Clamping deformation analysis and machining parameter optimization of weak stiffness ring parts

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Abstract. A series of turning experiments have been carried out to study the effect of different cutting speed, feed rate, pre-tightening torque and clamping mode on deformation during turning of weak stiffness ring parts. The roundness error of workpiece is measured by using a coordinate measuring instrument, and the roundness error is evaluated by using the least square circle method. The influence of various cutting parameters and clamping mode on the turning deformation of weak stiffness ring parts is analysed. The distribution of residual stress along depth direction was measured by X-ray diffraction method layer by layer. The optimization model of machining process parameters is established. MATLAB is used to solve the optimization model based on the multi-objective optimization function of genetic algorithm, optimizing cutting parameters including clamping force.

1. Introduction

Weak Stiffness ring parts are usually those whose ratio of wall thickness to radius of curvature of inner hole is less than 1:20. They are widely used in transmission systems and important supporting parts in many fields, such as vehicle and ship power, aerospace and so on. Its processing quality will directly affect the transmission accuracy, service life and product reliability. For this kind of parts, most of them are die forgings, and the material removal rate is up to 80%. Such a high material removal rate brings about the problem of machining efficiency and deformation. The weak stiffness and the decreasing of the stiffness in the process of machining bring challenges to the process control. The assembly accuracy of structural parts is high. The deformation in macroscopic and the surface residual stress in microcosmic all have an effect on the performance of the key structural parts of transmission system. Machining deformation and surface residual stress are produced under the combined action of cutting force, clamping force and cutting heat. Because there are many and complex factors affecting the workpiece and the interaction between them, the selection of suitable clamping scheme and clamping force is one of the key techniques to reduce the workpiece deformation and ensure the surface quality of the workpiece.

The research on machining process optimization of weak stiffness ring parts has been a hot spot in machining industry. The main reason lies in the large deformation caused by clamping force[1], cutting force[2,3] and residual stress[4,5] in weak stiffness ring parts. The clamping force and the working point
has an important influence on the workpiece deformation [6]. Yuan et al. [7] put forward a variable clamping force jig scheme, which can optimize the optimum position point and clamping force of the workpiece, reduce cutting deformation of machining system. Even so, the inhomogeneous initial stress is produced in the workpiece due to the clamping force, which also has a great influence on the distribution of residual stress and machining deformation [8]. On the basis of finite element simulation, the influence of initial residual stress on machining deformation is quantified based on finite element simulation [9]. In order to eliminate the problem of uneven initial internal stress distribution caused by common three-claw chuck when turning thin-walled ring parts, more and more special clamps have been designed for this kind of parts, such as sector chuck, elastic spring expansion sleeve, etc. Peng [10] used elastic expansion sleeve clamping to qualitatively study that the ring of prestressed cutting bearing can effectively produce residual compressive stress on the surface, but no quantitative analysis of residual stress distribution control and deformation control has been carried out. Because the machining deformation seriously affects the finished product rate of this kind of precision transmission parts, and the distribution of residual stress affects its performance. It is of engineering significance to control the residual stress and deformation in a better condition by optimizing the processing parameters, including clamping force.

In this paper, the effect of different cutting speed, feed rate, pre-tightening torque and clamping mode on deformation was analysed primarily. The distribution of residual stress along depth under different cutting parameters and clamping forces is measured by experimental analysis, and the relationship between cutting parameters, clamping force and residual stress distribution is established by multivariate regression analysis. Finally, the cutting parameters and clamping force are analyzed and optimized to improve the yield and performance.

2. Experimental study on outer circle turning of weak stiffness ring parts

2.1. Experiment condition

The lathe used in turning experiment is NC lathe of MORISEIKI, the workpiece material used for experiment is 20Cr2Ni4A alloy steel, the workpiece specification is 80mm in inner diameter, 86mm in outer diameter and 10mm in width. MAUE6020 finishing tool was used, the tip arc is 0.4mm, the front angle is 15°, the rear angle is 0°, the main angle is 75°, and the auxiliary angle is 5°. Two kinds of fixture systems are used in the cutting experiment, one is elastic expansion package clamp and the other is three-claw fan chuck clamping, as shown in Fig.1(a). The specific head of the clamping system of the elastic expansion package is centered on the spindle of the machine tool. The sample is inserted into the taper shaft of the fixture with the elastic expansion sleeve, and the end round nut exerts axial thrust by tightening the torque wrench and the round nut sleeve. Make the expansion sleeve expand evenly and center the workpiece, providing the quantitative pre-tightening moment. The three-claw sector chuck clamping system is shown in Fig.1(b). The clamping force of the three-claw chuck is adjusted by adjusting the hydraulic valve pressure of the machine tool.

