due to the uneven deformation of the workpiece during the cutting process. Toward the end, the main cutting force quickly decreases, because the amount of the workpiece being cut becomes less and the cutting resistance decreases, and when the cutting movement ends, the main cutting force becomes 0.

The simulation results show that the cutting temperature trend of workpiece and tool is shown in Fig. 9.

From Fig. 9, it can be seen that the temperature of the tool and the workpiece increases rapidly as the tool just cuts into the workpiece at the beginning of cutting. With the progress of cutting, the temperature of both keeps a relatively stable fluctuation. When the tool cuts out the workpiece, the temperature of both decreases rapidly. The maximum temperature of workpiece in the whole cutting process is 466°C, and the maximum temperature of the tool is 267°C. The temperature of workpiece in cutting is much higher than that of tool, and when the cutting is finished, the decreasing trend of temperature is much higher than that of tool, which also shows that the heat dissipation of tool is not good. According to the literature, the tool wear problem in the process of internal gear shaping is mainly caused by the interference in the process of gear shaping, mainly due to the elimination of the interference [12]. In this study, the simulation results at step 1140 are shown in Fig. 10.

From Fig. 10a, it can be seen that the temperature in the plastic deformation area of the workpiece is relatively high during gear shaping cutting, and most of the heat in the workpiece is exported through the chips. It can be seen from Fig. 10b that in the process of gear shaping, the temperature of the tool at the tip is higher, followed by the tool faces on both sides. Based on the simulation analysis, it can be found that the cutting heat is mainly concentrated in the contact part between the ring gear and the tool tip, and the temperature can reach up to 430°C. When the chips flow out, the friction between the chips and the front face makes the temperature decrease.

### Table 1 Expressions related to cogging modeling

| Content                                      | Equation                   | No. | Parameter description |
|----------------------------------------------|----------------------------|-----|-----------------------|
| Center distance between gear shaper and inner ring gear $O_1O_2$ | $O_1O_2 = R_1 - R_2 + a_p$ | (2-1) | $R_1$ is the radius of the tooth top circle of the workpiece, $R_2$ is the tool radius, $a_p$ is the cutting depth |
| Rotation angle of workpiece in each stroke $\omega_1$ | $\omega_1 = (f_c/\pi d_1) \times 360$ | (2-2) | $f_c$ is the circumferential feed rate of each stroke, $d_1$ is the diameter of the graduation circle of the workpiece |
| Tool rotation angle per stroke $\omega_2$ | $\omega_2 = (f_c/\pi d_2) \times 360$ | (2-3) | $d_2$ is the pitch circle diameter of the tool |

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![Fig. 4 Schematic diagram of cogging and cutting section](image-url)
near the cutting edge higher, which is consistent with the phenomenon that the tip of the gear shaper tool turns white when it is used for a long time in actual cutting.

Because of the poor thermal conductivity of the tool, the gear shaper tool tip is easy to wear under high temperature. In the process of gear shaping, the wear of gear shaper cutter has a direct impact on the product processing quality and efficiency. In actual production, the wear value of gear shaper cutter is usually set at 0.1~0.3mm, and different values are selected according to the modulus of gear shaper cutter. For example,
for small and medium modulus gear shaper cutter, the wear standard of 0.1 mm is often set. When the number of workpieces processed by the gear shaper cutter reaches the preset wear amount, the gear shaper cutter needs to be polished [13, 14].

2.3.3 Influence of cutting parameters on cutting force and cutting temperature

In order to study the influence of cutting parameters on cutting force and cutting temperature in gear forming process, an orthogonal cutting simulation experiment was designed with gear shaping parameters as influencing factors and cutting force and cutting temperature as indexes. The average value of the stable cutting stage is used as the simulation test value, and the value when the tool is cut in and out and part of the sudden change value are removed. The difference between test design and simulation junction is shown in Table 3. The range analysis of the test results is shown in Table 4. \( X_i \) represents the sum of the main cutting forces of each factor at level \( i \). \( \bar{X}_i \) represents the average value of the main cutting forces at each level at level \( i \). And the range is \( \bar{X}_{i_{max}} - \bar{X}_{i_{min}} \). The greater the range of the factor, the greater the influence of the factor on the value of the main cutting force index within the test range.

