Study on Counter-Roller Spinning Technology of Large Diameter Aluminum Alloy Cylindrical Parts

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Abstract. Counter-roller spinning is an optimal process for forming large diameter cylindrical parts. In this paper, the finite element model of large diameter aluminum alloy cylindrical parts Counter-roller spinning is established, the regularities of distribution of stress and strain of each pass of the workpiece is obtained, as well as the influence of the roller feed ratio and fillet radius on the forming quality is obtained. The process parameters were optimized by grey correlation analysis. In this paper, for large diameter aluminum alloy cylindrical parts, the optimal spinning parameters are obtained as follows: the feed ratio is 1.0mm/r, the rotary roller fillet radius is 8mm. The results of numerical simulation are consistent with those of process test. The technological parameters can be used to guide the actual production of such large diameter cylindrical parts.

Keywords. Counter-roller spinning, cylindrical parts, finite element simulation, optimization of process parameters.

1. Introduction

Large-diameter thin-walled cylindrical parts are widely used in aerospace, weapons, nuclear industry, electronic copper foil and other industries, typical parts include missile engine shell, rocket storage tank shell, etc. [1-2]. With the development of aerospace technology, the demand for large-diameter thin-walled cylindrical parts is increasing in China, and the forming quality, manufacturing cost and processing cycle are required to be higher.

At present, large diameter cylindrical parts are mainly formed by welding and spinning [3-4]. The accuracy of welded cylindrical parts is low, and the overall performance of cylindrical parts is affected by the existence of welding [5]. The cylindrical parts with spinning have the advantages of small size tolerance, low workpiece surface roughness and high material utilization rate [6-7]. Spinning is divided into mandrel spinning and counter-roller spinning according to whether mandrel is used in forming [8]. Although the precision of mandrel spinning is very high, it is necessary to process the corresponding mandrel. If the diameter of the part is too large, the mandrel is difficult to be manufactured, difficult to be connected, and expensive to manufacture [9].

In foreign countries, the spinning method is mainly used for forming large diameter thin wall cylindrical parts [10]. Inter roller is used to replace the mandrel in the counter-roller spinning method,
so the manufacture of large mandrel is avoided and the difficult problem of the manufacture of mandrel in the mandrel spinning method is solved.

In this paper, a method of counter-roller spinning of large diameter cylindrical parts with inner and outer roller is presented. Firstly, the finite element simulation of spinning process was carried out to obtain the distribution law of stress and strain of workpiece in each pass and the influence of process parameters on forming quality. Secondly, the process parameters are optimized by grey correlation analysis. Finally, the numerical simulation results are verified by spinning process test. Compared with the traditional spinning forming method, counter-roller spinning has the characteristics of low mandrel cost and flexible processing, so it is more advantageous in forming large diameter cylindrical parts with small batch and many varieties. At present, there are few studies on counter-roller spinning. Gangfeng Xiao [11] realize the overall grain refinement along the thickness direction, and studied the distribution of equivalent strain based on upper bound method. Yaming Guo [12] adopted the counter-roller spinning method for large high-strength steel tubular parts, and analyzed the influence law of thinning rate, roller feed, roller angle and number of roller on radial spinning pressure. NND Zhang [13] established the finite element simulation model by using the method of numerical simulation and verified the spinning test of 720 mm cylindrical parts. C Zhu [14], through a combination of numerical simulation and experimental research, spinning the pulley by counter-roller spinning, and discussed the variation rule of pulley thickness, stress value and spin pressure. To sum up, the forming quality of the workpiece is difficult to guarantee due to the lack of mandrel constraints in the counter-roller spinning process. Therefore, it is of great significance to carry out detailed research on the counter-roller spinning process.

2. Counter-Roller Spinning Forming Method

Counter-roller spinning is a spinning method in which the inner roller replaces mandrel, and the inner and outer roller exert a certain forming force on the inner and outer surfaces of the workpiece respectively, so that the inner and outer layer produce plastic deformation at the same time. The principle of counter-roller spinning is shown in figure 1.

\[ r_0 \text{ and } R_0 \text{ are the inner and outer radius of the undeformed zone respectively; } r_1 \text{ and } R_1 \text{ are the inner and outer radius of the deformed zone respectively.} \]

Technical characteristics of counter-roller spinning method:

Figure 1. Counter-roller spinning diagram.
- Counter-roller spinning does not need to use the mandrel, Counter-roller spinning can spinning the workpiece of different sizes by changing the radial position of the inner and outer roller, reducing the cost of the mandrel greatly;
- The internal stress state and metal accumulation of the workpiece are improved significantly because of the deformation symmetry of the counter-roller spinning;
- Under the condition of the same material and thinning amount of workpiece, the spinning force is only half of using mandrel spinning;
- In counter-roller spinning, the spinning passes reduce, the variation rate and total variation rate are very high, which improves the production efficiency;
- Therefore, this paper adopts the forming method of counter-roller spinning for large diameter aluminum alloy cylindrical parts.

