Study of dieless radial spinning for thick-walled cylindrical parts with external grooves

Famei Liu 1 · Junsong Jin 1 · Wei Rao 1 · Ying Wang 1 · Chang Gao 1 · Xuefeng Tang 1 · Xinyun Wang 1

Received: 5 March 2021 / Accepted: 4 July 2021 / Published online: 5 August 2021
© The Author(s), under exclusive licence to Springer-Verlag London Ltd., part of Springer Nature 2021

Abstract
Thick-walled cylindrical parts with external grooves are widely used in the automobile and aviation fields. Traditional processes for fabricating such components can’t meet the requirements of properties and efficiency. The dieless radial spinning process was proposed to produce the thick-walled cylindrical parts with external grooves. The forming characteristics of the spinning process and the effects of various process parameters on forming were studied by using orthogonal tests and finite element simulations. During the forming process, bulge and thinning occur because of material flow. Parameter study shows that the load-yield ratio ($\xi$) has no significant effect on forming quality. However, the feed-thickness ratio ($\eta$) and initial wall thickness of the tube ($t_0$) play a crucial role in the forming quality (e.g., the heights of bulges and thickness reduction in the groove area). Different thicknesses differ the forming quality because of various flexural capacities. The inner surface quality of the grooves is governed by the initial wall thickness. The processing window was defined to recommend suitable parameters for eligible parts.

Keywords Thick-walled · Dieless · Spinning · Orthogonal test · Finite element · Aluminum alloy

1 Introduction

The spinning forming process is a local forming method for producing hollow part, which is widely used in the aviation, aerospace, military, and automobile industries [1, 2]. As an advanced forming process, the spinning process has several significant merits [3]. Less load and energy are acquired for spinning process since the material is locally deformed. The production efficiency is much higher than traditional processes, because fewer working steps are acquired. Besides, it costs fewer metals because of high material utilization. Thus, the spinning process is a kind of green manufacturing technology. Spinning processes are mainly classified as conventional spinning, shear spinning, and tube spinning [3]. Tube spinning (i.e., flow forming) is a popular process for producing cylindrical tubular components [4, 5]. On the basis of the tube deformation characteristics, tube spinning can be divided into thickness-reducing spinning and diameter-reducing spinning. The diameter-reducing spinning process has been frequently reported and is widely used.

Huang et al. [6] used simulations and experiments to illustrate neck-spinning at the tube ends, which released the effects of friction, speed, and the tip radius of the rollers on forming. Zoghi et al. [7] investigated deformation behavior during neck-spinning at the tube ends by analyzing the strain distributions in different layers and axial positions. Xia et al. [8, 9] studied the stress and strain distributions and the dimensional accuracy in different passes and examined the defects that can occur during neck-spinning at the tube ends of non-axisymmetric offset tubes. Arai [10] proposed a three-dimensional CAD model for calculating the positions at which the roller touches the tube during neck-spinning at the tube ends of a non-axisymmetric offset tube. Yao and Murata [11] performed experiments on paraxial spinning at one end and identified the forming characteristics.
These processes mentioned above are to reduce the radius of the tube end. Some products, including corrugated pipes, exhaust pipes, and pulleys, require changes in the radius at the middle of the tube. Kwiatkowski et al. [12] used analytical models to develop dieless neck-spinning at the middle of a tube with two principal tool movements. Guo et al. and Yao and Murata [13, 14] used a paraxial spinning process to prepare a reducer tube and studied the plastic rheology and microstructural evolution of the workpiece. Grzancic et al. [15] manufactured tubes with various cross-sectional geometries by controlling the tool movements and established an analytical model for predicting forming behavior. Zhu et al. [16] compared four typical spinning methods for producing large sheaves and concluded that counter-roller spinning is the best option.

Above proposed spinning processes are capable of reducing the radius of a thin-walled tube. However, none of them involved thick-walled tubes. In general, when outer diameter-to-thickness ratio is less than 20, the tube can be considered thick-walled [17]. The spinning process for the thin-walled tube belongs to sheet forming, while the spinning process for thick-walled tube is bulk forming. Thus, it is valuable to research the thick-walled tubes by spinning process since the metal flow during neck-spinning varies with changes in the tube thickness.

Thick-walled cylindrical parts with annular grooves (e.g., pistons) are widely used in hydraulic and pneumatic transmission systems. These parts are cup-shaped and have annular grooves on the outer surface for O-ring seals. To ensure groove strength, the traditional manufacturing method usually machines the annular groove at the outer surface of a cup with a much thicker wall than that of the groove. The material utilization and production efficiency in this traditional method are low. The performance of the part is poor because the integrity of the material flow line is destroyed. The traditional method also increases the weight of the part, which is contrary to the principle of producing lightweight components. If the spinning method is used, the outer groove can be formed from a cup blank of constant thickness. The comparison of material utilization rate between traditional method and spinning process is shown in Fig. 1, where \( t_g \) is the thickness of groove required. \( t_{0s} \) and \( t_{0t} \) refer to the initial wall thickness of blank by spinning and traditional methods, respectively. Obviously, \( t_{0t} \) is much larger than \( t_{0s} \). Compared with the traditional method, the spinning process has obvious merits, such as high production efficiency, high material utilization, a continuous metal streamline, good mechanical properties, and light weight.