Through the range analysis of orthogonal experiment, it can be found that among the cutting parameters used in the experiment, the circumferential feed has the most significant effect on the main cutting force of tooth profile, followed by the cutting depth, and the stroke speed has the smallest effect on the main cutting force. The influence of circular feed rate and stroke speed on cutting temperature is almost equal, while the influence of cutting depth on cutting temperature is small. According to the results of orthogonal test and analysis, the effects of cutting parameters and indexes, main cutting force, and cutting temperature are shown in Fig. 11.

1. The influence of stroke speed on the main cutting force. As shown in Fig. 11, with the increase of stroke speed, the main cutting force shows a downward trend. Due to the influence of gear shaper and cutter, the stroke speed setting is relatively small (7.8~11.2 m/min). When the cutting speed is small, there will be great friction resistance. With the increase of cutting speed, the cutting temperature will increase, the strength and hardness of the material to be cut will decrease, the resistance of cutting deformation will decrease, and the main cutting force will also decrease.

2. The influence of the circumferential feed on the main cutting force. As shown in Fig. 11, the main cutting force increases with the increase of the circumferential feed. The circumferential feed can be expressed as the arc length of the workpiece rotation after each reciprocating motion of the tool. At the same cutting speed and cutting depth, the larger the arc length of the workpiece rotation, the larger the cutting area of the tool and the greater the cutting force.

3. The influence of cutting depth on the main cutting force. As shown in Figure 11, the main cutting force increases with the increase of cutting depth. With the increase of cutting depth, the depth of the tool cutting into the workpiece increases, and the single cutting amount in the same circle feed increases, which leads to the increase of cutting force.
4. The influence of chip area on the main cutting force. In the ProE software, the cutting section area of each experiment is extracted, and the relationship between the chip section area and the main cutting force is drawn. It can be seen from Fig. 12 that at the same stroke speed, the main cutting force increases with the increase of chip cross-section area. Because of the large cross-section area, the more resistance the gear shaper cutter overcomes, the greater the main cutting force is, and it can also be regarded as another way to verify the simulation results.

According to the results of orthogonal test analysis, the influence of each cutting parameter and cutting temperature is shown in Fig. 13, and the specific analysis is as follows:

1. The influence of stroke speed on cutting temperature. With the increase of stroke speed, the cutting temperature shows an increasing trend. The increase of stroke speed, that is, the increase of cutting speed, will increase the cutting heat and the cutting temperature, but the cutting temperature will not increase linearly with the increase of speed, because the increase of cutting speed will accelerate the conduction of cutting heat and affect the cutting temperature.

2. The influence of circumferential feed on cutting temperature. With the increase of the circular feed, the cutting temperature shows a trend of first rising and then falling. The increase of circumferential feed will increase the cutting thickness, resulting in an increase in the cutting area, which in turn increases the cutting force and the cutting temperature. But on the other hand, when the cutting thickness increases, it will also lead to the increase of the heat taken away by the chip and the decrease of the temperature in the cutting area.
The influence of cutting depth on cutting temperature. With the increase of cutting depth, the cutting temperature shows a trend of first decreasing and then increasing. The increase of cutting depth will increase the amount of cutting and the heat taken away by chips. But too large cutting depth will increase the cutting force and the cutting temperature.

3 Experimental research

In order to study the deformation of gear ring in the actual process of gear shaping, the relevant cutting experiments of gear ring deformation with gear shaping cutting parameters (stroke speed, circumferential feed, radial feed, and cutting depth) as factors and gear ring deformation (roundness difference before and after machining) as indicators were designed and implemented.

3.1 Experimental conditions

Details of the experiment mainly include test gear ring, cutter, machine tool, and testing equipment, and the design parameters of the ring gear are shown in Table 5.

