Roller design and optimization based on RSM with categoric factors in power spinning of Ni-based superalloy

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Abstract
Power spinning is a single-point high-pressure forming process which is usually studied with ideal regular blank. However, in some cases, the blank adopted in this process is from conventional spinning process with non-uniform wall thickness and springback. Therefore, the forming accuracy cannot be guaranteed because of the irregular blank. In this paper, cone, step, and arc rollers are compared and the length change of deformation zone is calculated to further understand the forming mechanism of different roller shapes. Multi-step process simulation considering conventional spinning and power spinning is established. The influence of roller parameters such as roller nose radius, straightening zone in step roller, and bite angle on the maximum roller force in feeding direction is discussed. In addition, the continuous factors such as installation angle and discrete factor roller shape are studied based on the response surface method (RSM) with categoric factors. The results show that roller shape has a big influence on the workpiece forming quality in power spinning process. Step roller is more suitable for use in this work. The roller nose radius and installation angle have great impacts on the maximum roller force in feeding direction.

Keywords Power spinning · Roller shape · Multi-step simulation · Categoric factor · Response surface method (RSM)

1 Introduction
Metal spinning is a rotary chipless forming process with a long history [1]. Traditionally, conventional spinning is considered as an unchanged wall thickness spinning process, while power spinning is a process with wall thickness reduction [2]. With combination of the different characteristics, the combined process can fabricate various products which can be applied in industries such as aerospace, nuclear, chemistry, and military.

Spinning of sheet metals into cylindrical part is a common spinning process and has various applications in industry. To change the sheet into cylindrical shape, several forming passes are needed. Going a step further, the material flows along the roller feeding direction which will cause the non-uniform wall thickness of the spun parts. To reduce this unavoidable variation, researches have been done. Russo et al. [3] found that in multi-pass spinning process, the variation of wall thickness in asymmetric spun part is more obvious than in axisymmetric spun part. In addition, they [4] established a roller trace database with the force and shape variation; the data were collected from skillful hand spinners. They found that for multi-pass conventional spinning, the reasonable roller trace design method can lead to lower thickness variation of spun parts. Similar results can be found in the following works [5–7]. To minimize the wall thickness variation, Xiao et al. [8] claimed that the circumferential distribution of the wall thickness can be varied by changing the geometry of the roller pass circumferentially in synchronous multi-pass spinning. Meanwhile, the concavity of the pass and the roller-mandrel clearance affect the thickness distribution obviously. Mohamed et al. [9] stated that minimum wall thickness thinning and springback can be obtained in high feed ratio with lubrication. However, the above studies are mainly focused on the easy-to-deform materials such as aluminum and carbon steel. And difficult-to-deform metals are usually formed in hot spinning process [10]. But in our previous work [11–13], the wall thickness distribution of difficult-to-deform material (Ni-based superalloy, GH3030) is investigated in multi-pass cold spinning.
process. The wall thickness varies a lot during rolling direction and the shape of cylindrical part is hard to keep in straight because of the springback and high resistance at room temperature.

For power spinning of tubes, two main advantages are the following: first, the strength and hardness of the spun part are increased by about 15–25%, and the fatigue life of the material is significantly improved. Second, power spinning is a kind of drawing thinning process, which can effectively detect the metallurgical defects in the metal. However, the nature of the deformation in this process is more complex [14]. To figure out the relationship between forming quality and process parameters, researchers [15] found that the axial feed rates play a key role in final shape and wall thickness distribution of tube spinning, while low feed rate induces higher elongation and lower thickness change. Xia et al. [16] and Xiao et al. [17] studied the relationship between temperature, thinning ratio, feed rate, and grain size in hot power spinning of Ni-based superalloy cylindrical parts in micro scale. Except the process parameters, roller parameters also play an important role in spinning process. The influence of roller nose radius and roller diameter has been investigated by Khaled et al. [18] in deep spinning process comprehensively. Lin et al. [19] also demonstrated that the roller nose radius obviously affects the accuracy of tube wall thickness in staggered spinning of C-276 cylindrical parts. However, compared with ideal tube blank in power spinning, the dimensional accuracy of final spun cylindrical part in multi-pass conventional spinning is low because of the wall thickness variation and springback. But few studies considered this difference when using the latter blank in power spinning.

Using single-factor experiments to get the influence law of parameters is expensive and time-consuming. The optimized process parameters which can improve the product performance are hard to be obtained. To solve this problem, design of experiments (DOE) [20] was adopted to reveal the complex input and output relationships of the process. Kleiner et al. [21] adopted a mixed-level design with three two-level and two three-level factors to optimize the surface quality and avoid wrinkling in shear spinning process. Zhang and Tang [22] set the maximum fluctuation value of spinning force as the target and established the BP neural network RSM with material and process parameters. The designed experiments were implemented in numerical simulation. Vundavilli et al. [23] adopted mandrel rotation speed, feed rate of rollers, thickness reduction, initial thickness, solution, and aging treatment time as input data, and trained the input–output relationship with BPNN, GA-NN, and ABC-NN neural network methods. Bhatt and Raval [24] studied three material parameters and two process parameters in a Taguchi L25 array experiment. Natarajan et al. [25] determined the spinning parameters by complex proportional

2 Experiment setup

2.1 Materials

The materials adopted in this work are difficult-to-deform material nickel-based superalloy GH3030. The basic mechanical properties and true stress–strain curve of GH3030 shown in Table 1 and Fig. 1 are based on our previous work [12].

2.2 Power spinning process

Experiments of conventional spinning and power spinning process have been carried out with the QX800-II spinning machine (see Fig. 2a, c). The main dimensions of the sheet
blank, mandrel, roller, and back-plate are shown in Fig. 2b. The diagram of spun tube with step surface in power spinning is shown in Fig. 2d. The multi-step simulation model that combined conventional spinning and power spinning process is shown in Fig. 2e.

### 2.3 Roller shape design

Metal spinning is essentially a point contact rotary forming process with high pressure in small deformation area. In the high-speed rotation process of mandrel and tube blank, the contact area between roller and tube blank is very small. The roller, as one of the most important forming tools, bears huge contact pressure, friction, and the heat released by friction and blank plastic deformation. Thus, the geometry, dimensional accuracy, and surface quality of the workpiece are all directly reflected by the roller. Therefore, it is necessary to study the deformation mechanism of roller with different shapes.