The two-wheel dieless radial spinning process (DRSP) was proposed for the production of thick-walled cylindrical parts with external grooves. Orthogonal tests and finite element (FE) simulations were used to investigate the deformation characteristics, stress and strain distributions, and effects of various parameters on the forming quality.

2 Materials and method

2.1 Dieless radial spinning process (DRSP)

The principle of the DRSP is shown in Fig. 2a. First, the upper die presses the cup blank on the lower die with a circular groove at a certain pressure \( F_Z \); the three components are coaxial. The upper and lower dies then rotate at an angular velocity \( \omega \), which drives the blank to rotate at the same velocity. At the same time, two rollers, which are symmetrically distributed on both sides of the blank, feed synchronously toward the blank axis at a speed \( v \). When the rollers contact the outer surface of the blank, they passively rotate along the opposite direction with respect to the blank. With progressive feeding of the rollers, the material in the contact area of the blank and the roller is plastically deformed, and an external groove is generated. The rollers stay for a certain time to finish the groove when they feed to the maximum depth, and then the rollers return to the initial position.

Since plastic deformation is mainly concentrated near the groove, the effect of the cup bottom on the forming process can be ignored. To reduce the difficulty of making blanks, the experimental blanks were simplified into bottomless cylindrical parts, as shown in Fig. 2b. The lower die was correspondingly designed as an annular groove consistent with the upper die.

2.2 Materials

The blanks are 6061-T6 aluminum alloy tubes. The initial blank has a height of 80 mm, inner diameter of 30 mm, and
wall thickness of 8 mm. Blanks with other specifications were produced by turning. The mechanical properties and true stress–strain curve of the blanks are shown in Table 1 and Fig. 3, respectively. The strain rates of 0.1 s$^{-1}$, 1 s$^{-1}$, and 10 s$^{-1}$ were selected since the strain rate was lower than 10 s$^{-1}$ during the process according to the simulation result. The samples of compression test were cut from the tubes along radial direction since the major deformation mode during the spinning process is compression in the radial direction, which is shown in the subgraph inside Fig. 3.

2.3 Experimental equipment and mold

The equipment used in the experiments in this study was the PS-CNCVGP450 vertical CNC spinning machine (Fig. 4). The rotational speed of the spindle and movement of the rollers in the X, Y, and Z directions are controlled by the CNC system, whose control accuracy is 0.01 mm. The pressure of the upper die is controlled by a hydraulic valve. The maximum diameter of the roller is 180 mm, the thickness is 10 mm, and the side is a semicircle of radius 5 mm. The rotational speed of the dies and blanks during the spinning process was set to a constant of 240 r/min.

2.4 Finite element (FE) simulation

In studies of spinning processes, FE simulation is an efficient method for understanding the deformation characteristics of plastic forming processes and defect prediction [18–21]. The FE software Simufact.forming was used for DRSP simulations. The simulation results together with experimental results were adopted to analyze and explain the deformation characteristics and parameter effects. The FE model of DRSP is shown in Fig. 5.

The key dimensions of the molds and the blank, the testing material, and all the spinning parameters used in the simulations were consistent with those in the experiments. The upper die, lower die, and rollers were set as rigid bodies. The blank was divided by hexahedral elements via the ring-meshing method. The initial element dimensions were 1.2 mm in the axial and radial directions and 12 mm in the tangential direction. The areas above and below the center face of the blank for 10 mm in the axial direction were locally refined by a refinement box to improve the simulation accuracy. The dimensions of refined element were 0.6 mm in the axial and radial directions and 6 mm in the tangential direction. The re-meshing technique was used during the simulation to avoid element distortion resulting from severe deformation.

### Table 1 Main mechanical properties of 6061-T6 aluminum alloy

| Property          | Value        |
|-------------------|--------------|
| Saturation stress | 343 MPa      |
| Yield stress      | 270 MPa      |
| Density           | 2900 kg/m$^3$|
| Young’s modulus   | 68.9 GPa     |
| Poisson’s ratio   | 0.33         |
The contacts between the blank and the upper and lower dies were set to be “glued,” which means that there was no relative displacement between the contact bodies. The contacts between the blank and the rollers were set to be “touching,” which means a relative movement between the contact bodies was allowable. The shear friction model was adopted, and the friction coefficient was 0.1, which was determined by the ring compression test used by Liu et al. [22]. The shear friction model is described by the formulation as follows:

\[ \tau_R = a \cdot k \quad \text{with} \quad k = 0.577 \cdot \sigma_V \]  

(1)

where \( \tau_R \) refers to friction stress, \( a \) refers to shear friction coefficient, \( k \) refers to ultimate shear strength, and \( \sigma_V \) is field strength.

During the forming process, the temperatures of the blank, the molds, and the environment were all set to 20 °C. The effect of the deformation temperature was not considered.