3. Finite Element Simulation Analysis Of Counter-Roller Spinning

3.1. The Establishment of Simulation Model

The software Simufact. forming was used to establish a three-dimensional finite element model for spinning. In the simulation process, the roller is defined as a rigid body, and the blank variable body is divided networks by Ringmesh. The finite element model and blank mesh model of counter-roller spinning are shown in figure 2 respectively.

![Finite element model and blank mesh model](image)

The blank material is aluminum alloy 2A12, inner diameter is 556mm, outer diameter is 640 mm, length is 450mm. The constitutive relation of this material is referred to reference [15]. The blank and the spindle are set as active "bonding"; The spindle is defined as active rotation; Roller is defined as local coordinate and rotation axis; Coulomb - shear friction model is used, the Coulomb friction coefficient is 0.1, and the shear friction coefficient is 0.1.

The numerical simulation process parameters of counter-roller spinning are shown in table 1.

| Rolling reduction (mm) | Pass 1 | Pass 2 | Pass 3 | Pass 4 | Pass 5 |
|------------------------|-------|-------|-------|-------|-------|
| Pass reduction ratio (%)| 8.5 | 7.5 | 6.0 | 5.0 | 4.0 |
| Fillet radius of roller (mm) | 6–12 |
| Feed ratio (mm/r) | 0.6–1.4 |
| Spindle speed (rpm) | 50 |
| Spinning temperature (°C) | 200-230°C |
3.2. Stress and Strain Distribution Law of Workpiece in Each Pass

In the spinning process, the equivalent stress distribution of each pass on the outer surface is shown in figure 3.

![Equivalent stress distribution of each pass](image)

*Figure 3. Equivalent stress distribution of each pass.*

Shown in figure 3, the equivalent stress is generally distributed in layers along the axial direction, and the values in the circumferential direction of the same layer are basically equal. The maximum stress occurs at the contact position between the roller and the blank at the end of spinning. Due to the lack of constraints, the actual diameter of the workpiece after spinning is larger than the theoretical value, the diameter will be expansion.

Figure 4 shows the strain distribution diagram of the outer surface of the spinning workpiece at each pass. We can be seen from the figure, the equivalent strain at the distal of the blank is relatively minimum. The outer surface of the first three passes is continuously fed by the roller, and the maximum area of equivalent strain is constantly expanding, covering the whole spinning process. Among them, the equivalent strain value of the second pass is the largest. It shows that the roller has more downward pressure at second pass. However, the maximum equivalent stress of the fourth and fifth passes occurs at the position where the blank is in contact with the roller. It can be seen from the equivalent strain value of the outer surface of the blank that the amount of downward pressure is smaller than the first three passes.
3.3. Influence of Roller Feed Ratio on Forming Quality

Higher feed ratio will produce higher pressure and lead to cracks, while lower feed ratio will lead to excessive metal regurgitation and excessive metal thinning [16-17].

Different feed ratios were used for simulation analysis, and the change curves of equivalent stress and ovality in spinning process were obtained. As shown in Figure 5 (a), in the range of 0.6-1.0 mm/r, the feed ratio and equivalent stress tended to be roughly inversely proportional. In the range of 1.0-1.4 mm/r, the feed ratio and equivalent stress tend to be directly proportional. 1.0 mm/r is the inflection point of the equivalent stress curve. As shown in Figure 5 (b), with the increase of feed ratio, the ovality curve decreases. When the feed ratio increased in the range of 1.0 mm/r to 1.2 mm/r, the ovality curve changed gently. The smaller the maximum ovality is, the higher the accuracy of the workpiece. The smaller the maximum equivalent stress, the workpiece and equipment will be better force.