According to Wang et al. summary [27] and the forming shape of tube blank studied in this paper, three types of rollers: cone roller E₁, step roller E₂, and arc roller E₃ are selected to calculate the length of the deformation zone in the two-dimensional plane (see Fig. 3). Roller E₁ is a cone roller, which is often used in shear spinning, including two conical working surfaces (see Fig. 4). The transition arc, bite angle $\alpha$, and exit angle $\beta$ can be flexibly designed according to the actual contact situation, and the adjustment range is large. But this roller also has some problems: when the blank wall thickness is large, the usage of roller E₁ will cause the workpiece surface coarseness, fuzzing, dropping, and accumulation. When the wall thickness is small, the material in front of the roller is prone to excessive bulge (the material bulge is also greatly related to the roller nose radius, as shown in Fig. 11), especially in the backward spinning process. Adopting roller E₂ can improve this situation. Different from the cone roller E₁, the step roller will generate a pressing step during the forming process, as shown in Fig. 5, and there is a designable straightening zone in the small fillet area. During the roller feeding process, the pressing step formed at the front of the roller will be flattened to realize thinning and stretching. Due to the existence of the step, the friction between the roller and the blank is large. Roller E₃ is the arc roller, which is widely used in power spinning.

### 3 Calculation of length variation of material deformation zone under different rollers

In power spinning process, the blank is formed between the roller and mandrel. Thus, the roller shape discussed in Sect. 2.3 has significant influence on the material flow and deformation. In order to further understand the deformation mechanism under different roller shape, the length variation of material deformation zone is discussed in this section.

#### 3.1 Length variation of material deformation zone under symmetrical roller

The target of the calculation is to get accurate geometry shape of the step on the spun tube. It is difficult to adopt equal volume conversion method because the tube blank
section is an irregular shape with non-uniform wall thickness and springback. Therefore, it is necessary to discuss different roller shapes in the material deformation zone.

For the symmetrical roller, it is applicable to the cone roller E1 and the arc roller E3, and the specific deformation should be discussed according to the geometric dimensions of the roller:

Case 1: When \( R(1 - \cos \theta_0) = \Delta t \),

While \( \Delta t = t_f - t_1 \), \( R \) is the roller nose radius, \( \theta_0 \) denotes the semi-circle central angle, \( t_f \) represents the initial wall thickness, and \( t_1 \) shows the deformation zone thickness after power spinning.

According to Fig. 4, we have:

\[
AB = t_1 \tag{1}
\]

\[
CD = R(1 - \cos \theta_0) + t_1 \tag{2}
\]

\[
OB = R + t_1 \tag{3}
\]

\[
HF = \frac{t_f}{\cos \Delta \alpha} \tag{4}
\]

where \( \Delta \alpha \) is the springback angle of tube blank.

\[
HG = HF - CD = \frac{t_f}{\cos \Delta \alpha} - R(1 - \cos \theta_0) - t_1 \tag{5}
\]

Fig. 2 Experimental setup. (a) Conventional spinning process. (b) Diagram of conventional spinning. (c) Power spinning process. (d) Diagram of conventional spinning with step surface. (e) Multi-step process simulation
Because $\angle HDG = \Delta a'$ is a little bigger than $\Delta a$, thus we have

$$\Delta a' \approx \Delta a + (1^\circ \sim 2^\circ)$$

And CDHF could be approximately regarded as a right-angle trapezoid; then,

$$l_1 = CF = DG = \frac{HG}{\tan \Delta a'} = \frac{t_f - \cos \Delta a'[R(1 - \cos \theta_0) + t_1]}{\cos \Delta a \tan \Delta a'}$$

Fig. 3 Geometric design of power spinning roller. (a) E1 roller. (b) E2 roller. (c) E3 roller

Fig. 4 Deformation zone length variation of the symmetrical roller
\[ l_2 = BC = R \sin \theta_0 \]  

(8)

Therefore, each deformation area \((S_1, CDHF, S_2, CDAB)\) can be calculated as:

\[ S_1 = \frac{(CD + HF) \times CF}{2} = \frac{t_f^2 - \cos^2 \Delta \alpha [R(1 - \cos \theta_0) + t_1]^2}{2 \cos^2 \Delta \alpha \tan \Delta \alpha'} \]  

(9)

\[ S_2 = \frac{(CD + OB) \times BC - S_{AOD}}{2} = R^2 \sin \theta_0(1 - \frac{\cos \theta_0}{2}) + t_1 R \sin \theta_0 - \frac{\theta_0 \pi R^2}{360} \]  

(10)

The original length of deformation zone \(l\) is:

\[ l = l_1 + l_2 = \frac{t_f - \cos \Delta \alpha [R(1 - \cos \theta_0) + t_1]}{\cos \Delta \alpha \tan \Delta \alpha'} + R \sin \theta_0 \]  

(11)

After power spinning process, the length changes to \(l'\):

\[ l' = \frac{S_1 + S_2}{t_1} = \frac{t_f^2 - \cos^2 \Delta \alpha [R(1 - \cos \theta_0) + t_1]^2}{2 t_1 \cos^2 \Delta \alpha \tan \Delta \alpha'} + \frac{R^2 \sin \theta_0(2 - \cos \theta_0)}{2 t_1} + R \sin \theta_0 - \frac{\theta_0 \pi R^2}{360 t_1} \]  

(12)

When \(R(1 - \cos \theta_0) < \Delta t\), as can be seen in Fig. 4,

\[ D'E' = \Delta t - E'M = \Delta t - R(1 - \cos \theta_0) \]  

(13)

\[ CC' = D'E' \tan \alpha_\rho = [\Delta t - R(1 - \cos \theta_0)] \tan \alpha_\rho \]  

(14)

\[ S_2' = \frac{(CD + C'D') \times CC'}{2} = \frac{(2CD + D'E') \times CC'}{2} = \frac{[R(1 - \cos \theta_0) + 2t_1 + \Delta t] \cdot [\Delta t - R(1 - \cos \theta_0)] \tan \alpha_\rho}{2} \]  

(15)

\[ l = l_1 + l_2 + CC' = \frac{t_f - \cos \Delta \alpha [R(1 - \cos \theta_0) + t_1]}{\cos \Delta \alpha \tan \Delta \alpha'} + R \sin \theta_0 + [\Delta t - R(1 - \cos \theta_0)] \tan \alpha_\rho \]  

(16)

\[ l' \] can be calculated as:

\[ l' = \frac{S_1 + S_2 + S_2'}{t_1} = \frac{t_f^2 - \cos^2 \Delta \alpha [R(1 - \cos \theta_0) + t_1]^2}{2 t_1 \cos^2 \Delta \alpha \tan \Delta \alpha'} + \frac{R^2 \sin \theta_0(2 - \cos \theta_0)}{2 t_1} + \frac{\theta_0 \pi R^2}{360 t_1} + \frac{R \sin \theta_0 - \frac{\theta_0 \pi R^2}{360 t_1}}{2 t_1} \]  

(17)

Case 2: When \(R(1 - \cos \theta_0) > \Delta t\), the contact length between roller and blank in the deformation zone becomes smaller, \(\theta_0\) changes to \(\theta_0'\), and \(\theta_0' < \theta_0\).

