Roller Design and Optimization Based on RSM with Categorical Factors in Power Spinning of Ni-Based Superalloy

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Roller Design and Optimization Based on RSM with Categorical

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 billet. However, in some cases, the billet adopted in this process is from conventional spinning process with non-uniform wall thickness and springback. Therefore, the forming accuracy is low because this unpredictable spun billet. 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 are 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 categorical factors. The results show that roller shape have 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.

Keywords: Power spinning, Roller shape, Multi-step simulation, Categorical factor, Response surface method (RSM)

1. Introduction

Metal spinning is a kind of rotary chipless forming process with a long history [1]. Traditionally, conventional spinning is considered as a type of unchanged wall thickness spinning process; while power spinning is a kind of process with wall thickness reduction [2]. With combination of these two different characteristics, the combined process can produce 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 inevitable 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 [5-8]. To reduce the wall thickness variation, Xiao et al. [9] 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.

[10] found 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 [11]. But in our previous work[13][15], 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 as follows: 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 [16]. To figure out the relationship between forming quality and process parameters, researchers [17],[18] found that axial feed rates play a key role in shape and thickness of tube spinning, while low feed rate produces higher elongation and lower thickness change. Xia et al. [19] and Xiao et al. [20] 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, tool parameters such as roller, also plays a more important role in power spinning compared with in conventional spinning process. The influence of roller nose radius and roller diameter have been investigated by Khaled et al. [21] in deep spinning process comprehensively. Lin et al. [22] 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 billet in power spinning, the dimensional accuracy of final spun cylindrical part in multi-pass conventional spinning is lower because of the wall thickness variation and springback. But few studies considered this difference when using the latter billet in power spinning.

To find the optimized parameters in spinning process, using single-factor experiments to get the influence law of factors is expensive and time-consuming. In addition, the optimized process parameters which can improve the product performance are hard to be obtained. To solve this problem, design of experiments (DOE) [23] was adopted to reveal the complex input and output relationships of the process. Kleiner et al. [24] 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 [25] 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. [26] 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 [27] studied three material parameters and two process parameters in a Taguchi L25 array experiment. Natarajan et al. [28] determined the spinning parameters by complex proportional assessment method to obtain minimum surface roughness and spinning time. Razani et al. [29] used DOE to determine the influence of some continuous factors such as rotational speed of mandrel, feed rate, and wall thickness reduction on the hardness of flow forming tubes. The above researches mainly focused on the influence of continuous factors, however, some discrete factors such as roller shape [30] also have important to the final performance which are rarely studied in DOE.

In general, power spinning is formed with completely regular tube billet, but for the combine

process of conventional spinning and power spinning, the initial billet of power spinning is an irregular cylindrical part with non-uniform wall thickness distribution along the forming height direction, springback of flange and certain deviation between the diameter of top and bottom section, which makes it difficult to form accurately. Therefore, in this paper, taking the spun cylindrical part in conventional spinning as the initial billet, the mathematical models of the length change of the deformation zone based on different type of rollers are established, a multi-step simulation model of the conventional spinning process and power spinning process is set up based on the difficult-to-deform material GH3030; in addition, by comparing the 2D and 3D power spinning simulation models, the influence laws of roller parameters on forming quality and forming force are obtained; finally, based on the RSM with categoric factors, the optimized continuous and discrete parameters of power spinning are obtained.

2. Experiment set up

2.1 Materials

The materials used in experiments 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 [14].

Fig. 1 True stress-strain curve of GH3030.

Table 1 Measurement parameters of GH3030.

Material	Young's modulus / GPa	Yield strength / MPa	Tensile strength / MPa	Elongation / %
GH3030	96.55	268	733	29

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 and 2c). 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 that combined conventional spinning and power spinning process is shown in Fig. 2e.

Fig. 2 Experimental set up. (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.

2.3 Roller shape design

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

According to Wang et al.'s summary [30] and the forming shape of tube billet 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. The transition arc, bite angle α and exit angle β can be flexibly designed according to the actual contact situation, and the adjustment range is large. But this type of roller also has some problems: when the billet wall thickness is large, the use of roller E1 will cause the workpiece surface to be not smooth,

fuzzing, dropping and accumulation, etc. 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 Figure 9), 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 billet is large. Roller E3 is the arc roller, which is widely used in power spinning.

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

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

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

3.1 Length variation of material deformation zone under symmetrical roller

The order 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 billet section is an irregular shape with non-uniform wall thickness and springback. Therefore, it is necessary to classify and discuss the forming of 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 $\Delta t=t_f-t_l$, R is the roller nose radius, θ_0 denotes the semi-circle central angle, t_f represents the initial wall thickness, t_l shows the deformation zone thickness after power spinning.

According to Fig. 4, we have:

$$AB=t_l \quad (1)$$

$$CD=R(1-\cos\theta_0)+t_l \quad (2)$$

$$OB=R+t_l \quad (3)$$

$$HF=\frac{t_f}{\cos\Delta\alpha} \quad (4)$$

While $\Delta\alpha$ is the springback angle of tube billiet.