The experimental cutter used the bowl-shaped straight gear cutter produced by Hanjiang Tool Company, and its detailed parameters are shown in Table 6.

| Test No | Stroke speed $n$ (str/min) | Circumferential feed $f_c$ (mm/str) | Cutting depth $a_p$ (mm) | Chip section area $S$ (mm²) | Main cutting force $F$ (N) | Cutting temperature $T$ (°C) |
|---------|--------------------------|----------------------------------|-------------------------|-----------------------------|--------------------------|-----------------------------|
| 1       | 140                      | 0.8                              | 3                       | 0.34589                     | 2387                     | 405                         |
| 2       | 140                      | 1.4                              | 4                       | 1.00983                     | 7348                     | 416                         |
| 3       | 140                      | 2                                | 5                       | 1.99855                     | 12029                    | 346                         |
| 4       | 170                      | 0.8                              | 4                       | 0.479789                    | 4110                     | 329                         |
| 5       | 170                      | 1.4                              | 5                       | 1.25831                     | 8556                     | 466                         |
| 6       | 170                      | 2                                | 3                       | 1.07982                     | 8462                     | 420                         |
| 7       | 200                      | 0.8                              | 5                       | 0.524891                    | 4028                     | 444                         |
| 8       | 200                      | 1.4                              | 3                       | 0.762778                    | 5443                     | 418                         |
| 9       | 200                      | 2                                | 4                       | 1.5444                      | 9408                     | 426                         |

Table 3 Simulation test and results of gear shaping cutting force

Table 4 Range analysis results

| Level | Factor | $n$ (str/min) | $f_c$ (mm/str) | $a_p$ (mm) |
|-------|--------|---------------|----------------|------------|

| Main cutting force $F$ (N) | $T_1$ | 21764 | 10525 | 16538 |
| $T_2$ | 21128 | 21593 | 20866.00 |
| $T_3$ | 19125 | 29899 | 24613.00 |
| $X_1$ | 7254.67 | 3508.33 | 5512.67 |
| $X_2$ | 7042.67 | 7197.67 | 6955.33 |
| $X_3$ | 6375.00 | 9966.33 | 8204.33 |
| Range | 879.667 | 6458.000 | 2691.667 |
| Importance ranking | 3 | 1 | 2 |

| Cutting temperature $T$ (°C) | $T_1$ | 1167 | 1178 | 1243 |
| $T_2$ | 1215 | 1300 | 1171.00 |
| $T_3$ | 1288 | 1192 | 1256.00 |
| $X_1$ | 389.00 | 392.67 | 414.33 |
| $X_2$ | 405.00 | 433.33 | 390.33 |
| $X_3$ | 429.33 | 397.33 | 418.67 |
| Range | 40.333 | 40.667 | 28.333 |
| Importance ranking | 2 | 1 | 3 |
The machine tool is Yichang Changjiang Machine Technology CNC gear shaper YK5150H, and its detailed parameters are shown in Table 7.

Roundness measuring equipment is Italian COORD3 (Ares Series) CMM, and its detailed parameters are shown in Table 8.

### 3.2 Experimental design method

#### 3.2.1 Data collection equipment installation

The force acting on the workpiece and the tool during gear shaping is the relationship between the acting force and the reaction force. Therefore, the cutting force on the workpiece can be decomposed into the cutting force in the Z-axis direction, the cutting force in the X-axis direction, and the Y-axis direction, as shown in Fig. 14.

The thin film pressure sensor is installed on the lower surface and outer ring of the ring gear to monitor the change of Z-axis cutting force and X-axis radial cutting force. The sensors are shown in Fig. 15. The red film pressure sensor is used to sense the change of the main cutting force $F_z$, and the yellow film pressure sensor is used to sense the change of the radial cutting force $F_x$. Figure 15a and Fig. 15b are the placement positions of the thin film pressure sensor when the gear is not installed. Figure 15c is a schematic diagram of the relative position of the sensors and the ring gear. As shown in Fig. 15d, the gear shaping is performed after installing the sensors.

#### 3.2.2 Experimental parameters

In the gear shaping process, there are four variables (stroke speed, circumferential feed, radial feed, and cutting depth) in one cycle, and some of the variables have a large span. In order to reduce the number of tests and costs, orthogonal tests are used. In the test, the roundness difference before and after processing is used to indicate the deformation. Before and after processing, the ring gear is cleaned and dried, and the roundness of the outer circle of the ring gear is measured with a three-coordinate instrument, and the difference in the roundness measurement is used as the deformation the amount. Combining the actual industrial production process, set the machining and cutting parameters, and discuss the influence of each cutting parameter on the deformation of the ring gear. The gear ring is processed under the cooling of L-HM 46 anti-wear hydraulic oil. The designed orthogonal test scheme is shown in Table 9.