![Figure 4. Equivalent stress distribution of each pass.](image)

![Figure 5. Influence of different feed ratio.](image)
When the fillet radius is larger, the surface roughness of the workpiece can be improved, and the roller feed speed can be increased, but the spinning pressure will be increase, will be instability phenomenon. When the fillet radius is too small, the fillet part will "bite" into the blank. Rough, dropping crumbs, scaling and snapping will appear [18-19].

Different roller fillet radius were used for simulation analysis, and the change curves of equivalent stress and ovality in spinning process were obtained. As shown in figure 6 (a). The roller fillet radius and equivalent stress tended to be roughly inversely proportional. When the roller fillet radius was 12mm, the equivalent stress generated in the spinning process was minimum. As shown in figure 6 (b), the roller fillet radius and ovality tend to be directly proportional. The larger the fillet radius, the smaller the equivalent stress and the larger the ovality of the workpiece.

![Figure 6](image_url)

(a) Equivalent stress  (b) Ovality

**Figure 6.** Influence of different roller fillet radius.

### 4. Optimization Design of Counter-Roller Spinning Process Parameters

Grey correlation analysis can quantitatively describe the correlation degree of each process parameter, and can characterize the main factors that affect the system and the difference of the influence of each process parameter on the system [20]. According to the results of the finite element numerical simulation of roller, the process parameters of feed ratio and roller fillet radius were optimized by using the grey correlation analysis method.

Single factor analysis method was used in numerical simulation, only single variable was changed, and other technological parameters remained unchanged. The numerical simulation results of changing roller feed ratio are shown in table 2, and the numerical simulation results of changing roller fillet radius are shown in table 3.

![Table 2](image_url)

**Table 2.** Numerical simulation results of feed ratio.

| Feed ratio /mm/r | Equivalent stress /MPa | Ovality /mm |
|------------------|-------------------------|-------------|
| 1                | 0.6                     | 187.84      | 0.591       |
| 2                | 0.8                     | 185.97      | 0.541       |
| 3                | 1.0                     | 181.18      | 0.484       |
| 4                | 1.2                     | 190.85      | 0.466       |
| 5                | 1.4                     | 210.59      | 0.359       |

![Table 3](image_url)

**Table 3.** Numerical simulation results of fillet radius.

| Feed ratio /mm/r | Equivalent stress /MPa | Ovality /mm |
|------------------|-------------------------|-------------|
| 1                | 6                       | 190.67      | 0.421       |
| 2                | 8                       | 181.41      | 0.484       |
| 3                | 10                      | 181.78      | 0.578       |
| 4                | 12                      | 180.22      | 0.612       |
| 5                | 14                      | 190.59      | 0.591       |
4.1. Data Sequence Normalization Processing

The medium equivalent stress and ovality data of the evaluation indexes were taken as the comparison data series to be analysed, and make a dimensionless normalization, the calculation formula is as follows:

\[
y_i(j) = \frac{x_i(k) - \min_k x_i(k)}{\max_k x_i(k) - \min_k x_i(k)}
\]

\(i = 1, 2, k = 1, 2, ..., 16\)

In the formula (1), \(x_i(k)\) is the value of kth test under the ith index, and \(y_i(k)\) is the normalized result value of the kth test under the ith index.

The results of comparison data series after dimensionless normalization are shown in table 4 and table 5.

| Feed ratio/mm/r | Equivalent stress/MPa | Ovality/mm | Feed ratio/mm/r | Equivalent stress/MPa | Ovality/mm |
|-----------------|-----------------------|------------|-----------------|-----------------------|------------|
| 1               | 0.6                   | 6.66       | 1               | 6                     | 11.45      |
| 2               | 0.8                   | 4.79       | 2               | 8                     | 2.19       |
| 3               | 1.0                   | 0          | 3               | 10                    | 2.56       |
| 4               | 1.2                   | 9.67       | 4               | 12                    | 1          |
| 5               | 1.4                   | 29.41      |                 |                       | 0          |

4.2. Evaluate Grey Correlation Coefficient and Grey Correlation Degree

The calculation formula of grey correlation coefficient is as follows:

\[
\xi_i(k) = \frac{\min_k |y_0(k) - y_i(k)| + \xi \max_k |y_0(k) - y_i(k)|}{|y_0(k) - y_i(k)| + \xi \max_k |y_0(k) - y_i(k)|}
\]

\(\xi\) is the resolution coefficient.