![Elastic expansion sleeve](image1)
![Three-claw fan chuck](image2)

Figure 1. Cutting experimental clamping system
A single factor analysis method is used to set up the experimental parameters. The coordinate measuring instrument of 350AC produced by HEXAGON is used to measure the coordinates of 16 sampling points uniformly distributed on the same plane of the outer circle of the workpiece by using the single point touch method. The coordinate values are calculated and evaluated by using the least square circle method. The corresponding roundness errors under different machining parameters are shown in Fig 2. Using X-350A residual stress measuring instrument measured the residual stress of machined surface, as shown in figure 3. The X-ray stress tester can only measure the residual stress of the workpiece surface, in order to measure the variation of residual stress in the depth direction of the workpiece, the residual stress at different depth is measured by electrolytic corrosion layer by layer peeling.

![Figure 2. Three-coordinates measuring machine](image)

![Figure 3. Residual stress tester](image)

### 2.2. Experiment results and analysis

#### 2.2.1. Clamping deformation analysis

The deformation of ring parts with weak stiffness is mainly reflected in the roundness error of the outer circle. The roundness error of the workpiece is measured by coordinate method. Table 1 shows the experimental grouping and roundness error under the elastic expansion package. Table 2 shows roundness errors under different clamping modes.

| No. | Cutting depth(mm) | Cutting speed (m/min) | Feed(mm/r) | Pre-tightening torque(N m) | Deviation(mm) |
|-----|-------------------|-----------------------|------------|---------------------------|---------------|
| 1   | 0.1               | 200                   | 0.1        | 45                        | 0.061         |
| 2   | 0.2               | 200                   | 0.1        | 45                        | 0.069         |
| 3   | 0.3               | 200                   | 0.1        | 45                        | 0.082         |
| 4   | 0.2               | 100                   | 0.1        | 45                        | 0.062         |
| 5   | 0.2               | 300                   | 0.1        | 45                        | 0.077         |
| 6   | 0.2               | 200                   | 0.05       | 45                        | 0.065         |
| 7   | 0.2               | 200                   | 0.15       | 45                        | 0.079         |
| 8   | 0.2               | 200                   | 0.1        | 30                        | 0.057         |
| 9   | 0.2               | 200                   | 0.1        | 60                        | 0.092         |
Table 2. Roundness errors under different clamping modes

| No. | Cutting depth (mm) | Cutting speed (m/min) | Feed (mm/r) | Clamping mode                  | Deviation (mm) |
|-----|--------------------|-----------------------|-------------|--------------------------------|----------------|
| 1   | 0.2                | 100                   | 0.1         | Elastic expansion sleeve       | 0.062          |
| 2   | 0.2                | 200                   | 0.1         | Elastic expansion sleeve       | 0.069          |
| 3   | 0.2                | 300                   | 0.1         | Elastic expansion sleeve       | 0.077          |
| 4   | 0.2                | 100                   | 0.1         | Three-claw fan chuck           | 0.113          |
| 5   | 0.2                | 200                   | 0.1         | Three-claw fan chuck           | 0.125          |
| 6   | 0.2                | 300                   | 0.1         | Three-claw fan chuck           | 0.147          |

Fig. 4. Influence of processing parameters on roundness deviation

Fig. 4 shows the effect of machining parameters on roundness error under the elastic expansion clamping mode drawn from Table 1. It can be seen that the roundness error of the workpiece increases with the depth of cutting and feed rate. This is because the increase of the cutting depth and feed rate plays a decisive role in the increase of the cutting force, and the increasing of the cutting force leads to the deterioration of the state of the machining process. The roundness error of workpiece also increases with the increase of cutting speed, which is because the increase of cutting speed has a slight effect on the reduction of cutting force, but has a strong effect on cutting temperature, and the elastic-plastic deformation of workpiece is aggravated because of the increase of temperature. The roundness error of workpiece increases with the increase of pretightening torque, because the pretightening stress formed in the workpiece equivalent to increasing the load of cutting force. But theoretically, the elastic expansion sleeve is the uniform contact around the circle and the clamping force is uniformly distributed, there should be no roundness error, the roundness error obtained by the measurement should be the non-uniformity of the workpiece material, the instability of the cutting process and the accumulative measurement error. This is coincides with the actual measurement roundness error with small variance.
Fig. 5 shows the comparison of the influence of clamping method on turning deformation. It can be seen that the roundness error of the workpiece after turning with elastic expansion package clamp is smaller than that with sector chuck clamping.

2.2.2. Machining residual stress analysis

The machined surface was electrochemically corroded by electrolytic polishing corrosion instrument. The surface layer of the parts was stripped layer by layer and the residual stress values were measured layer by layer. The results are shown in Table 3.