### 3.3 Experimental results and analysis

In the gear shaping experiment, we use MY2901 digital conversion module to convert the resistance value of the sensor
into digital signal (AD value) to get the stress of the sensor. There was a positive correlation between AD and pressure. When the pressure value increases, the AD value will also increase. In this way, we can use the positive correlation between the AD value and the pressure value to find out the influence of processing parameters on the cutting force by collecting the AD value. Because of the complex shape of the clamp, it is difficult to calibrate the membrane pressure sensor. In order to solve this problem, we use the method of reading relative value.

3.3.1 Results and analysis of main cutting force

The clamping force of the clamping device is recorded when not processing; the value displayed at this time is the initial value, which is recorded as $F_0$. The main movement of the gear shaper cutter is up and down reciprocating linear movement, including the downward cutting stroke and the upward return empty stroke which are the main movements. When the gear shaper moves downward, the indication of the thin film pressure sensor is larger than the initial value, and the indication at this time is recorded as $F_{\text{down}}$. Subtract the initial value from the reading of the downward movement sensor as a reference value for measuring the main cutting force, as shown in Eq. 3-1.

$$F = F_{\text{down}} - F_0 \quad (3-1)$$

According to the above method, the main cutting force signals are analyzed and processed, and the results are shown in Table 10.

From Table 10 and Fig. 16, we can see that the influence of cutting parameters on the main cutting force in descending order is circumferential feed, depth of cut, stroke speed, and radial feed. The cutting depth and circumferential feed have a very obvious influence on the main cutting force, and the main cutting force increases in proportion to the increase in the cutting depth and circumferential feed. On the premise that other cutting parameters remain unchanged, the cutting depth increases, the cross-sectional area of the shear layer cut by the tool will increase, the cutting resistance during cutting will increase, and the corresponding main cutting force will also increase. The increase in the circumferential feed will also

| Table 5 Gear design parameters | Value |
|-------------------------------|-------|
| Materials                     | 42CrMo |
| Modulus                       | 2.25  |
| Number of teeth               | 95    |
| Pressure angle                | 25°   |
| Base circle diameter          | 193.723 |
| Diameter of index circle      | 213.75 |
| Starting diameter of involute | Max 210.9 |
| Tooth root circle diameter    | 221.0 $^{+0.30}$ |
| Tooth width                   | 20    |

| Table 6 Experimental cutter information | Value |
|----------------------------------------|-------|
| Material                               | S390  |
| Hardness                               | 66–67HRC |
| Coating                                | TiAIN |
| Coating thickness                      | 2μm   |
| Normal phase modulus                   | 2.25  |
| Pressure angle                         | 25°   |
| Front angle                            | 7°    |
| Back angle                             | 5°    |
| Base circle helix angle                | 2°34′ |
| Number of teeth                        | 56    |
| Chemical composition                   | C<0.2%; Si<0.4%; Mn<1.4%; P<0.025%; S<0.015% |

| Table 7 Machine-tool information | Value |
|----------------------------------|-------|
| Name                             | Yichang Changji Technology CNC Gear Shaper YK5150H |
| Model                            | YK 5150H |
| Maximum machining internal tooth diameter | 600mm |
| Maximum processing modulus       | 10    |
| Maximum machining tooth width    | 140mm |
| Maximum stroke speed             | 400str/min |
| Total power                      | 22.5Kw |

| Table 8 Roundness measuring equipment information | Value |
|--------------------------------------------------|-------|
| Model                                            | Compact bridge type coordinate measuring machine ARES |
| Positioning accuracy                             | 0.001mm |
| Scope of application                             | 700*650*500mm |
| Measuring stroke                                 | X: 700mm; Y: 650mm; Z: 500mm |
| Measurement accuracy                             | ISO MEPP=3+3.5 L/1000μm |
| Three-dimensional velocity                       | ≤517mm/s |
increase the cross-sectional area of the shear area, so the main cutting force will increase accordingly. When cutting at a lower cutting speed, there is greater frictional resistance. When the cutting speed increases to a certain value, the cutting temperature rises, and the strength and hardness of the material to be cut will decrease, so the cutting resistance in the shearing zone will decrease. The main cutting force is reduced. Han Jun et al. used a bowl-shaped gear shaper to design and experimentally process a 20Cr2Ni4A gear ring, and obtained the relationship between cutting force and processing parameters. The cutting speed is between 20 and 32 m/min, and the cutting force decreases as the cutting speed increases. The amount of back attack is between 1.0 and 3.0 mm, and the cutting force increases with the increase of the amount of back attack [8]. This is similar to the result of our experiment. Comparing Fig. 11 and Fig. 16, the results obtained by finite element simulation are basically the same as those obtained by experiments. Stroke speed, circumferential feed, and cutting depth have the same order of influence on the main cutting force. And their influence trends on the main cutting force are very close. The feasibility of using finite element simulation to analyze the influence trend of machining parameters on the main cutting force is proved.