Then, \(l\) is

\[ E_1 F_1 \approx \Delta t - R_1(1 - \cos \theta_1) - \Delta \]  

(24)

And \(\Delta = (0.2 \sim 0.5)\) is the length compensation.
\[ l_{22} = C_1G_1 = \frac{E_1F_1}{\tan \alpha_p} = \frac{\Delta t - R_1(1 - \cos \theta_i) - \Delta}{\tan \alpha_p} \]

where \( \alpha_p \) is the bite angle of step roller.

\[ E_1G_1 = C_1D_1 + E_1F_1 = t_f - \Delta \]

\[ J_1H_1 = \frac{t_f}{\cos \Delta \alpha} \]

\[ J_1I_1 = J_1H_1 - E_1G_1 = t_f(\frac{1}{\cos \Delta \alpha} - 1) + \Delta \]

Thus, we have each deformation area \((S_{11}, E_1G_1, J_1H_1, S_{21} = C_1D_1A_1B_1, S_{22} = C_1D_1G_1)\) as follows:

\[ S_{11} = \frac{(E_1G_1 + J_1H_1) \times G_1H_1}{2} = \frac{t_f^2 - \cos^2 \Delta \alpha(t_f - \Delta)^2}{2 \cos^2 \Delta \alpha \tan \Delta \alpha t} \]

\[ S_{21} = \frac{(C_1D_1 + O_1B_1) \times B_1C_1}{2} - S_{A_1O_1D_1} = R_1^2 \sin \theta_i(1 - \cos \frac{\theta_i}{2}) + t_1R_1 \sin \theta_i - \frac{\theta_i x R_1^2}{360} \]

\[ S_{22} = \frac{(C_1D_1 + E_1G_1) \times C_1G_1}{2} = \frac{(t_f - \Delta)^2 - [R_1(1 - \cos \theta_i) + t_1]^2}{2 \tan \alpha_p} \]

Then, the original deformation length \( l_o \) can be calculated as:

\[ l_o = l_{11} + l_{21} + l_{22} = \frac{t_f}{\tan \Delta \alpha}(\frac{1}{\cos \Delta \alpha} - 1) + \frac{\Delta}{\tan \Delta \alpha} + R_1 \sin \theta_i + \frac{\Delta t - R_1(1 - \cos \theta_i) - \Delta}{\tan \alpha_p} \]

After power spinning process, the length changes to \( l'' \):

\[ l'' = \frac{S_{11} + S_{21} + S_{22}}{t_1} = \frac{t_f^2 - \cos^2 \Delta \alpha(t_f - \Delta)^2}{2t_1 \cos^2 \Delta \alpha \tan \Delta \alpha t} + \frac{R_1^2 \sin \theta_i(2 - \cos \theta_i)}{2t_1} \]

\[ + R_1 \sin \theta_i - \frac{\theta_i x R_1^2}{360} \]

\[ \Delta \]

In conclusion, the real forming height in power spinning could be calculated as:

\[ l_{real} = \frac{\mu(l_{tube} - \Delta \epsilon l_{step})}{l_o} + l_{step} \]

where \( l_{real} \) is the theoretical forming height, \( l_{tube} \) denotes the height of tube blank, \( l_{step} \) is the step length, and \( \Delta \epsilon \) represents the error compensation which mainly comes from the change of springback angle \( \Delta \alpha \) during the roller feeding process, and the error of the average wall thickness.

To verify the above equations, we chose Sect. 3.1 case 1 as an example. Based on Eqs. (33), (34) and (35), the detailed parameters used in the calculation are given in Table 2, and the error compensation is taken as 0.4 (based on our calculation, we think the better selection range of \( \Delta \epsilon \) is among 0.3–0.5). The theoretical calculation result is 69.895 mm, and the simulation forming height is shown in Fig. 13. The results show that the theory matches with the simulation well.

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**Fig. 5** Deformation zone length variation of the step roller
Table 2. Comparison of theoretical and numerical value of forming height

| \( R_1 \) (mm) | \( \theta \) (°) | \( \alpha_r \) (°) | \( \Delta \alpha \) (°) | \( \Delta \alpha' \) (°) | \( \Delta \) (mm) | \( t_1 \) (mm) | \( t_f \) (mm) | \( l_{tube} \) (mm) | \( l_{real} \) (mm) | \( l_{simu} \) (mm) |
|----------------|----------------|--------------------|------------------|------------------|----------------|----------------|----------------|----------------|----------------|----------------|
| 0.5            | 30             | 30                 | 8.4              | 9.4              | 0.2            | 1.08           | 1.58           | 52.5           | 69.895         | 70.5           |

Fig. 6. Comparison of experimental and simulation cylindrical part. (a) Wall thickness measurement of workpiece by caliper gauge. (b) Wall thickness distribution comparison

Fig. 7. (a) Forward spinning. (b) Backward spinning. (c) Forward–backward spinning

Fig. 8. In the forward spinning process. (a) Withdrawal roller at step surface. (b) Feeding roller at step surface. (c) Cylindrical sheet metal casing forming at the flange

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Table 3  Geometry parameters of the roller

| Roller shape | a-Roller width (mm) | r-Roller nose radius (mm) | R-Roller radius (mm) | α-bite angle (°) | β-exit angle (°) | Straightening zone (mm) |
|--------------|-------------------|--------------------------|---------------------|-----------------|-----------------|------------------------|
| a            | 20                | 1.2                      | 52                  | 25              | 25              | –                      |
|              | 20                | 1.2                      | 52                  | 45              | 45              | –                      |
|              | 20                | 1.2                      | 52                  | 60              | 60              | –                      |
| b            | 9.6               | 0.5                      | 52                  | 30              | 60              | –                      |
|              | 9.6               | 0.5                      | 52                  | 30              | 60              | 0.4                    |
| c            | 44                | 1                        | 68.5                | –               | –               | –                      |
|              | 44                | 2                        | 68.5                | –               | –               | –                      |
|              | 44                | 3                        | 68.5                | –               | –               | –                      |

4 Result and discussion

4.1 2D simulation of power spinning process based on spun tube blank

Multi-step process which combines conventional spinning and power spinning process is adopted in this work via Simufact.Forming 14.0. Before analysis, the wall thickness comparison results of the cylindrical part are added in Fig. 6. Although there is a little difference in the thinning zone (height range 20–30 mm in Fig. 6b), we think the wall thickness distribution of the simulation matches with experimental result well. Thus, the simulation result adopted in this work is reliable.