Table 3. The value of residual stress

| No. | Surface Layer | Depth Level 1 | Depth Level 2 | Depth Level 3 | Depth Level 4 | Depth Level 5 |
|-----|---------------|---------------|---------------|---------------|---------------|---------------|
|     | RS            | DFS           | RS            | DFS           | RS            | DFS           |
| 1   | 0             | 0             | 0.021         | -122          | 0.091         | -58           |
| 2   | 0             | 0             | 0.027         | -33           | 0.103         | 0.125         |
| 3   | 0             | 0             | 0.024         | -37           | 0.095         | 0.125         |
| 4   | 0             | 0             | 0.029         | -32           | 0.102         | 0.116         |
| 5   | 0             | 0             | 0.023         | -40           | 0.099         | 0.123         |
| 6   | 0             | 0             | 0.025         | -56           | 0.093         | 0.115         |
| 7   | 0             | 0             | 0.031         | -97           | 0.112         | 0.119         |
| 8   | 0             | 0             | 0.028         | -115          | 0.119         | 0.13          |
| 9   | 0             | 0             | 0.026         | -122          | 0.123         | 0.123         |

Notes: RS is short for ‘Residual Stress’; DFS is short for ‘Distance from the Surface’.

The machined residual stress is distributed regularly due to the force load distribution and thermal load distribution under the surface. Surface residual stress (SRS) is a key parameter affecting surface strength and fatigue life. The greater the residual tensile stress on the surface, the more easily fatigue cracks occur. Therefore, it is an effective way to restrain the fatigue crack by controlling the residual tensile stress decrease or even change to the state of compressive stress. The peak residual compressive stress (PRCS) is an important parameter affecting the fatigue life and fracture strength of the parts. Therefore, the precision and strength of the workpiece can be effectively guaranteed by controlling the peak residual compressive stress. The data in Table 3 show that: 1) cutting depth and cutting speed have no obvious influence on surface residual tensile stress and maximum residual compressive stress. 2) with the increase of feed rate, the absolute values of surface residual tensile stress and maximum residual compressive stress increase. 3) with the increase of pretension moment, the surface residual tensile stress decreases, the absolute value of the maximum residual compressive stress increases, and the residual...
stress distribution curve moves down as a whole. It is summing up that the residual stress distribution can be controlled by adjusting the pretightening moment.

3. Machining parameter optimization
Reasonable clamping is the basis of correct processing. On the one hand, the selection of clamping force needs to ensure the stable clamping of the workpiece, which will not move, rotate or break away from the fixture during processing. On the other hand, too large clamping force will lead to plastic deformation of workpiece. Due to the uniform ring clamping force applied on the inner wall of the part, the internal tension of the workpiece produces the toroidal tensile prestressing force, in order to ensure that the workpiece is still in the elastic state under the clamping force. The ultimate pressure at yield critical state can be obtained as shown in formula (1), and the final selection interval of pre-tightening torque value is [20,180].

\[
P_{\text{lim}} = \frac{b^2 - a^2}{b^2} \cdot \frac{\sigma_s}{2}
\]

In which, \(\sigma_s\) is the yield limit.

Based on the results of residual stress analysis, a second order multivariate general regression model is established, with feed and preload moment as input parameters, surface residual tensile stress and maximum residual compressive stress as output. The regression model after parameter fitting is shown in formula (2).

\[
y(Y_1, Y_2, \ldots, Y_N) = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \sum_{j=1}^{k} \beta_{ij} X_i X_j + \sum_{i=1}^{k} \beta_{i} X_i^2 + \epsilon
\]

The machining process was optimized from machining efficiency and residual stress distribution, and the optimization model was established with feed rate and residual stress eigenvalue as the optimization objective. The multi-objective optimization function based on genetic algorithm in MATLAB is used to solve the optimization model. The Pareto front view was drawn, as shown in figure 6. Synthetic optimal cutting parameters is 175N·m, 0.26mm/r, the target value is 200MPa and the maximum residual compressive stress is -326MPa.

![Figure 6. Comparison of the influence of clamping method on turning deformation](image)

4. Conclusion
Taking the outer circle turning process of the ring parts with weak stiffness as the research object, the deformation of the workpiece under different clamping conditions is analyzed by setting the cutting experiment. and the cutting speed, feed rate and clamping force are taken as the optimum variables. The
optimization model of machining process parameters is established with cutting speed, feed rate and clamping force as the optimum variables, with feed rate and residual stress eigenvalue as the optimization objective. MATLAB is used to solve the optimization model based on the multi-objective optimization function of genetic algorithm, and the non-inferior optimal target domain is drawn, and the optimal solution set satisfying the multi-objective equilibrium is obtained. The experimental results verify the effectiveness of the optimization model and provide the optimal processing parameters under multi-objective conditions for practical production and processing.

Acknowledgments
This work was financially supported by Major Science and Technology Project in Henan Province (171100210300), Ph.D. Start-up Fund (BSJ2018003) and Anyang Science and Technology Research.

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