### 3.3.2 Results and analysis of radial cutting force

Firstly, record the clamping force of the clamping device when it is not machined, the value displayed at this time is the initial value, which is recorded as $F_{r0}$. Then, place the workpiece to be machined in the fixture. Under the action of the radial cutting force, the indication value of the film pressure sensor will increase. Record the value at this time as $F_{r\text{max}}$, the added value can be used to measure the radial cutting force.
The force, which is recorded as $F_r$, and the calculation method is Eq. 3-2.

$$F_r = F_{\text{max}} - F_{r0} \quad (3 - 2)$$

Analyze and process the collected radial cutting force induction signals, and the results are shown in Table 11.

From Table 11 and Fig.17, we can see that the order of the influence of cutting parameters on the radial force from large to small is cutting depth, radial feed, circumferential feed, and stroke speed. Among them, the cutting depth and radial feed have a very obvious influence on the radial cutting force. The radial cutting force increases proportionally as the depth of cut increases, and increases proportionally as the radial feed increases.

### 3.3.3 Measurement and analysis of ring gear deformation

Roundness refers to the condition that the circle on the part is kept equidistant from its center, also called the degree of rounding. It can be expressed as the difference between the...

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### Table 9 42CrMo gear ring gear shaping uniform design test table

| Test No. | Stroke speed $n$ (str/min) | Circumferential feed $f_c$ (mm/str) | Cutting depth $a_p$ (mm) | Radial feed $f_r$ (mm/str) |
|----------|---------------------------|------------------------------------|--------------------------|---------------------------|
| 1        | 140                       | 0.8                                | 3                        | 0.0015                    |
| 2        | 140                       | 1.4                                | 4                        | 0.002                     |
| 3        | 140                       | 2                                  | 5                        | 0.0025                    |
| 4        | 170                       | 2                                  | 3                        | 0.002                     |
| 5        | 170                       | 0.8                                | 4                        | 0.0025                    |
| 6        | 170                       | 1.4                                | 5                        | 0.0015                    |
| 7        | 200                       | 1.4                                | 3                        | 0.0025                    |
| 8        | 200                       | 2                                  | 4                        | 0.0015                    |
| 9        | 200                       | 0.8                                | 5                        | 0.002                     |

### Table 10 Experimental results and analysis of main cutting force

| Test No. | Stroke speed $n$ (str/min) | Circumferential feed $f_c$ (mm/str) | Cutting depth $a_p$ (mm) | Radial feed $f_r$ (mm/str) | Test result |
|----------|---------------------------|------------------------------------|--------------------------|---------------------------|-------------|
| 1        | 140                       | 0.8                                | 3                        | 0.0015                    | 386         |
| 2        | 140                       | 1.4                                | 4                        | 0.002                     | 418         |
| 3        | 140                       | 2                                  | 5                        | 0.0025                    | 447         |
| 4        | 170                       | 2                                  | 3                        | 0.002                     | 413         |
| 5        | 170                       | 0.8                                | 4                        | 0.0025                    | 397         |
| 6        | 170                       | 1.4                                | 5                        | 0.0015                    | 425         |
| 7        | 200                       | 1.4                                | 3                        | 0.0025                    | 392         |
| 8        | 200                       | 2                                  | 4                        | 0.0015                    | 413         |
| 9        | 200                       | 0.8                                | 5                        | 0.002                     | 401         |
| I        | 1251                      | 1184                               | 1191                     | 1224                      |             |
| II       | 1235                      | 1235                               | 1228                     | 1232                      |             |
| III      | 1206                      | 1273                               | 1273                     | 1236                      |             |
| I        | 417                       | 394.6667                           | 397                      | 408                       |             |
| II       | 411.6667                  | 411.6667                           | 409.3333                 | 410.6667                  |             |
| III      | 402                       | 424.3333                           | 424.3333                 | 412                       |             |
| Range    | 15                        | 29.6667                            | 27.3333                  | 4                         |             |
| Importance ranking | 3 | 1 | 2 | 4 | |
Fig. 16 The influence trend of parameters on the main cutting force