2.5 Orthogonal tests

Changing the pressure \( F_Z \) of the upper die changes the axial stress on the blank. An excessive \( F_Z \) causes the blank to collapse, and the blank will slide because of the small frictional force when \( F_Z \) is too small. The effect of \( F_Z \) is related to the strength of the blank; therefore the load-yield ratio \( \xi \) (the ratio of the applied stress to the yield stress) is investigated and defined as

\[ \xi = \frac{F_Z}{(A_S \cdot \sigma_S)} \]  

(2)

where \( A_S \) is the cross-sectional area of the blank and \( \sigma_S \) is the yield stress of the blank.

The material flow during spinning is mainly affected by the initial blank thickness \( t_0 \). The material flow is similar to sheet-metal forming when \( t_0 \) is small but resembles volume forming when \( t_0 \) is large. The value of \( t_0 \) directly affects the resistance during the feeding of the rollers. Experimental results show that the feeding distance per revolution, \( m \) (unit is mm/r), is an important parameter in the spinning process. The resistance in the tangential direction of the roller increases with the
increasing \( m \), which affects the stability of the experiment. If \( m \) is too small, the outer surface of the groove will be peeled because of repeated grinding over a long period. To exclude the effect of \( t_0 \), the feed-thickness ratio \( \eta \) (the ratio of the feeding distance per round of the roller to the tube wall thickness) defined as Eq. (3) was investigated.

\[
\eta = \frac{m}{t_0} \tag{3}
\]

It can be seen from the pre-experiment that when \( 0.05 < \xi < 0.3 \), the blank will not collapse or slide during the forming process. According to the pre-simulation, when \( \eta > 0.3 \), the impact of \( \eta \) on the forming quality is small. Figure 13 also supports the conclusion, which shows that the effect of \( \eta \) on strain distribution decreases with the increase of \( \eta \). Particularly, the effective strains are nearly consistent when \( \eta = 0.2 \) and \( 0.3 \). The wall thickness of the common piston is less than 10 mm, so \( t_0 < 10 \) mm. The values of the parameters are shown in Table 2.

SPSS software and the data in Table 2 were used to produce the \( L_{16}(4^3) \) orthogonal test table shown in Table 3.

### 3 Results and discussion

#### 3.1 Typical forming process

Figure 6 shows a typical material deformation during the DRSP. The material of the blank in the contact area is compressed in the radial and tangential directions and flows along the two sides of the groove along the axial direction after the blank is in contact with the rollers. The flow distance in the radial direction of the material near the inner surface of the groove is smaller than that of the material near the outer surface. A wall thickness reduction is therefore observed as the rollers feeding in the radial direction. A little proportion of material flows along the arc surface of the roller, and two bulges are formed near the upper and lower faces of the roller. At the same time, the tube height increases. Throughout the entire forming process, the strains on the upper and lower straight walls of the tube are always zero. The strain in the deformation area increases gradually, and the strain on the outer surface contacting the roller is highest. The strain decreases gradually from the outer to the inner surface, and the overall strain increases with roller feeding.

#### 3.2 Comparison of results obtained by simulations and experiments

Figure 7 shows a comparison of the tubes obtained via simulations and experiments of tests no. 4 and no. 8 in Table 3. The profile of the simulated tube is in good agreement with the longitudinal section obtained by experiments. Figure 8 shows comparison curves for the thicknesses of the grooves obtained in tests no. 4 and no. 8 via simulations and experiments. The measurement position is on the arbitrary longitudinal section along the diameter direction. Under the two sets of conditions, the thickness distributions obtained by simulations and experiments are similar. The thickness of the grooves is less than \( t_0 \), indicating the thickness reduction occurs.

#### 3.3 Orthogonal test results

The shape parameters of the blank were taken as the quantitative evaluation indexes in orthogonal tests. The forming quality indicators were the bulge height (the upper bulge height \( h_u \) and lower bulge height \( h_l \)) on the outer surface, the groove thinning ratio of groove \( n \), and the tube height \( h \). The bulge height and thinning ratio were defined as follows:

\[
h_u = \frac{(d_u - d_0)}{2} \tag{4}
\]

\[
h_l = \frac{(d_l - d_0)}{2} \tag{5}
\]

\[
n = \left(1 - \frac{t}{t_0}\right) \times 100\% \tag{6}
\]

where \( d_0 \) and \( t_0 \) are the initial outer diameter and wall thickness of the blank, respectively; \( h \) is the tube height; \( d_u \) and \( d_l \) are the initial inner and outer diameter of the tube, respectively; \( t \) is the thickness of the groove.
and $d_i$ are the outer diameter of the upper and lower bulges, respectively; and $t$ is the wall thickness at the groove center. The parameters are shown in Fig. 9. All the parameters are measured on the arbitrary longitudinal section along the

**Fig. 6** Typical forming process of DRSP ($\xi = 0.06$, $\eta = 0.02$, $t_0 = 8$ mm)

**Fig. 7** Comparison of shapes obtained by experiments and simulations

**Tube from No. 4 test**
$\xi = 0.06$, $\eta = 0.3$, $t_0 = 4$ mm

**Tube from No. 8 test**
$\xi = 0.14$, $\eta = 0.3$, $t_0 = 8$ mm
diameter direction. A spinning part with good forming quality requires small absolute values of \( h, h_u, h_l, \) and \( n \).