In the power spinning process, the tube blank contains all the results of the previous conventional spinning process.

Fig. 9  Force analysis of rollers with different geometry

Fig. 10  The effect of installation angle on Z force of roller
simulation, namely stress, strain, displacement, etc. First, the blank is not a regular cylindrical part, but a “special-shaped part.” Therefore, the traditional hexahedron mesh generation is difficult to refine in some fillet areas. Second, the calculation time of multi-step process is long. When the initial blank contains a large number of results of the previous process, this calculation is more difficult. Therefore, a 2D fast simulation model [13] is set up to judge the feasibility of the established roller trace and roller shape.

Taking a section of the spun tube as the initial blank for 2D simulation and selecting the element type as Quad, the element size is 0.2 mm, and the number of elements is 2631. Material properties are based on Sect. 2.1.

To form the step on the tube, the forming effects of three different roller traces are compared in Fig. 7. Figure 7a shows the results of forward spinning trace with an obvious step on the spun part. Figure 7b shows the results obtained from the backward spinning trace. There is an area at the flange where the roller does not contact with the tube, so a small section of the flange has not been formed. This is mainly because the backward spinning trace is adopted. If the roller is feeding directly from the flange to the top with a certain thinning rate, the flange is not fixed, the material will move with the feeding roller, that is, the blank wrinkle in Fig. 7b occurs at the beginning stage. When the forward–backward spinning trace shown in Fig. 7c is adopted, the step surface is taken as the dividing point, the upper section formed with backward trace while the lower section formed with forward trace. First, during the backward spinning process, metal flows upward with the roller trace, and finally the excess metal appears at the fillet area of the tube in the form of drum. In addition, since the roller trace does

Fig. 11 The effect of roller nose radius on Z force of roller

Fig. 12 The effect of straightening zone on Z force of roller
not contact with the step surface, the step is not fully contacted with the mandrel, so the forming quality is poor. In conclusion, the result of forward spinning trace is better and the following works are mainly based on this type of trace.

Figure 8 shows the 2D analysis under roller E2 with forward spinning trace. The whole spinning process is also a straightening process because there is a certain amount of springback in the tube blank. Figure 8a is the roller withdrawal process when forming to the upper step surface. The roller continues to feed and reshape the step surface. Figure 8b shows the roller forming at the lower step surface. At this time, the lower step surface is in contact with the exit angle of the step roller. Therefore, the shape of the upper and lower steps has a great relationship with the roller shape. Because when using asymmetric roller, the step shapes (upper and lower step) are not consistent. According to our previous work [12], the wall thickness distribution is not uniform, and there is a metal accumulation phenomenon at the flange. Thus, when the roller is fed to the flange, the unforming part of the blank almost completely fits with the pressing stage of the roller (see Fig. 8c). However, there are certain gaps in Fig. 8a and b. Due to the increasing wall thickness, the force on the roller will continue to increase in the forming process which can be demonstrated in Fig. 10.

4.2 Roller shape design and optimization

The corresponding roller parameters as mentioned in Fig. 3 are shown in Table 3. The numerical simulation models are
established based on these roller parameters and the maximum force of the roller in Z direction (feeding direction) is taken as the index (it can be seen from the analysis of the process that the main force of roller comes from the roller feed direction). The influence of different roller parameters on the forming quality is studied.

Similar to Gondo et al. work [28], the roller force is also decomposed into different directions for analysis. Figure 9 shows the force of roller 1 and roller 2 (corresponding to E3 and E2). Taking one point as the analysis object, when the roller contacts with the blank, the stress direction of a contact point is perpendicular to the contact plane. For roller 1, the direction of force $P_1$ is related to the arc radian. For the contact point at the position shown in the figure, the force $P_{z1}$ in the $Z$ direction is obtained after decomposing the force $P_1$, as shown below:

$$P_{z1} = P_1 \sin \alpha_1$$ (36)

For roller 2, we have:

$$P_{z2} = P_2 \sin \alpha_2$$ (37)

Assuming that the sizes of $P_1$ and $P_2$ at the same height are equal, for these two $Z$ direction components, roller 2 has a smaller bite angle. Therefore, the smaller the $Z$ direction component, the smaller the deformation resistance in the feeding process.

Figure 10 shows the influence of the adjustment of the installation angle on the roller $Z$ force. According to Fig. 10, four installation angles of $-5^\circ$, $0^\circ$, $5^\circ$, and $10^\circ$ are selected for simulation. The first large peak value appears near area 1. At this time, the roller has just bitten into the blank, and there is a large resistance in the stretching and thinning process due to the springback and high yield strength of the blank. When the roller feeds to the upper step surface and withdrawal (the position of area 2 in Fig. 10), the force decreases to the minimum. At this time, the roller continues to feed and starts shaping the step surface, and the force increases slightly. When feeding to the lower step surface, the roller bites in the blank again. But the force on the $Z$ direction decreases again because the roller only moves in $X$ direction. When it is formed to the flange of tube blank, due to the maximum springback, serious metal accumulation, and large wall thickness, the $Z$ force of roller is increasing significantly, and the maximum force exists in area 3 near the end of forming. As for different installation angles of the roller, when it is negative, the peak force in the $Z$ direction of the roller is the smallest, and the peak force of the roller increases gradually with the positive increasing of the installation angle. According to the analysis of Fig. 9, when the installation angle is negative, the material at the front of the roller is pressed into a small slope (the slope can be seen in Fig. 5). The smaller the slope, the easier the roller feeds and the smaller the $Z$
force of the roller. However, when the negative angle is too large, the material removal in front of the roller is very serious and the surface quality of the workpiece is poor.

