Simulation Design of 30KHz Ultrasonic Rolling Tool Head

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Abstract. In order to explore the types of ultrasonic rolling tool head used in ultrasonic rolling and finishing processing device, ANSYS Workbench is taken as a tool to simulate the machining process of ultrasonic rolling processing through transient dynamic analysis, and the maximum residual stress distribution and stress concentration of 45 steel workpiece are analyzed. Based on the simulation result, the ball-type ultrasonic rolling tool head is selected in this work. In addition, the transient dynamics module of ANSYS Workbench is also used to simulate the ultrasonic rolling tool head of different structure parameter, in that way, the accurate and reasonable structure parameters of rolling components of ultrasonic rolling tool head can be achieved. The results of this work show that a ball-type ultrasonic rolling tool head of a diameter of 8mm can make the maximum residual stress minimum and stress concentration slightest under the condition of normal processing of the 45 steel workpiece. In other words, it suggests that this ultrasonic rolling tool head can produce the best surface quality of 45 steel workpiece.

1. Introduction

As a new technology, it is very meaningful to study reasonable processing parameters for improving the surface quality and mechanical properties of the workpiece. The main process parameters that affect the quality of ultrasonic rolling finishing include the frequency and amplitude of ultrasonic wave, the spindle speed of the lathe, the feed rate, the press down and the roll times. The influence of each technological parameter on the processing effect of ultrasonic rolling finishing is different, but the effect of each technological parameter is interrelated and restricted.

Ultrasonic rolling finishing processing combines the advantages of ultrasonic processing and rolling processing, which can improve the surface quality of the processed parts to a large extent. The microscopic process of ultrasonic rolling processing is shown in Figure 1[1]. The ultrasonic frequency electrical signal emitted by the ultrasonic generator is converted into a tiny mechanical vibration of ultrasonic frequency by the transducer, which is then amplified by the amplitude transformer, and finally acts on the ultrasonic rolling tool head to realize the reciprocating vibration of the ultrasonic rolling tool head[2]. At the same time, the pressure force of the tool head can be carried out to the surface of the processed parts, making the surface metal of the workpiece plastic deformation, and the wave peak is filled in the trough, so that the surface roughness can be greatly reduced, and the comprehensive mechanical properties of the high surface are proposed. The test shows that the surface roughness can be reduced to Ra0.02~0.08, the machining accuracy can reach 0.01~0.02mm, and the surface rockwell hardness can be increased by 20% ~ 50%[3].
In this paper, the ultrasonic rolling machining system is taken as the research object, and the finite element model of the machining system is established. The maximum residual stress distribution and stress concentration on 45 steel workpiece produced after ultrasonic rolling machining are analyzed, thus the type and structural parameters of ultrasonic rolling tool head are established. This paper provides a theoretical basis for the design, optimization and selection of ultrasonic rolling tool head.

Figure 1 micro-process of ultrasonic rolling

2. Type of ultrasonic rolling tool head

There are various kinds and types of ultrasonic rolling tool heads with different functions and effects. There are five types of rolling elements in the most commonly used cylindrical ultrasonic rolling tool head: ball type, arc type, small arc type, cone type and cylindrical type[4], as shown in Figure 2.

(a) ball type (b) circular arc type (c) small circular arc type (d) conical roller type (e) cylindrical roller type

Figure 2. type of rolling element

The ball used in machining can be the standard ball used in high precision ball bearings. This kind of ball is made of GCr15 bearing steel after cold heading, quenching and processing. The hardness is HRC62 ~ 65. After fine grinding, its surface has a high shape accuracy and a very low surface roughness, which is very convenient and economical. Arc-shaped rolling elements have a short contact with the workpiece surface, and the metal plastic deformation and the degree of hardening of the workpiece surface after processing is relatively large, while the small arc-shaped rolling elements have a smaller contact area with the surface of the workpiece being processed, and the machining enhancement effect is more significant, which is suitable for machining shaft with steps or the workpiece with poor rigidity. Arc radius \( r = (0.5 \sim 1) \) D. The taper tool head can make a uniform and gradual transition between the processed surface and the unprocessed surface. Cylindrical tool head can make the cylindrical part smooth transition to arc part, often used for small and medium-sized shaft parts and step-less long shaft processing. In general, the width of the cylinder part \( b \) is about 3 times of the feeding amount, and the phi Angle is within the range of 3° ~ 5°.
3. Simulation of different types of rolling elements

3.1. Establishment of finite element model

In order to improve the accuracy of finite element analysis and shorten the analysis time, we appropriately simplified the three-dimensional finite element model of ultrasonic rolling processing, and only selected a small section of the processed workpiece to simulate and analyze the distribution of the maximum residual stress of the processed workpiece when different rolling elements are processed.