The orthogonal experimental results are shown in Table 4. The data were analyzed by using SPSS, range analysis, and analysis of variance (ANOVA).

The results of range analysis of the experimental data in Table 4 are shown in Table 5. More details of the range analysis are given in Appendix 1. The trends in the effects of the process parameters \( \xi, \eta, \) and \( t_0 \) on the measurement indexes \( h, h_u, h_l, \) and \( n \) are shown in Fig. 10.

Table 5 and Fig. 10 show that the order of the effects of the parameters on \( h \) is \( \xi > \eta > t_0 \). The value of \( h \) decreases with increasing \( \xi \) and \( \eta \) and with decreasing \( t_0 \).

The order of the effects of the parameters on \( h_u \) and \( h_l \) is \( t_0 > \eta > \xi \). With increasing \( \xi \), \( h_u \) and \( h_l \) fluctuate within a small range. Increases in \( \eta \) and decreases in \( t_0 \) caused decreases in \( h_u \) and \( h_l \).

The order of the effects of the parameters on \( n \) is \( t_0 > \eta > \xi \). The value of \( n \) decreases with increasing \( \xi \) and \( \eta \) and decreases with decreasing \( t_0 \).

The analysis of variance (ANOVA) results for the experimental data in Table 3 are shown in Table 6. More details of the ANOVA process are given in Appendix 2.

The data in Table 6 show that \( \xi, \eta, \) and \( t_0 \) have no significant effects on \( h \). The values of \( h_u, h_l, \) and \( n \) are significantly affected by \( t_0 \) and \( \eta \), but \( \xi \) had no significant effects.

### Table 4: Experimental orthogonal test data

| Series | \( h \) (mm) | \( h_u \) (mm) | \( h_l \) (mm) | \( t \) (mm) | \( n \) |
|--------|-------------|-------------|-------------|------------|------|
| 1      | 84.2        | 1.5         | 2.2         | 5          | 37.5%|
| 2      | 82.3        | −0.5        | −0.4        | /*         | /    |
| 3      | 81.45       | 0.6         | 0.6         | 5.2        | 13.3%|
| 4      | 81.15       | −0.2        | −0.2        | 3.7        | 7.5% |
| 5      | /           | /           | /           | /          |      |
| 6      | 81.2        | 0.9         | 1.1         | 4.8        | 20%  |
| 7      | 81.25       | −0.1        | 0           | 3.7        | 7.5% |
| 8      | 80.75       | 1.1         | 1.1         | 7.3        | 8.8% |
| 9      | 82.2        | 1.5         | 2           | 4.1        | 31.7%|
| 10     | 80.7        | 0.4         | 0.4         | 3.5        | 12.5%|
| 11     | 81.25       | 1.1         | 1.1         | 7.1        | 11.3%|
| 12     | 79.95       | −0.7        | −0.7        | 2.1        | −5%  |
| 13     | 80.5        | 1.5         | 1.5         | 3.4        | 15%  |
| 14     | 81.4        | 1.3         | 1.5         | 6.4        | 20%  |
| 15     | 79.75       | −0.6        | −0.6        | 2.1        | −5%  |
| 16     | 80.85       | 0.45        | 0.5         | 5.6        | 6.7% |

*The symbol “/*” indicates that the data cannot be obtained because of fracture or breakage at the groove.
Figure 10 shows that each process parameter has a certain influence on $h$, but the ANOVA results show that the effects are not significant.

| Table 5 Range analysis results |
|---|
| Parameters | Indexes | $k_1$ | $k_2$ | $k_3$ | $k_4$ | $R$ |
| $\xi$ | $h$ | 82.28 | 81.07 | 81.03 | 80.63 | 1.65 |
| $h_u$ | 0.35 | 0.63 | 0.58 | 0.66 | 0.31 |
| $h_l$ | 0.55 | 0.73 | 0.7 | 0.73 | 0.18 |
| $n$ | 19.4 | 12.1 | 12.6 | 9.2 | 10.2 |
| $\eta$ | $h$ | 82.3 | 81.4 | 80.93 | 80.68 | 1.62 |
| $h_u$ | 1.5 | 0.53 | 0.25 | 0.16 | 1.34 |
| $h_l$ | 1.9 | 0.65 | 0.28 | 0.18 | 1.72 |
| $n$ | 28.1 | 17.5 | 6.8 | 4.5 | 23.6 |