Figure 11 shows that different roller nose radii also have a great impact on the maximum roller force. The function of the roller with smaller nose radius is similar to the cutting

Table 4 Parameters in RSM design with categorical factors

| Level | A-Maximum thinning rate (%) | B-Feeding velocity (mm/s) | C-Installation angle (°) | D-Roller radius (mm) | E-Roller shape | R4-Maximum roller force (kN) |
|-------|----------------------------|--------------------------|--------------------------|----------------------|---------------|-----------------------------|
| −1    | 25                         | 30                       | −5                       | 62                   | E1            | −                           |
| 0     | 30                         | 90                       | 0                        | 68.5                 | E2            | −                           |
| 1     | 35                         | 150                      | 5                        | 75                   | E3            | −                           |
tool. If the roller nose radius is small and the feeding velocity is large, the nose is very easy to bite into the blank, resulting in bump of the blank and large resistance in front of the roller feeding direction. It may cause rough workpiece surface, chip dropping, and even crack on the workpiece. When the roller nose radius is set to 1 mm, the workpiece will be crack in the initial stage of forming (see Fig. 11). In power spinning process, the roller with large nose radius is more like thinning the blank by extrusion force, which can increase the overlapping spinning part on the surface, so as to improve the workpiece smoothness and indirectly improve the feeding velocity of the roller. However, the $Z$ force of roller increases with the increasing roller nose radius which may cause the blank instability.

For the step roller, the straightening zone is often considered in its design. The main function of the straightening zone is to reduce the unevenness of the workpiece surface by using the elastic recovery effect. The existence of the straightening zone can reduce the roller nose radius and improve the forming accuracy of the workpiece. However, the surface quality cannot be revealed through simulation model. Figure 12 shows the influence of the roller with and without straightening zone on $Z$ force of the roller. The peak force difference between the two rollers is small (about 0.15 kN).

Figure 13a shows the influence of the bite angle on the $Z$ force of roller. The force increases with the increasing bite angle, which also confirms the influence of the aforementioned roller shape on the forming force. For the roller radius, as an index affecting the circumferential forming

| Table 5 Parameters of roller shape |
| Roller shape | a-Roller width (mm) | r-Roller nose radius (mm) | R-Roller radius (mm) | $\alpha$-Bite angle (°) | $\beta$-Exit angle (°) |
| E1 | 20 | 1.2 | 62 – 75 | 25 | 25 |
| E2 | 9.6 | 0.5 | 62 – 75 | 30 | 60 |
| E3 | 44 | 2 | 62 – 75 | – | – |

| Table 6 Runs and results for RSM with categorical factors |
| Number | A | B | C | D | E | R4 |
| 1 | –1 | –1 | –1 | 1 | E2 | 3.016 |
| 2 | 0 | 1 | 1 | 1 | E3 | 3.856 |
| 3 | 1 | –1 | –1 | –1 | E2 | 2.496 |
| 4 | –1 | –1 | –1 | –1 | E1 | 3.069 |
| 5 | 1 | 1 | –1 | 1 | E2 | 4.013 |
| 6 | 1 | 1 | 1 | 1 | E1 | 3.607 |
| 7 | 1 | –1 | 1 | –1 | E1 | 3.15 |
| 8 | –1 | –1 | 1 | –1 | E2 | 3.061 |
| 9 | 1 | –1 | 0 | 1 | E3 | 3.542 |
| 10 | 1 | –1 | 0 | –1 | E3 | 3.565 |
| 11 | 1 | 0 | 0 | 0 | E2 | 3.288 |
| 12 | 1 | 1 | –1 | –1 | E1 | 3.834 |
| 13 | 0 | –1 | –1 | –1 | E3 | 3.765 |
| 14 | –1 | 1 | –1 | –1 | E2 | 2.448 |
| 15 | –1 | 1 | 1 | 1 | E2 | 3.309 |
| 16 | 0 | 0 | –0.5 | 0 | E3 | 3.775 |
| 17 | 1 | 1 | –1 | 0 | E3 | 3.979 |
| 18 | 0 | –1 | 0 | 0 | E1 | 3.373 |
| 19 | –1 | 1 | 0 | –1 | E3 | 3.553 |
| 20 | 1 | –1 | –1 | 1 | E1 | 3.066 |
| 21 | –1 | –1 | 1 | 1 | E1 | 3.19 |
| 22 | 0 | 1 | –1 | –1 | E3 | 3.756 |
| 23 | –1 | 0 | –1 | 1 | E3 | 3.78 |
| 24 | 1 | 0 | 1 | –1 | E3 | 3.777 |
| 25 | –0.5 | 0.5 | 0.5 | 0 | E1 | 3.609 |
| 26 | –1 | 1 | 1 | –1 | E1 | 3.173 |
| 27 | –1 | 1 | –1 | 1 | E1 | 3.048 |
| 28 | –1 | –1 | 1 | 0 | E3 | 3.549 |
| 29 | 1 | –1 | 1 | 1 | E2 | 3.324 |
| 30 | 1 | 1 | 1 | –1 | E2 | 3.289 |
Table 7  Variance analysis of regression equation for R4

| Source | Sum of squares | DF  | Mean square | F       | Pr > F  | Significance |
|--------|---------------|-----|-------------|---------|---------|--------------|
| Model  | 4.172976      | 20  | 0.208649    | 5.7353  | 0.0053  | Significant  |
| A-A    | 0.340826      | 1   | 0.340826    | 9.3686  | 0.0136  | Significant  |
| B-B    | 0.406722      | 1   | 0.406722    | 11.1800 | 0.0086  | Significant  |
| C-C    | 0.036571      | 1   | 0.036571    | 1.0052  | 0.3422  |              |
| D-D    | 0.210811      | 1   | 0.210811    | 5.7947  | 0.0394  | Significant  |
| E-E    | 1.98383       | 2   | 0.991915    | 27.2658 | 0.0002  | Significant  |
| AB     | 0.526151      | 1   | 0.526151    | 14.4628 | 0.0042  | Significant  |
| AC     | 0.039165      | 1   | 0.039165    | 1.0766  | 0.3265  |              |
| AD     | 0.005712      | 1   | 0.005712    | 0.1570  | 0.7012  |              |
| AE     | 0.031666      | 2   | 0.015833    | 0.4352  | 0.6600  |              |
| BC     | 0.009707      | 1   | 0.009707    | 0.2668  | 0.6179  |              |
| BD     | 0.032932      | 1   | 0.032932    | 0.9052  | 0.3662  |              |
| BE     | 0.020302      | 2   | 0.010151    | 0.2790  | 0.7628  |              |
| CD     | 0.022455      | 1   | 0.022455    | 0.6172  | 0.4523  |              |
| CE     | 0.119136      | 2   | 0.059568    | 1.6374  | 0.2475  |              |
| DE     | 0.510929      | 2   | 0.255465    | 7.0222  | 0.0145  | Significant  |

Fig. 16  Factors disturbance distribution. (a) E1. (b) E2. (c) E3
effect, its size mainly affects the contact area between roller and the blank on the circumferential direction. The larger the roller radius, the larger the contact area with the blank, but at the same time, the heavier the weight of the roller and the higher the cost. Yang et al. [29] pointed out that the smaller the roller radius, the smaller the deformation force. They verified this conclusion by comparing the experimental measurement of 74-mm and 30-mm rollers. When selecting the roller with radius of 50 mm and 100 mm and comparing the force in $Z$ direction (see Fig. 13b), it is found that the curves basically coincide, and we think the roller radius has little effect on $Z$ force of roller in power spinning process.