Fig. 4 Deformation zone length variation of the symmetrical roller.

$$HG=HF-CD=\frac{t_f}{\cos\Delta\alpha}-R(1-\cos\theta_0)-t_l \quad (5)$$

Because $\angle HDG=\Delta\alpha'$ is a little bigger than $\Delta\alpha$, thus we have

$$\Delta\alpha'\approx\Delta\alpha+(1^\circ\sim2^\circ) \quad (6)$$

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

$$l_1 = CF = DG = \frac{HG}{\tan \Delta\alpha'} = \frac{t_f - \cos \Delta\alpha [R(1 - \cos \theta_0) + t_1]}{\cos \Delta\alpha \tan \Delta\alpha'} \quad (7)$$

$$l_2 = BC = R \sin \theta_0 \quad (8)$$

Therefore, each deformation area (S_1 -CDHF, S_2 -CDOB) can be calculated as:

$$S_1 = \frac{(CD + HF) \times CF}{2} = \frac{t_f^2 - \cos^2 \Delta\alpha [R(1 - \cos \theta_0) + t_1]^2}{2 \cos^2 \Delta\alpha \tan \Delta\alpha'} \quad (9)$$

$$S_2 = \frac{(CD + OB) \times BC}{2} - S_{AOB} = R^2 \sin \theta_0 (1 - \frac{\cos \theta_0}{2}) + t_1 R \sin \theta_0 - \frac{\theta_0 \pi R^2}{360} \quad (10)$$

The original length of deformation zone l is:

$$l = l_1 + l_2 = \frac{t_f - \cos \Delta\alpha [R(1 - \cos \theta_0) + t_1]}{\cos \Delta\alpha \tan \Delta\alpha'} + R \sin \theta_0 \quad (11)$$

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

$$l' = \frac{S_1 + S_2}{t_1} = \frac{t_f^2 - \cos^2 \Delta\alpha [R(1 - \cos \theta_0) + t_1]^2}{2 t_1 \cos^2 \Delta\alpha \tan \Delta\alpha'} + \frac{R^2 \sin \theta_0 (2 - \cos \theta_0)}{2 t_1} + R \sin \theta_0 - \frac{\theta_0 \pi R^2}{360 t_1} \quad (12)$$

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

$$D'E' = \Delta t - CD = \Delta t - R(1 - \cos \theta_0) \quad (13)$$

$$CC' = D'E' \tan \alpha_\rho = [\Delta t - R(1 - \cos \theta_0)] \tan \alpha_\rho \quad (14)$$

$$\begin{aligned} S_2' &= \frac{(CD + C'D') \times CC'}{2} = \frac{(2CD + D'E') \times CC'}{2} \\ &= \frac{[R(1 - \cos \theta_0) + 2t_1 + \Delta t] \cdot [\Delta t - R(1 - \cos \theta_0)] \tan \alpha_\rho}{2} \end{aligned} \quad (15)$$

l is

$$l = l_1 + l_2 + CC' = \frac{t_f - \cos \Delta\alpha [R(1 - \cos \theta_0) + t_1]}{\cos \Delta\alpha \tan \Delta\alpha'} + R \sin \theta_0 + [\Delta t - R(1 - \cos \theta_0)] \tan \alpha_\rho \quad (16)$$

l' can be calculated as:

$$\begin{aligned} l' &= \frac{S_1 + S_2 + S_2'}{t_1} = \frac{t_f^2 - \cos^2 \Delta\alpha [R(1 - \cos \theta_0) + t_1]^2}{2 t_1 \cos^2 \Delta\alpha \tan \Delta\alpha'} + \frac{R^2 \sin \theta_0 (2 - \cos \theta_0)}{2 t_1} \\ &+ R \sin \theta_0 - \frac{\theta_0 \pi R^2}{360 t_1} + \frac{[R(1 - \cos \theta_0) + 2t_1 + \Delta t] \cdot [\Delta t - R(1 - \cos \theta_0)] \tan \alpha_\rho}{2 t_1} \end{aligned} \quad (17)$$

Case 2: when $R(1 - \cos \theta_0) > \Delta t$, the contact length between roller and billet in the deformation zone becomes smaller, θ_0 changes to θ_0' , and $\theta_0' < \theta_0$.

Then, l is

$$l = l_1 + l_2 = \frac{t_f - \cos \Delta \alpha [R(1 - \cos \theta_0') + t_1]}{\cos \Delta \alpha \tan \Delta \alpha'} + R \sin \theta_0' \quad (18)$$

l' is

$$l' = \frac{S_1 + S_2}{t_1} = \frac{t_f^2 - \cos^2 \Delta \alpha [R(1 - \cos \theta_0') + t_1]^2}{2t_1 \cos^2 \Delta \alpha \tan \Delta \alpha'} + \frac{R^2 \sin \theta_0' (2 - \cos \theta_0')}{2t_1} + R \sin \theta_0' - \frac{\theta_0' \pi R^2}{360 t_1} \quad (19)$$

The above calculation is suitable for roller E1 and E3.