In the process of modeling, the size of the processed workpiece to \( \phi \times 20 \times 20 \) mm, material is 45 steel, but also try to set the parameters of the rolling element of close, five are choosing the material of rolling element GCr15, working point diameter of 8 mm, in addition to the ball of the rolling element \( B \) is the width of 5 mm, type of ball rolling element of radius \( r = 4 \) mm; The radius of arc type rolling element \( r = 8 \) mm; The radius of small circular arc type rolling element \( r = 2.5 \) mm; The width of the cone roller rolling element \( b = 3 \) mm, \( \phi = \phi_1 = 5^\circ \); Width of cylindrical roller rolling element \( b = 3 \) mm, \( r = 1 \) mm. Parameters of GCr15 and 45 steel are shown in Table 1. Simplified finite element models of different types of rolling elements are shown in Figure 3.

| Materials     | Elasticity modulus \( E \) (GPa) | Poisson's ratio \( \nu \) | Density \( \rho \) (kg/m\(^3\)) | Yield strength \( \sigma_y \) (MPa) | Tensile strength \( \sigma_b \) (MPa) |
|---------------|-------------------------------|---------------------------|------------------------------|---------------------------------|---------------------------------|
| 45 steels     | 210                           | 0.269                     | 7850                         | 355                             | 600                             |
| GCr15         | 208                           | 0.3                       | 7800                         | 518.42                          | 861.3                           |

Figure 3. simplified finite element model of ultrasonic rolling for different types of rolling elements

3.2. Contact definition and grid division

According to relevant literature[5], the friction coefficient in ultrasonic rolling process is \( 10^{-5} \sim 3 \times 10^{-3} \), and the variation range of the friction coefficient is very small. Therefore, the friction coefficient in ultrasonic rolling process is regarded as a constant, and the friction coefficient is set as \( 10^{-3} \). In addition, the rolling element is defined as the target surface and the 45 steel workpiece as the contact surface.

Figure 4. meshing of simplified finite element model of ultrasonic rolling with different types of rolling elements

For three-dimensional graphics, ANSYS Mesh has many different Mesh division methods, such as automatic Mesh division method, tetrahedron Mesh division method, hexahedron dominant Mesh division method, sweep method, multi-area method, expansion method etc[6 ~ 8]. Through different
mesh division of the model, it is found that when other conditions are the same, the mesh quality of the 3d finite element model established by multi-area method is the highest, all above 0.9. Therefore, multi-area method is selected to conduct mesh division. The 3d finite element models of ball type, circular arc type, small circular arc type, conical roller and cylindrical roller respectively contain 1373, 1509, 1757, 1469 and 1461 elements. The mesh division of 3d model is shown in Figure 4.

3.3. Apply loads and constraints
In five finite element models, the analytical settings and applied loads and constraints should be set to the same. In the analysis setting, the number of analysis steps is set to two. The termination time of the first analysis step is 5.5s, and the termination time of the second analysis step is 6s. The solver of the two analysis steps was set as a direct solver. The initial step size and the minimum step size were set as $5 \times 10^{-3}$s, and the maximum stride size was set as $2 \times 10^{-2}$s, and the large deformation was turned on and the weak springs were turned off. Moreover, the position of the rolling element in the z direction should be constrained. The specific applied load is shown in Table 2. Since two displacement constraints cannot be applied on the rolling element, the ultrasonic vibration of 30kHz should be replaced by the impact force of 30kHz.

3.4. Residual stress analysis
After the workpiece is processed by ultrasonic rolling, residual stress will inevitably occur. Residual stress does great harm to the workpiece, affecting its fatigue life, machining accuracy, corrosion resistance and reliability[9]. After being processed by five kinds of rolling elements, the residual stress generated by 45 steel workpiece is shown in Figure 5, and the radial distribution of residual stress is shown in Figure 6.

| Time quantum/s | The workpiece speed/(rad/s) | Roll element x direction position change/m | Load on roll element in x direction/N | Feed quantity of roll element in y direction/(m/s) |
|----------------|-----------------------------|-------------------------------------------|-------------------------------------|-----------------------------------------------|
| 0～0.5         | 62.8                         | $0 \sim -6.0 \times 10^{-5}$               | $100 \times \sin(108000000 \times t)$ | 0.001                                         |
| 0.5～5.5       | 62.8                         | invariability                             | $100 \times \sin(108000000 \times t)$ | 0.001                                         |
| 5.5～6         | 62.8                         | $-6.0 \times 10^{-5} \sim 5.0 \times 10^{-5}$ | —                                   | 0.001                                         |

(a) ball type   (b) circular arc type   (c) small circular arc type   (d) conical roller   (e) cylindrical roller

**Figure 5.** residual stress nephogram of 45 steel workpiece

(a) ball type   (b) circular arc type   (c) small circular arc type   (d) conical roller   (e) cylindrical roller

**Figure 6.** radial distribution of residual stress of 45 steel workpiece

It can be seen from Figure 5 that the maximum residual stress generated by the workpiece processed by the arc-shaped rolling element is the largest, followed by the minor arc-shaped type,
taper roller, cylindrical roller and ball type, respectively 59.2MPa, 43.9MPa, 34.8MPa, 28.2MPa and 10.4MPa. From Figure 6 can see, ball, small circular arc surface and conical roller roller element influence depth than the circular arc surface and cylindrical roller is big, small circular arc surface type and cylindrical roller rolling element both on the processed workpiece surface tensile stress and compressive stress, and circular arc surface of small circular arc surface and the cylindrical roller rolling element the workpieces exist serious stress concentration phenomenon. Therefore, the machining quality of ball type and cone type roller element is better. In view of the fact that the maximum residual stress generated by the machining of ball type roller element is smaller than that of cone type roller, the workpiece processed with ball type roller element is of higher quality, and ball type roller element is more suitable for ultrasonic rolling processing.