For power spinning process, except the above influencing factors related to the roller parameters, another important factor is the maximum thinning rate. Figure 13c shows the impact on the $Z$ force of roller when the blank wall thickness is 2 mm and the maximum thinning rate is 25%, 30%, and 35% respectively. The greater the thinning rate, the greater the deformation resistance, and the greater the forming force required.

**Fig. 17** Interaction effect of factors A and B on R4 under E1 roller effect. (a) Factors C and D on –1 level. (b) Factors C and D on 0 level. (c) Factors C and D on +1 level

### 4.3 Power spinning process analysis based on the optimized roller parameters

Although the calculation time of 2D simulation is short, the accuracy of the model is lower than that of 3D simulation. Therefore, 3D simulation model is also implemented in this paper, as shown in Fig. 2e. Sheetmesh is adopted and the element size is 2 mm, the number of elements is 22005, the feed ratio of the roller is 0.48 mm/r, and the mandrel velocity is 300 rpm.

The 3D simulation results after spinning are compared with the 2D simulation model under the same process and roller parameters, as shown in Fig. 14. The forming height shown in Fig. 14 is about 70.5 mm. The flange of the 3D model is more likely a curve. One reason is because of the anisotropy of the material; another is because the flange has seriously metal accumulation phenomenon and a certain springback. When the roller is feeding to the flange, the process is similar as necking process with diameter reduction. The non-uniform deformation at the flange may occur at this area. However, the forming height...
of the two models is basically close. But the 3D model can reflect the real dimension variation of the tube.

Figure 15 shows the wall thickness distribution of the 3D simulation result, in which the gray area is the wall thickness value of the step surface. As also shown in this area, the wall thickness of the step ranges from 1.4 to 1.6 mm. In the first stage, the roller has just bitten into the blank, and the wall thickness value is the largest at this time, about 1.8–1.9 mm. At the beginning of the second stage, the roller forms the upper step surface, and the wall thickness value at the step surface is larger than that at the lower step surface formed in the third stage. The metal accumulation and the springback of the experimental sample are similar to simulation result in third stage, which is shown in the figure. At the beginning of the fourth stage, the roller enters the reducing diameter and necking stage. Compared with 4 and 4–1 in Fig. 15, roller b has a bite transition section which shows the characteristics of large fillet and gentle slope. It has a pre-forming function before the roller bites into the blank, which makes the forming process more stable. The forming effect of roller c is more like a cutting tool without any transition section, and the forming effect is not as good as that of roller b. In the fifth stage, the roller is closed to the end of the flange, and the final forming effect is shown in the simulation model in Fig. 15. The forming height fluctuates up and down in the circumferential direction because of the curve flange, and there are scattered strain concentration areas on the outer surface of the tube near the flange. These strain concentrations may cause wrinkle in the flange. As mentioned above, this phenomenon is mainly due to the large wall thickness and springback of the flange under the conventional spinning process. The power spinning in the fifth stage will cause non-uniform deformation, resulting in strain concentration of the tube blank. Based on the wall thickness distribution in Fig. 15, the optimized roller trace to obtain more uniform wall thickness can be designed.

4.4 Parameter optimization of power spinning process based on the RSM with categoric factors

4.4.1 Design of experiments

In order to further study the influence and interaction effect of process parameters and roller parameters in power spinning, DOE is adopted in this section. For the continuous and discrete factors mentioned above, Brenneman and Myers [30] proposed

Fig. 18 Interaction effect of factors A and B on R4 under E2 roller effect. (a) Factors C and D on – 1 level. (b) Factors C and D on 0 level. (c) Factors C and D on + 1 level
a RSM design method considering categoric factors for the sealing process. For the sealing machine, there are three continuous factors, temperature, pressure, and speed, and a discrete factor, supplier. The type of roller studied in this paper is also a discrete factor which can be considered the categoric factor in RSM. For the optimization of the power spinning process, four continuous factors of the maximum thinning rate, the roller feeding velocity, the roller installation angle, and the roller radius as well as a discrete factor of the roller shape are selected for the RSM design. The detailed parameters of each factor are shown in Table 4. Among them, the roller shape (as a discrete factor) is a categoric parameter which divides into three types (see Fig. 3, E1, E2 and E3). Detailed roller shape parameters are shown in Table 5.

The D-optimal design method is selected in this work. For the numerical simulation experiment, it is not necessary to repeat the experiment to verify the model disturbance and error. A total of 30 groups of experiments are designed. The maximum roller force R4 as the response and four continuous variables and one discrete variable as the factors are taken into account, as shown in Table 6. Because the long calculation time of 3D multi-step simulation, the 2D simulation is taken as the experimental design object.

4.4.2 Model setup and reliability test

According to the analysis of the results in Table 6, the disturbance distribution diagram of various factors is presented in Fig. 16. For R4 as small as possible, under the condition of roller E1, when factors A and B are close to −1 level and factors C and D are close to 1 level, R4 is about 3.2 kN. Under the condition of roller E2, when factors A, B, C, and D are close to −1 level, R4 decreases to about 3 kN. Under the condition of roller E3, when factors A and B are close to −1 level and factors C and D are close to 1 level, R4 is about 3.7 kN.

Adopting 2FI model and fitting the data, the fitting equation considering roller E1, E2, and E3 is shown as follows:
The analysis of variance for each factor is shown in Table 7, in which the maximum thinning rate, feeding velocity, roller radius and roller shape, the interaction between the maximum thinning rate and feeding velocity, and the interaction between roller radius and roller shape are all significant factors affecting the maximum roller force. After verification, the fitting degree of the model is good and the reliability is high.