Table 11 Orthogonal test analysis of radial cutting force

| Test No. | Test parameters | Circumferential feed $f_c$ (mm/str) | Cutting depth $a_p$ (mm) | Radial feed $f_r$ (mm/str) | Radial compressive force | Test result |
|----------|-----------------|-------------------------------------|--------------------------|----------------------------|--------------------------|-------------|
| 1        | 140             | 0.8                                 | 3                        | 0.0015                     | 89                       |
| 2        | 140             | 1.4                                 | 4                        | 0.002                      | 106                      |
| 3        | 140             | 2                                   | 5                        | 0.0025                     | 118                      |
| 4        | 170             | 2                                   | 3                        | 0.002                      | 97                       |
| 5        | 170             | 0.8                                 | 4                        | 0.0025                     | 121                      |
| 6        | 170             | 1.4                                 | 5                        | 0.0015                     | 103                      |
| 7        | 200             | 1.4                                 | 3                        | 0.0025                     | 97                       |
| 8        | 200             | 2                                   | 4                        | 0.0015                     | 95                       |
| 9        | 200             | 0.8                                 | 5                        | 0.002                      | 114                      |
| I        | 313             | 324                                 | 283                      | 287                        |                          |             |
| II       | 321             | 306                                 | 322                      | 317                        |                          |             |
| III      | 306             | 310                                 | 335                      | 336                        |                          |             |
| I        | 104.3333        | 108                                 | 94.3333                  | 95.6667                    |                          |             |
| II       | 107             | 102                                 | 107.3333                 | 105.6667                   |                          |             |
| III      | 102             | 103.3333                            | 111.6667                 | 112                        |                          |             |
| Range    | 5               | 6                                   | 17.3333                  | 16.3333                    |                          |             |
| Importance ranking | 4            | 3                                   | 1                        | 2                          |                          |             |
radii of two concentric circles that contain the actual contour of the same cross-section and have the smallest radius difference [14]. It is the limit to the actual circle. An indicator of the variation of the ideal circle, the tolerance zone is the area between two concentric circles with the tolerance value $t$ as the radius difference, and the actual motion trajectory of the tool tip point is an arbitrary curve in this area, as shown in Fig. 18a.

The roundness of the gear ring before and after machining is measured by Italian COORD3 (Ares Series) CMM, shown in Fig. 18b. The measurement results of roundness difference are shown in Table 12, and the influence trend of various parameters on the deformation of ring gear is obtained through analysis, as shown in Fig. 19.

It can be seen from the test results that different cutting parameters will cause different degrees of deformation of ring teeth. The original roundness error is subtracted from the roundness error before and after machining. When the difference is positive, the tolerance zone representing the difference between the radii of two concentric circles becomes larger, that is, the deformation is more serious; When the difference is negative, the tolerance zone of the difference between the radii of two concentric circles becomes smaller, which
indicates that the situation is improved compared with the original deformation.

From the results in Table 12 and Fig. 19, it can be seen that the radial feed has the greatest impact on the deformation of the ring gear. When the value of the radial feed increases, the deformation of the ring gear decreases linearly, and the impact is very significant. According to the simulation results in section 2, in the range of cutting parameters, the cutting force decreases with the increase of stroke speed, and the cutting temperature increases with the increase of stroke speed. But at the same time, the increase of cutting temperature will reduce the friction coefficient and the cutting force [11].

### 3.4 Establishment of deformation model of gear ring

In order to analyze the relationship between gear ring deformation and cutting parameters, a uniform design test was carried out on the basis of orthogonal experiments. According to the obtained ring gear deformation data, the prediction model of the ring gear deformation was fitted, which can be used to control the deformation of ring gear in its machining process.