| Table 6 Analysis of variance |
|---|
| Indexes | Parameters | $S$ | $f$ | $M$ | $F$ | Significance |
| $h$ | $\xi$ | 3.107 | 3 | 1.036 | 1.833 | No significance |
| $\eta$ | 3.132 | 3 | 1.044 | 1.848 | No significance |
| $t_0$ | 2.647 | 3 | 0.882 | 1.562 | No significance |
| Error | 2.260 | 4 | 0.565 |
| $h_u$ | $\xi$ | 0.197 | 3 | 0.066 | 0.791 | No significance |
| $\eta$ | 1.734 | 3 | 0.578 | 6.953 | Significance |
| $t_0$ | 3.4 | 3 | 1.133 | 13.632 | Significance |
| Error | 0.333 | 4 | 0.083 |
| $h_l$ | $\xi$ | 0.059 | 3 | 0.020 | 1.81 | No significance |
| $\eta$ | 3.476 | 3 | 1.159 | 107.459 | Significance |
| $t_0$ | 3.984 | 3 | 1.328 | 123.169 | Significance |
| Error | 0.043 | 4 | 0.011 |
| $n$ | $\xi$ | 0.011 | 3 | 0.004 | 2.730 | No significance |
| $\eta$ | 0.073 | 3 | 0.024 | 18.924 | Significance |
| $t_0$ | 0.032 | 3 | 0.011 | 8.33 | Significance |
| Error | 0.005 | 4 | 0.001 |

$F_{0.05}(3, 4) = 6.59$ (critical value obtained by looking up $F$ distribution table)

Fig. 10 Effects of process parameters on measurement indexes (a) tube height, (b) upper bulge height, (c) lower bulge height, (d) thinning ratio according to range analysis
3.4 Effects of process parameters on forming quality

According to the results via experiments and simulations, two phenomena—bulge formation and thickness reduction—affect the forming quality of the spinning parts. The $h_u$, $h_l$, $n$, and $h$ values are important indexes in the evaluation of the forming quality. The effects of the process parameters on these indexes were therefore investigated.

3.4.1 Thickness reduction at groove

Feeding in the radial direction of the rollers leads to a bending of the wall of the deformation area, and a groove is formed. The wall of the groove may be thinned because of material flow.

The experimental results show that thickening at the groove was observed under certain sets of parameters (tests no. 12 and no. 15 in Table 4). According to Fig. 10b and c, under small $t_0$ and large $\eta$, bulge formation is restrained, and an even concavity is formed. However, the thinning ratio is declined. This means more material flows to the middle of the groove, which can lead to thickening.

Figure 11 shows the strain distributions during the forming process in the deformation area for the same $t_0$ and $\xi$, but different $\eta$. The strain at the outer surface of the deformation area is significantly larger, and $n$ is larger for the tube with $\eta = 0.02$ than that with $\eta = 0.3$. This is consistent with the finding that $n$ decreased with increasing $\eta$, as shown in Fig. 10d.

Figure 12 shows the strain distributions at the middle of the groove from outside to inside for different $\eta$ values when $\xi = 0.14$ and $t_0 = 8$ mm. From the outer surface to the inner surface, the effective plastic strain first decreases and then remains stable. The strain near the outer surface of the groove increases with decreasing $\eta$, but the strain near the inner surface does not noticeably change.

The outer surface of the blank suffers from friction and rolling of the rollers; therefore the strain there is large. There is no direct contact between the inner surface and the rollers; therefore the strain decreases from outside to inside. The forming time is longer for a smaller $\eta$, and the time of interaction between the rollers and the blank outer surface is longer, which leads to increased strain. The strain changes little with changes in $\eta$ because the impact of the rollers’ action is small near the inner surface.

A larger difference between the strain values at the inner and outer surfaces in the groove means more uneven deformation between the internal and external material, indicating that more material flows to the area outside the groove, which leads to a smaller wall thickness of the groove and larger $n$. Consequently, a smaller $\eta$ will produce a larger $n$. Figure 13 shows that the grooves of the tubes obtained by experiments in tests no. 2 and no. 5 are cracked or even broken. On the one
hand, the smaller $\eta$ leads to a larger $n$, and the initial wall thicknesses of the both cases are small, which increases the possibility of break. On the other hand, a number of repeated bending back because of the thin tubes when $\eta$ is small promote the crack and break.

Figure 14 shows the axial profiles of tubes obtained by experiments with $\eta = 0.02$ and $t_0 = 4, 8$ mm. The $n$ of the tube with $t_0 = 4$ mm and 8 mm is 15% and 37.5%, respectively.

Figure 15 shows an axial profile schematic diagram of the DRSP. It is assumed that the thickness of the groove is uniform. $r_0$ is the inner diameter of the blank, $R_r$ is the rim radius of the roller, and $t$ is the wall thickness of the groove.

The average axial strain of the groove can be calculated from the arc length $l$ and the initial length $l_0$ because the
change in $h$ was small and can be ignored, according to the experimental results:

$$\varepsilon_z = \ln \left( \frac{1}{t_0} \right) = \ln \left( \frac{\pi R_r}{2R_r} \right) = \ln \left( \frac{\pi}{2} \right)$$  \hspace{1cm} (11)

The circumferential strain can be calculated as the natural logarithm of the circumference ratio:

$$\varepsilon_\theta = \ln \left( \frac{2(r_0 + t_0 - R_r)}{2(r_0 + t_0)} \right) = \ln \left( \frac{r_0 + t_0 - R_r}{r_0 + t_0} \right)$$  \hspace{1cm} (12)

According to the principle of volume invariance, the radial strain can be expressed as

$$\varepsilon_r = \varepsilon_x + \varepsilon_\theta = \ln \left( \frac{2}{\pi} \left( 1 + \frac{R_r}{r_0 + t_0 - R_r} \right) \right)$$  \hspace{1cm} (13)

The radial strain is the natural logarithm of the wall thickness ratio. From Eq. (13), the ratio of the wall thickness of the groove to the initial wall thickness can be expressed as

$$\frac{t}{t_0} = \frac{2}{\pi} \left( 1 + \frac{R_r}{r_0 + t_0 - R_r} \right)$$  \hspace{1cm} (14)

The ratio of the wall thickness of the groove to the initial wall thickness decreases with increasing $t_0$, i.e., $n$ increases.