4.4.3 Influence and interaction analysis of power spinning parameters

For the four factors (A, B, C, and D), the maximum thinning rate A and the feeding velocity B can be classified as process parameters, and the installation angle C and the roller radius D can be divided as roller parameters; the detail of the factors and levels are presented in Table 4. The final target of this optimization is to minimize the maximum roller force in feeding direction (R4 in the DOE). Thus, the following analysis will focus on how to obtain the minimum R4 under different factors.

According to Fig. 16a, when using roller E1 to find the influence of factors A and B on the maximum roller force R4, factors C and D should be discussed under different levels. Therefore, the influence distribution of factors A and B is obtained by horizontal adjustment of the levels of factors C and D (see Fig. 17). When both C and D are at level 1, the blue area in Fig. 17c is large, and the peak value of R4 in this area is small. While C and D are in 0 level (see Fig. 17b), the blue area is the smallest, and the distribution range of R4 is wide (varies from 3.2 to 3.7 kN). Therefore, at this level of C and D, R4 is more sensitive to the changes of factors A and B and mainly in the range of 3.2–3.3 kN. R4 is also sensitive under level −1, but the main range is under 3.3 kN.

\[
R4 = 3.39 + 0.12A + 0.12B + 0.035C + 0.092D - 0.063E1 - 0.27E2
+ 0.164B - 0.045AC - 0.017AD + 0.0083AE1 + 0.041AE2 - 0.022BC
+ 0.04BD + 0.02BE1 + 0.022BE2 - 0.033CD - 0.003509CE + 0.092CE2
- 0.13DE1 + 0.2DE2
\]  

(38)

The International Journal of Advanced Manufacturing Technology (2022) 120:447–469

Fig. 20 Interaction effect of factors A and B on R4 when factors C and D on +1 level (a) under E1 roller effect, (b) under E2 roller effect, and (c) under E3 roller effect and (d) factors C and D on −1 level, under E2 roller effect.
When roller E2 is adopted and factors C and D are at the $-1$ level, R4 is the smallest. Therefore, the horizontal adjustment of the two factors can obtain the influence distribution diagram of different factors A and B as follows (see Fig. 18). When factors C and D are at the $-1$ level, all the areas in Fig. 18a are blue, and the maximum roller force in this area is small (lowest value under 2.6 kN). When C and D are at level 1 (see Fig. 18c), there is no blue area distribution, and the distribution range of R4 is wide (varies from 3.4 to 3.9 kN). Therefore, at this level, R4 is more sensitive to the changes of factors A and B.

When roller E3 is adopted and factors C and D are at the $-1$ level (see Fig. 19c), R4 is the smallest. Therefore, the influence distribution diagram of different factors A and B is obtained by horizontal adjustment of the two factors. It can be seen from Fig. 19 that no matter which level C and D are located, almost all areas in the figure are red, and R4 in this area is large (the peak value can be larger than 4 kN). Therefore, we think the roller E3 is not suitable for power spinning process.

When C and D are at level 1, roller E1 has the smallest R4 (see Fig. 20a, lowest value under 3.2 kN). At this level, roller E2 does not have any advantages (peak value larger than 3.9 kN). However, when C and D factors are at level $-1$, that is, after adjusting the installation angle and roller radius, the influence distribution of factors A and B under the roller E2 is shown in Fig. 20d. It can be seen by comparing Fig. 20a and d, roller E2 has obvious advantages under power spinning process, and its shape is more conducive to reduce R4 and improve the performance of the equipment under the same roller trace and thinning rate.

![Images of graphs and figures]

**Fig. 21** Interaction effect of factors C and D on R4 when factors A and B on $-1$ level (a) under E1 roller effect, (b) under E2 roller effect, and (c) under E3 roller effect.

| Scheme | A | B | C | D | E     | $R_{1,pre}$ | $R_{1,act}$ |
|--------|---|---|---|---|------|------------|-------------|
| $-1$   | 1 | $-1$ | $-1$ | E2 | 2.44018 | 2.448      |

**Table 8** Optimization design
It can be seen from Fig. 21 that R4 is small when AB is at level for the three types of rollers. Thus, Fig. 21 shows the distribution diagram of the influence of factors C and D on R4. In order to clearly display the distribution, different scales are used in the diagram. The comparative values show that R4 of E2 is the smallest (smaller than 2.6 kN) and the blue area (varies from 2.6 to 3 kN) is the largest.

4.4.4 Model optimization and simulation verification

No. 14 of designed experiments in Table 8 is the optimized scheme. The maximum roller force under this scheme is small, the predicted value is 2.44018 kN, the simulation value is 2.448 kN, and the error is about 0.3%. The influence of various factors selected in this experimental scheme is also obtained, that is, the smaller the maximum thinning rate, the greater the roller feeding velocity, the smaller the installation angle (negative angle), and the smaller the roller radius. When the roller E2 is adopted, the maximum roller force is smaller.

Although the results obtained through simulation and experimental design show that roller E2 is better among the three types, it can be seen in Fig. 3 and Table 3 that there are great differences in the roller width of the three types of rollers due to their different applications, among which roller E2 is the smallest. Based on the three rollers (E1, E2, and E3) with the same roller width of 9.6 mm, the process parameters in scheme 14 are adopted for simulation, and the force distribution in Z force of roller is compared to verify the influence of the roller width on the maximum roller force, as shown in Fig. 22. Under the condition of the same roller width, the stress distribution of roller E2 is still the smallest. Therefore, this roller shape can be preferred.

The 3D simulation results of the same process with 0° installation angle and −5° installation angle are compared in Fig. 23. The wall thickness distribution results of the two processes are similar, but the wall thickness deviation of the −5° installation angle process at the step surface is smaller, and the wall thickness variation at the flange is smaller. The maximum roller force also decreased significantly, and the maximum peak force decreased by nearly 3 kN, about 37.5%.
5 Conclusion

This paper has presented an investigation into the roller shape design and roller parameter optimization in power spinning process of difficult-to-deform material GH3030. The main conclusions can be drawn as follows:

1. For the multi-step process of conventional spinning and power spinning, the section of blank is an irregular shape with non-uniform wall thickness and springback which cannot be calculated by the equal volume principle. Based on the deduced equations in this paper, the accurate forming height and step surface position can be obtained. It can be used for roller trace optimization of power spinning process.