The calculation formula of grey correlation degree \(\gamma_k\) is:

\[
\gamma_k = \frac{1}{m} \sum_{i=1}^{m} \xi_i(k)
\]

In this paper, take distinguish coefficient \(\xi = 0.9\). According to the actual working condition, under the condition that the equipment capacity allows, the forming quality is finally evaluated by the dimensional accuracy of the workpiece. So the equivalent stress and ovality the two weights of evaluation indexes on the a1, α2, carried out in accordance with the importance weights allocation, selection of evaluation index weight ratio for: \(\alpha_1 = 0.2\), \(\alpha_2 = 0.8\). According to the above weight ratio, the grey correlation coefficient and grey correlation degree of the feed ratio and fillet radius were respectively calculated, as shown in table 6 and table 7.
Table 6. Grey correlation coefficient and grey correlation degree of feed ratio.

| Grey correlation coefficient | Grey correlation degree |
|-----------------------------|-------------------------|
| Equivalent stress | Ovality | 0.11905 | 0.79505 | 0.29613 |
| 1 | | 0.15817 | 0.83179 | 0.31485 |
| 2 | | 1.0 | 0.87805 | 0.45732 |
| 3 | | 0.08515 | 0.89374 | 0.32558 |
| 4 | | 0.02969 | 1 | 0.35445 |

Table 7. Grey correlation coefficient and grey correlation degree of fillet radius.

| Grey correlation coefficient | Grey correlation degree |
|-----------------------------|-------------------------|
| Equivalent stress | Fillet radius | 0.07287 | 1 | 0.36093 |
| 1 | | 0.29126 | 0.93458 | 0.37079 |
| 2 | | 0.26012 | 0.85147 | 0.33703 |
| 3 | | 0.47368 | 0.82493 | 0.35978 |

According to table 6 and table 7, the spinning process parameter with the highest grey correlation degree is the optimal process parameter. The optimal process parameters are as follows: the roller feed ratio is 1.0 mm/r, and the roller fillet radius is 8 mm.

5. Process Test of Counter-Roller Spinning

5.1. Test Tooling and Blank

In this test, an inter and outer roller is used to spin the parts. The test equipment and blank are shown in figure 7. The inner diameter of the blank is 556 mm, the outer diameter is 640 mm, and the length is 450 mm. The diameter of the inner roller is 360 mm, the diameter of the outer roller is 400 mm, the fillet radius of the inner and outer rollers are 8 mm, and the working angle and exit angle are 20°.

![Test equipment and blank](image)

Figure 7. Test equipment and blank.

5.2. Test Results and Analysis

According to numerical simulation and optimization design of process parameters, the final selection of process parameters as follows, feed ratio is 1.0 mm/r, and speed is 50 r/min. The simulation results of counter-roller spinning process are shown in figure 8.
In this paper, using propane-oxygen heating, the spinning temperature is controlled at 200–230℃, through the infrared thermometer to detect the temperature, adjust the flame distance and flame size to ensure stable spinning temperature. The process of the counter-roller spinning is shown in figure 9, and the spinning workpiece is shown in figure 10.

**Figure 8.** Simulation results of counter-roller spinning process.

**Figure 9.** Process of counter-roller spinning.

**Figure 10.** Spinning workpiece.

**6. Conclusion**
In this paper, using the finite element simulation method, the finite element model of large diameter aluminum alloy cylindrical part counter-roller spinning is established. The distribution law of stress and strain of workpiece in each pass is obtained: The equivalent stress and equivalent strain are generally distributed in layers along the axial direction, and the distal of workpiece is the most dangerous section in the spinning process, which will produce the phenomenon of diameter expansion;
In this paper, by the finite element simulation method, the finite element model of large diameter aluminum alloy cylindrical part counter-roller spinning is established. The distribution law of stress and strain of workpiece in each pass is obtained: The equivalent stress and equivalent strain are generally distributed in layers along the axial direction, and the distal of workpiece is the most dangerous section in the spinning process, which will produce the phenomenon of diameter expansion;

Through the finite element simulation, the influence of the feed ratio and fillet radius on the forming quality was obtained, and the grey correlation analysis method was used to optimize the design of the feed ratio and fillet radius in the spinning process of the counter-roller spinning. The optimal process parameters were obtained as follows: the roller feed ratio is 1.0 mm/r, and the roller fillet radius is 8 mm;

Spinning process test of large diameter aluminum alloy cylindrical parts was carried out. The workpiece obtained from the test achieved the expected results, which proved that the process parameters obtained from the finite element model of counter-roller spinning can be used to guide the actual production of this kind of large diameter cylindrical parts.

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