Figures 16 and 17 show the strain distributions of grooves with different $t_0$ values when $\xi = 0.14$ and $\eta = 0.2$. The strain on the outer surface of the groove increases, and the strain on the inner surface decreases with increasing $t_0$. Figure 18 shows deformations of grooves with different $t_0$ values and the same feeding distance. The deformation of the inner wall is smaller when $t_0$ is larger, and the radial resistance of the material is greater during roller feeding. More material flows up and down, and then $n$ increases.

Figure 19 shows the strain distributions of grooves with different $\xi$ values when $\eta = 0.2$ and $t_0 = 6$ mm. The strain distributions of the grooves near the inner surface change little with changes in $\xi$, but the strains close to the outer surface increase with increasing $\xi$. The maximum strain difference at the same position of the grooves with different $\xi$ values is smaller than 0.5. It can be concluded that $\xi$ had little effect on the material flow during the forming process; therefore the effect of $\xi$ on the $n$ values of the grooves is not significant.

According to the analysis in Section 3.4.1, the wall thickness of the groove decreases during radial spinning. This thickness reduction means that some material flows from the groove to upper and lower sides, and bulges are formed.

Figure 20 shows the bulges are formed on both sides of the groove in experiments with different $\eta$ values. It is observed that a small $\eta$ promotes the generation of bulges. Figure 21 shows the radial stress distributions of the deformation zone at $\eta$ values of 0.02 and 0.30, with a feeding distance of 3 mm. The areas on both sides of the roller are under tensile stress in the radial direction when $\eta$ is small, but the stress becomes compressive at high $\eta$ values. More material flows upward and downward from the groove when $\eta$ is small, which was proposed in Section 3.4.1. The material is pushed to flow outward by the pressure from upper and lower dies. Then, the tensile stress in the radial direction and higher bulges appear. Conversely, less material involved in flowing leads to smaller tensile stress even compressive stress when $\eta$ is large. The compressive stress is led by the pressure from the rollers. Then, the height of bulges is small and concavity emerged.

Figure 22 shows longitudinal sections of tubes via experiments with different $t_0$ values. The figure shows that $h_u$ and $h_l$ increase with increasing $t_0$. The flexural capacity is weak.
when the tube wall is thin. The radial force from the rollers makes the wall bend. That counteracts some plastic deformation. Less material flows upside and downside, and the height of bulges is smaller. When the bulge could not compensate for the bending, concavity appears. Conversely, the flexural capacity is strong for the thick tube wall. More plastic deformation occurs pushed by the roller, that is, more material flows to both sides, and higher bulges are formed. That is shown in Fig. 18.

As shown in Section 3.4.1, $\xi$ has little effect on the material flow of the blank during the forming process and therefore has little effect on $h_u$ and $h_l$.

3.4.3 Tube height

The ANOVA results show that the three factors have no significant effect on $h$. However, the range analysis results show that there are influence rules of each parameter on $h$.

During roller feeding, the roller produces an axial force on the upper and lower straight walls. The lower die is fixed, and the upper die is controlled by $\xi$. The upper straight wall could be lifted when $\xi$ is small, which will increase $h$. The pressure of the upper die increases with increasing $\xi$, more material flows to the groove or bulge, and the increase in $h$ is suppressed. However, the amount of material involved in deformation is small relative to that in the whole tube. Therefore, the material flow caused by $\xi$ makes little difference to $h$.

As discussed in Sections 3.4.1 and 3.4.2, $h_u$, $h_l$, and $n$ decrease with increasing $\eta$ and with decreasing $t_0$, which suppresses the increase in $h$. Similarly, the effect is small because the change in the amount of material involved in deformation is small relative to that in the whole tube.

3.4.4 Inner surface quality of the groove

Axial expansion and circumferential contraction occur on the inner surface during the spinning process. So, wrinkles and cracks may appear at the inner surface. The larger the strain is, the greater the deformation is, which means that wrinkling or even cracking is more likely to occur. Figure 17 shows the strain increases with the decrease of $t_0$. Therefore, the tubes with the thinner wall are more possibly cracked at the inner surface. However, Figs. 12 and 19 show that various $\xi$ and $\eta$ don’t change the strain of the inner surface. The results show that the inner surface quality of the groove is determined by the initial wall thickness. Figure 23 shows the inner surface of the grooves with different $t_0$. When $t_0$ decreases from 8 to 4 mm, the surface roughness of the inner surface gradually increases. The inner surface is cracked when $t_0 = 2$ mm.