2. For negative installation angle, the smaller the slope, the easier the roller feeding and the smaller the roller force on the feed direction. However, large negative installation angle may cause surface defect and crack. The function of roller with small nose radius is similar as the cutting tool, and the material removal effect is more easily to be obtained, while the effect of roller with large nose radius is more like the press forming.

3. The uneven flange is mainly due to the serious metal accumulation phenomenon, the springback, and the non-uniform deformation. In order to obtain a step surface with uniform wall thickness, the roller trace at the step surface should be a negative slope line.

4. The RSM with categoric factors can be a method to design experiments with continuous and discrete factors. The results in this paper show that the maximum roller force is closely related to the maximum thinning rate, the roller installation angle, the roller nose radius, and the roller shape. Step roller is more suitable for the power spinning process in this work.

Author contribution
Zixuan Li: conceptualization, simulation, experiments, writing—original draft, funding acquisition.
Xuedao Shu: review, funding acquisition.

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Availability of data and material
All data and materials are fully available without restriction.

Declarations

Ethics approval
Not applicable.

Consent to participate
Written informed consent for participation was obtained from all participants.

Consent for publication
Written informed consent for publication was obtained from all participants.

Competing interests
The authors declare no competing interests.

References

1. Wong CC, Dean TA, Lin J (2003) A review of spinning, shear forming and flow forming processes. Int J Mach Tool Manu 43:1419–1435
2. Music O, Allwood JM, Kawai K (2010) A review of the mechanics of metal spinning. J Mater Process Tech 210:3–23
3. Russo IM, Cleaver CJ, Allwood JM, Loukaides EG (2020) The influence of part asymmetry on the achievable forming height in multi-pass spinning. J Mater Process Tech 275:116350
4. Russo IM, Cleaver CJ, Allwood JM (2021) Seven principles of toolpath design in conventional metal spinning. J Mater Process Tech 294:117131
5. Liu JH, Yang H, Li YQ (2002) A study of the stress and strain distributions of first-pass conventional spinning under different roller-traces. J Mater Process Tech 129:326–329
6. Wang L, Long H (2013) Roller path design by tool compensation in multi-pass conventional spinning. Mater Design 46:645–653
7. Frnčík M, Sugárová J, Sugár P, Ludrovcová B (2018) The effect of conventional metal spinning parameters on the spun-part wall thickness variation. IOP Conf Ser Mater Sci Eng 448:012017
8. Xiao Y, Han ZR, Zhou SY, Jia Z (2021) Control of wall thickness distribution in synchronous multi-pass spinning. Int J Adv Manuf Tech 114:1457–1469
9. Mohamed AA, Mahmoud A, Mohamed Y (2018) Experimental investigation on the geometrical accuracy of the CNC multi-pass sheet metal spinning process. J Manuf Mater Process 2(59):1–21
10. Xia QX, Zhu NY, Cheng XQ, Xiao GF (2017) The classification and a review of hot power spinning of difficult-to-deform metals. Int J Mater Prod Technol 1a3(54):212–235
11. Li ZX, Shu XD (2021) Residual stress analysis of multi-pass cold spinning process. Chinese J Aeronaut. https://doi.org/10.1016/j.cja.2021.07.004
12. Li ZX, Shu XD (2019) Involute curve roller trace design and optimization in multipass conventional spinning based on the forming clearance compensation. J Manuf Sci E-T ASME 141(9):1–14
13. Li ZX, Shu XD (2019) Numerical and experimental analysis on multi-pass conventional spinning of the cylindrical part with GH3030. Int J Adv Manuf Tech 103:2893–2901
14. Mohan TR, Mishra R (1972) Studies on power spinning of tubes. Int J Prod Res 10(4):351–364
15. Roy BK, Korkolis YP, Arai Y et al (2021) Influence of axial feed rate on shape and thickness changes during multi-pass tube spinning: experiments and modelling. Form Future Miner Metal Mater Ser. https://doi.org/10.1007/978-3-030-75381-8_179
16. Xia QX, Long JC, Zhu NY et al (2019) Research on the microstructure evolution of Ni-based superalloy cylindrical parts during hot power spinning. Adv Manuf 7:52–63
17. Xiao GF, Zhu NY, Long JC et al (2018) Research on precise control of microstructure and mechanical properties of Ni-based superalloy cylindrical parts during hot backward flow spinning. J Manuf Process 34:140–147
18. Khaled IA, Mohamed SG, Mohamed GE (2015) Deep spinning of sheet metals. Int J Mach Tool Manu 97:72–85
19. Lin YC, Qian SS, Chen XM et al (2019) Staggered spinning of thin-walled Hastelloy C-276 cylindrical parts: numerical simulation and experimental investigation. Thin Wall Struct 140:466–476
20. Montgomery DC (2001) Design and analysis of experiments. John Wiley and Sons, New York
21. Kleiner M, Ewers R, Kunert J et al (2005) Optimisation of the shear forming process by means of multivariate statistical methods. University of Dortmund 23:1–16
22. Zhang J, Tang YC (2007) Optimization of tube spinning based on BP neural network response surface methodology. China Metal-form Equip Manuf Technol 1:71–75 (in Chinese)
23. Vundavilli PV, Kumar JP, Priyatham CS et al (2015) Neural network-based expert system for modeling of tube spinning process. Neural Comput Applic 26:1481–1493
24. Bhatt RJ, Raval HK (2016) Investigation of effect of material properties on forces during flow forming process. Int Symp Plast Impact Mech 173:1587–1594
25. Natarajan H, Paramasivam SSSS, Kumar D et al (2021) Evaluation of process parameters selection by COPRAS and ANOVA methods to get better spinning cylindrical cups. Mater Today Proc. https://doi.org/10.1016/j.matpr.2021.06.210

26. Razani NA, Aghchaei AJ, Dariani BM (2014) Flow-forming optimization based on hardness of flow-formed AISI321 tube using response surface method. Int J Adv Manuf Tech 70:1463–1471
27. Wang CH, Liu KZ, Zhou L (2017) Xuan ya ji shu. Fujian Science & Technology Publishing House. (in Chinese)
28. Gondo S, Arai H, Kajino S et al (2021) Evolution of strain state of a rolled aluminum sheet in multi-pass conventional spinning. J Manuf Sci E-T ASME 143:061011
29. Yang GP, Xu WC, Chen Y et al (2008) Research on material flow rule of backward tube spinning process. J Plasticity E 15(6):48–52 (in Chinese)
30. Brenneman WA, Myers WR (2003) Robust parameter design with categorical noise variables. J Qual Technol 35(4):335–341

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