4. Simulation of different diameter ball rolling elements

4.1. Finite element model pretreatment

The 3D finite element model when the diameter of the ball is 6mm, 8mm and 10mm is shown in Figure 7 respectively, and the specific size is shown in Table 3. The contact definition, mesh division and application of loads and constraints are the same as those in the simulation of different types of rolling elements.

Table 3. Parameters of finite element model.

| Ball diameter $d$ (mm) | Ball material | Workpiece diameter $D$ (mm) | Workpiece length $L$ (mm) |
|------------------------|---------------|-----------------------------|---------------------------|
| 6                      | GCr15         | 20                          | 20                        |
| 8                      | GCr15         | 20                          | 20                        |
| 10                     | GCr15         | 20                          | 20                        |

Figure 7. Simplified finite element model of different diameter ball rolling elements.

4.2. Post-processing of finite element model.

After being processed by three kinds of ball type rolling elements with different diameters, the residual stress generated by 45 steel workpiece is shown in Figure 8, and the radial distribution of residual stress is shown in Figure 9.

Figure 8. Residual stress nephogram of steel workpiece 45

As can be seen from Figure 8, the maximum residual stresses generated by the workpiece processed by ball type rolling elements with diameters of 6mm, 8mm and 10mm are 20.2MPa, 10.4MPa and 0.364MPa in turn. It can be seen from Figure 9 that the machining depth of three kinds of ball type rolling elements with different diameters is similar, and the workpiece surface processed
by ball type rolling elements with diameters of 10mm has both tensile stress and compressive stress, and there is a very serious stress concentration phenomenon. Therefore, the machining quality of ball rolling elements with diameters of 6mm and 8mm is better. Considering that the maximum residual stress produced by the machining of ball rolling elements with diameters of 8mm is smaller than that of ball rolling elements with diameters of 6mm, the workpiece processed with ball rolling elements with diameters of 8mm is of higher quality and more suitable for ultrasonic rolling processing.

![Figure 9](image1.png)

**Figure 9.** radial distribution of residual stress on steel workpiece 45.

5. Simulation of different number of ball type rolling elements

5.1. Finite element model pretreatment

The 3D finite element model of ultrasonic rolling processing with a diameter of 8mm and a number of ball bearings of 1, 2 and 3 are shown in Figure 10 respectively. The contact definition, mesh division and application of loads and constraints are the same as those in the simulation of different types of rolling elements.

![Figure 10](image2.png)

**Figure 10.** Simplified finite element model of different number of ball type rolling elements

5.2. Post-processing of finite element model

After being processed by different Numbers of ball type rolling elements with a diameter of 8mm, the residual stress generated by 45 steel workpiece is shown in Figure 11, and the radial distribution of residual stress is shown in Figure 12.

![Figure 11](image3.png)

**Figure 11.** 45 residual stress nephogram of steel workpiece

As can be seen from Figure 11, the maximum residual stresses generated by the processing of 8mm ball rolling elements with a number of 1, 2 and 3 are 10.4MPa, 33.6MPa and 355.8MPa in turn. It can be seen from Figure 12 that the two ball type rolling elements with a diameter of 8mm are processed evenly, and the impact depth of machining is greater than that of one. The machining effect of three ball type rolling elements with a diameter of 8mm is uneven, the surface of the workpiece has both tensile stress and compressive stress, and there is a very serious stress concentration phenomenon. So number for type 1 and 2 of 8 mm diameter ball rolling components processing quality
is better, the diameter of the given number of 2 type 8 mm ball rolling element processing to produce the maximum residual stress is larger than the number of 1, so use quantity of 1 d = 8 mm diameter ball type rolling element processing and the quality of the workpiece to a higher, more suitable for ultrasonic rolling processing.

![Figure 12. Radial distribution of residual stress in 45 steel workpiece](image)

6. Conclusion

Based on the above research and analysis, the following conclusions can be drawn:

1) the ultrasonic rolling processing process of different types of rolling elements was simulated by ANSYS, and it was found that the maximum residual stress generated by the processing of ball-type rolling elements was the minimum, and the workpiece surface quality was also the best.

2) ANSYS Workbench software was used to simulate the ultrasonic rolling processing process of ball type rolling elements with different diameters, and the workpiece surface quality obtained by ultrasonic rolling processing of ball type rolling elements with a diameter of 8mm was the best.

3) ANSYS Workbench software was used to simulate the ultrasonic rolling processing process of ball type rolling elements with a diameter of 8mm. It was found that the surface quality of the workpiece obtained by ultrasonic rolling processing was the best when the number of ball type rolling elements with a diameter of 8mm was 1.

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