In order to improve the uniformity and dispersion of the experimental parameters and ensure the accuracy of the established model, the process parameters of the uniform test are determined by combining the actual production process and the selection of the orthogonal test parameters, and the roundness of the gear ring is measured by using Italian coordinate 3 (Ares Series). The scheme and results of uniform experiment are shown in Table 13.

In this study, stepwise regression analysis method is used to establish the regression model of cutting parameters and ring gear deformation. In the process of stepwise regression analysis, when the selected variable becomes no longer significant after introducing a new variable, it will be eliminated; When the excluded variable becomes significant after introducing a new variable, it will be included in the equation again. The quadratic regression equation established by stepwise regression analysis is as Eq. (3-3).

\[
R = 318.5676 - 14.4133 \cdot f_c - 148.5199 \cdot a_p - 0.0059 \cdot n^2 \\
+ 2698803.1874 \cdot f_r^2 \\
+ 6.0793 \cdot a_p^2 - 0.959 \cdot n \cdot f_c - 102.0474 \cdot n \cdot f_r \\
+ 0.5408 \cdot n \cdot a_p + 6.6275 \cdot f_c \cdot a_p 
\]

(3 – 3)

Significance test is usually needed for the established regression equation. In this experiment, the \( F = 4.5432 > F_{0.05}(9, 7) = 3.68 \), so the regression effect is significant. Determination factor \( R^2 \) is an index to evaluate the linear relationship between variables of regression model. The closer the value is to 1, the better the fit of the regression equation. Calculate \( R^2 \) according to Eq. (3-4). Decision coefficient obtained in the paper \( R^2 = 0.854 \), indicating that the dependent
variable is very related to the independent variable, and the fitting results are shown in Fig. 20. From the fitting results, it can be seen that the predicted value of the model is very close to the measured value, which indicates that the model can predict the machining deformation of gear ring gear shaping.

\[ R^2 = \frac{SSR}{SST} = \frac{\sum_{i=1}^{n} (\tilde{y}_i - y)^2}{\sum_{i=1}^{n} (y_i - \bar{y})^2} \]  

(3-4)

In actual gear shaping, the cutting parameters can be adjusted according to the roundness error of the original workpiece to reduce the deformation of the ring gear. Taking the large roundness error of the original workpiece as an example, the cutting parameters can be selected according to the influence trend of the cutting parameters on the deformation of the ring gear in Fig. 20. Then calculate the corresponding gear ring deformation according to Eq. (3-3). If the calculated deformation is still greater than the processing requirements, continue to adjust the parameters to reduce the deformation.

### 4 Conclusions

This paper mainly introduces the simulation analysis and experimental research on the deformation of the ring gear in the process of gear shaping, and finds out the influence factors of
the process parameters on the deformation of the ring gear and their importance order. The main conclusions are as follows:

1. The finite element simulation analysis of 42CrMo gear shaping process shows that the circumferential feed has the greatest influence on the main cutting force. The main cutting force increases with the increase of circumferential feed. For cutting temperature, circumferential feed rate and stroke speed have greater influence, while cutting depth has less influence.

2. The influence of cutting parameters on the deformation of gear ring is analyzed by orthogonal experiment. The results show that the radial feed has the greatest influence on the deformation of the ring gear, and the deformation of the ring gear decreases with the increase of the radial feed. With the increase of circumferential feed, the deformation of ring gear first decreases and then increases. The deformation of ring gear decreases with the increase of travel speed. The deformation of the ring gear first increases and then decreases with the increase of the cutting depth.

3. The influence of the main cutting parameters on the deformation of the ring gear, from large to small, is in order: radial feed, circumferential feed, stroke speed, cutting depth.

The above research results can provide the basis for the actual gear shaping process, so as to adjust the process parameters according to the requirements of gear deformation control, ensure that the gear deformation is controlled within the required range, and avoid the production of unqualified products.

Availability of data and material The datasets used or analyzed during the current study are available from the corresponding author on reasonable request.

Code availability The code for current study is available from the corresponding author on reasonable request.

Author contribution Xiuxu Zhao: Conceptualization, methodology, data curation, investigation, writing—review and editing. Qingzhuang Liu: Validation, experiment, review and editing. Yu Fu: Writing original draft, visualization, data curation. Peng Chen: Finite element analysis, formal analysis.

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Declarations

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