3.5 Definition of processing window

As discussed in Section 3.4, thickness reduction and bulge formation are major indexes for evaluating the forming quality. These are significantly affected by $t_0$ and $\eta$. According to the general accuracy requirement for thick-walled cylindrical parts with annular grooves, if $h_b$ (the average of $h_u$ and $h_l$) and $n$, respectively, meet the criteria $-0.5 \text{ mm} \leq h_b \leq 0.5 \text{ mm}$ and $-10\% \leq n \leq 10\%$, the tube is considered to be an eligible part.
Fig. 20 Upper/lower bulges formed in tubes during experiments with different $\eta$ values ($t_0 = 4\, \text{mm}$, $\xi = 0.14$)

Fig. 21 Radial stress distributions of deformation zones at different $\eta$ values and feeding distance of $3\, \text{mm}$ ($t_0 = 8\, \text{mm}$, $\xi = 0.14$)

Fig. 22 Upper/lower bulges formed in tubes during experiments with different $t_0$ values ($\eta = 0.2$, $\xi = 0.14$)
Fig. 23  The inner surface of the grooves with different $t_0$

Fig. 24  The forming qualities with different $t_0$ and $\eta$ values obtained by experiments

Springer
Figure 24 shows the forming qualities at different $t_0$ and $\eta$ values through the experimental results of orthogonal tests. Only three parts (with $t_0 = 4$ mm and $\eta = 0.2$, $t_0 = 4$ mm and $\eta = 0.3$, and $t_0 = 6$ mm and $\eta = 0.3$) are completely eligible. When $t_0$ and $\eta$ are too small or too large, the grooves have defects; that is, they are over-swollen, over-sunken, over-thin, cracked, or broken. The results suggest that $t_0$ should be set at 4–6 mm; the selected $\eta$ value should be 0.2 when $t_0 = 4$ mm and 0.2–0.3 when $t_0 = 6$ mm.

4 Conclusions

In this study, orthogonal experiments and FE simulations were performed to investigate the DRSP with double rollers. The experimental and simulation results were in good agreement. The effects and mechanisms of the process parameters on the forming quality were analyzed. The following conclusions were drawn.

1. In the forming process, the material in contact with the rollers shrinks in the radial and tangential directions of the blank because of roller feeding. Meanwhile, some material flows along the axial direction to both sides of the groove. This can decrease the groove thickness and cause the formation of upper and lower bulges. Severe deformation of grooves may cause wrinkling or even crack at the inner surface. The results show that the inner surface quality is governed by the initial wall thickness of the tube.

2. Range analysis and ANOVA results show that the load-yield ratio has no significant effect on the forming quality of the tube. The feed-thickness ratio and initial wall thickness have significant effects on the thinning ratio and bulge heights. In the case of bulge height, the effect of the initial wall thickness is greater than that of the feed-thickness ratio. For the thinning ratio, the two effects are approximately equal. None of the investigated parameters significantly affected the tube height.

3. The thinning ratio, bulge heights, and tube heights decrease with increasing feed-thickness ratio. All three indexes increase with an increasing initial thickness of the blank.

4. The difference of deformation between the thick and thin walls is caused by the difference in flexural capacity. Only when the plastic deformation and bending counteract each other, bulges and concavity would not appear.

5. To ensure good forming quality, the initial wall thickness of the blank should be set at 4–6 mm, and the appropriate feed-thickness ratio should be 0.2 when $t_0 = 4$ mm and 0.2–0.3 when $t_0 = 6$ mm.

Appendix 1. Range analysis

Range analysis was used to compare the effects of various factors on target indexes by calculating the range.

In Table 4, $k_i$ refers to the average value of the index at no. $i$ level, and $R$ represents the maximum difference among the $k_i$ values, i.e., $R = \max(k_i) - \min(k_i)$. The change in $k_i$ indicates the trend in the effect of the factor. As the value of $R$ increases, the effect of the factor on the index becomes more significant [23].

Appendix 2. Analysis of variance

Variance analysis was used to evaluate the effects of factors on target parameters.

In Table 5, $S$ refers to the sum of the squared deviations (DEVSQ) of the factor; $f$ is the degree of freedom (DOF); $M$ is the average DEVSQ, namely, the ratio of DEVSQ to DOF; $F$ is the standard for evaluating the significance and equals $M$ of the factor divided by $M$ of the error. Given a significance level $\beta$, the critical value $F_{\beta}(f_e, f)$ can be obtained by consulting the critical value table of the $F$ distribution. The significance can be evaluated by comparing $F$ and $F_{\beta}(f_e, f)$, where $F_i$ and $F_e$ are the DOF of the factor and error, respectively [22].

In this study, the DOF of the process parameters was 3 and the DOF of the error was 4. The critical value $F_{0.05}(3, 4) = 6.59$ was obtained from the critical value table of $F$ distributions. When $F < F_{0.05}(3, 4)$, it is considered that the effect of the process parameters on the indexes is not significant; when $F > F_{0.05}(3, 4)$, it is considered that the effect of the process parameters on the indexes is significant.

Acknowledgements The authors are grateful for the technical assistance from the Analytical and Testing Center of Huazhong University of Science and Technology.

Author contribution Famei Liu: experiment, data analysis, simulated analysis, and original draft writing
Junsong Jin: methodology, experiment, and review and editing
Wei Rao: experiment, formal analysis, and original draft writing
Ying Wang: Experiment
Chang Gao: Experiment
Xuefeng Tang: Experiment
Xinyun Wang: Review and editing

Funding This work was financially supported by the National Science Fund for Distinguished Young Scholars of China (grant number 51725504), National Natural Science Foundation of China (grant number 51675201), and National Science and Technology Major Project of China (Grant number 2018ZX04024001-003).

Availability of data and materials All data generated or analyzed during this study are included in this manuscript.

Declarations

Ethics approval Not applicable.
Consent to participate  Not applicable.

Consent for publication  Not applicable.

Competing interests  The authors declare no competing interests

References

1. Zhan M, Yang H, Guo J, Wang X (2015) Review on hot spinning for difficult-to-deform lightweight metals. T Nonferr Metal Soc 25:1732–1743. https://doi.org/10.1016/S1003-6326(15)63778-5

2. Yuan S, Xia Q, Long J, Xiao G, Cheng X (2020) Study of the microstructures and mechanical properties of ZK61 magnesium alloy cylindrical parts with inner ribs formed by hot power spinning. Int J Adv Manuf Technol 111:851–860. https://doi.org/10.1007/s00170-020-06091-2

3. Music O, Allwood JM, Kawai K (2010) A review of the mechanics of metal spinning. J Mater Process Technol 210:3–23. https://doi.org/10.1016/j.jmatprotec.2009.08.021

4. Wong CC, Dean TA, Lin J (2003) A review of spinning, shear forming and flow forming processes. Int J Mach Tools Manuf 43:1419–1435. https://doi.org/10.1016/j.ijmachtools.2009.08.02110.1016/S0890-6955(03)00172-X

5. Parsa MH, Pazooki AMA, Nili Ahmadabadi M (2009) Flow-forming and flow formability simulation. J Adv Manuf Technol 42:463–473. https://doi.org/10.1007/s00170-008-1624-0

6. Huang C, Hung J, Hung C, Lin C (2011) Finite element analysis on neck-spinning process of tube at elevated temperature. Int J Adv Manuf Technol 56:1039–1048. https://doi.org/10.1007/s00170-011-3247-0

7. Zoghi H, Fallahi Arezoodar A, Sayehtafibi M (2013) Enhanced finite element analysis of material deformation and strain distribution in spinning of 42CrMo steel tubes at elevated temperature. Mater Design 47:234–242. https://doi.org/10.1016/j.matdes.2012.11.049

8. Xia QX, Xie SW, Huo YL, Ruan F (2008) Numerical simulation and experimental research on the multi-pass neck-spinning of non-axisymmetric offset tube. J Mater Process Technol 206:500–508. https://doi.org/10.1016/j.jmatprotec.2007.12.066

9. Xia Q, Cheng X, Long H, Ruan F (2012) Finite element analysis and experimental investigation on deformation mechanism of non-axisymmetric tube spinning. Int J Adv Manuf Technol 59:263–272. https://doi.org/10.1007/s00170-011-3494-0

10. Arai H (2019) Noncircular tube spinning based on three-dimensional CAD model. Int J Mach Tools Manuf 144:103426. https://doi.org/10.1016/j.ijmachtools.2019.103426

11. Yao J, Makoto M (2002) An experimental study on paraxial spinning of one tube end. Journal of Materials Processing Tech 128:324–329. https://doi.org/10.1016/S0924-0136(02)00473-9

12. Kwiatkowski L, Tekkaya AE, Kleiner M (2013) Fundamentals for controlling thickness and surface quality during dieless necking-in of tubes by spinning. CIRP Ann 62:299–302. https://doi.org/10.1016/j.cirp.2013.03.054

13. Yao J, Makoto M (2002) Effects of indented feed of roller tool on parallel spinning of circular aluminum tube. Journal of Materials Processing Tech 128:274–279. https://doi.org/10.1016/S0924-0136(02)00465-X

14. Guo X, Li B, Jin K, Wang H, Wan B, Tao J (2017) A simulation and experiment study on paraxial spinning of Ni-based superalloy tube. Int J Adv Manuf Technol 93:4399–4407. https://doi.org/10.1007/s00170-017-0855-3

15. Grzancic G, Lübée C, Ben Khalifa N, Tekkaya AE (2019) Analytical prediction of wall thickness reduction and forming forces during the radial indentation process in Incremental Profile Forming. J Mater Process Technol 267:68–79. https://doi.org/10.1016/j.jmatprotec.2018.12.003

16. Zhu C, Zhao S, Li S, Fan S (2019) Comparison of mandrel and counter-roller spinning methods for manufacturing large sheaves. Int J Adv Manuf Technol 100:409–419. https://doi.org/10.1007/s00170-018-2707-1

Publisher’s note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.