3.2 Length variation of material deformation zone under step roller

Fig. 5 Deformation zone length variation of the step roller.

For step roller E2, because the roller nose radius is quite small, thus, only $R(1 - \cos \theta_0) \leq \Delta t$ be considered,

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

$$A_1 B_1 = t_1 \quad (20)$$

$$C_1 D_1 = R_1 (1 - \cos \theta_1) + t_1 \quad (21)$$

$$O_1 B_1 = R_1 + t_1 \quad (22)$$

$$l_{21} = B_1 C_1 = R_1 \sin \theta_1 \quad (23)$$

$$E_1 F_1 \approx \Delta t - R_1 (1 - \cos \theta_1) - \Delta \quad (24)$$

And $\Delta = (0.2 \sim 0.5)$ is the length compensation.

$$l_{22} = C_1 G_1 = \frac{E_1 F_1}{\tan \alpha_\rho} = \frac{\Delta t - R_1(1 - \cos \theta_1) - \Delta}{\tan \alpha_\rho} \quad (25)$$

Where α_ρ is the bite angle of step roller.

$$E_1 G_1 = C_1 D_1 + E_1 F_1 = t_f - \Delta \quad (26)$$

$$J_1 H_1 = \frac{t_f}{\cos \Delta \alpha} \quad (27)$$

$$J_1 I_1 = J_1 H_1 - E_1 G_1 = t_f \left(\frac{1}{\cos \Delta \alpha} - 1 \right) + \Delta \quad (28)$$

$$l_{11} = G_1 H_1 = \frac{J_1 I_1}{\tan \Delta \alpha'} = \frac{t_f}{\tan \Delta \alpha'} \left(\frac{1}{\cos \Delta \alpha} - 1 \right) + \frac{\Delta}{\tan \Delta \alpha'} \quad (29)$$

Thus, we have each deformation area (S_{11} - $E_1 G_1 J_1 H_1$, S_{21} - $C_1 D_1 O_1 B_1$, S_{22} - $C_1 D_1 E_1 G_1$) as follows:

$$S_{11} = \frac{(E_1 G_1 + J_1 H_1) \times G_1 H_1}{2} = \frac{t_f^2 - \cos^2 \Delta \alpha (t_f - \Delta)^2}{2 \cos^2 \Delta \alpha \tan \Delta \alpha'} \quad (30)$$

$$S_{21} = \frac{(C_1 D_1 + O_1 B_1) \times B_1 C_1}{2} - S_{A_1 O_1 B_1} = R_1^2 \sin \theta_1 \left(1 - \frac{\cos \theta_1}{2} \right) + t_1 R_1 \sin \theta_1 - \frac{\theta_1 \pi R_1^2}{360} \quad (31)$$

$$S_{22} = \frac{(C_1 D_1 + E_1 G_1) \times C_1 G_1}{2} = \frac{(t_f - \Delta)^2 - [R_1(1 - \cos \theta_1) + t_1]^2}{2 \tan \alpha_\rho} \quad (32)$$

Then, the original deformation length l_a can be calculated as:

$$l_a = l_{11} + l_{21} + l_{22} = \frac{t_f}{\tan \Delta \alpha'} \left(\frac{1}{\cos \Delta \alpha} - 1 \right) + \frac{\Delta}{\tan \Delta \alpha'} + R_1 \sin \theta_1 + \frac{\Delta t - R_1(1 - \cos \theta_1) - \Delta}{\tan \alpha_\rho} \quad (33)$$

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

$$l'' = \frac{S_{11} + S_{21} + S_{22}}{t_1} = \frac{t_f^2 - \cos^2 \Delta \alpha (t_f - \Delta)^2}{2 t_1 \cos^2 \Delta \alpha \tan \Delta \alpha'} + \frac{R_1^2 \sin \theta_1 (2 - \cos \theta_1)}{2 t_1} + R_1 \sin \theta_1 - \frac{\theta_1 \pi R_1^2}{360 t_1} + \frac{(t_f - \Delta)^2 - [R_1(1 - \cos \theta_1) + t_1]^2}{2 t_1 \tan \alpha_\rho} \quad (34)$$

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

$$l_{real} = \frac{l''(l_{tube} - \Delta_e l_{step})}{l_a} + l_{step} \quad (35)$$

Where l_{real} is the theoretical forming height, l_{tube} denotes the height of tube billet, l_{step} is the step length, Δ_e represents the error compensation which mainly comes from the change of springback angle Δ during the roller feeding process, and the error of the average wall thickness.

4. Result and discussion

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

Multi-step process which combines conventional spinning and power spinning process is adopted in this work via Simufact.Forming 14.0. In the power spinning process, the tube billet contains all the results of the previous conventional spinning process simulation, namely stress, strain, temperature, displacement, etc. First, the billet 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 spinning process, is long. When the initial billet contains a large number of results of the previous process, this calculation is more difficult. Therefore, a 2D fast simulation model [15] of billet is established to judge the feasibility of the established roller trace and the roller shape.

Take a section of the spun tube as the initial billet for 2D simulation, select the element type as Quad, the element size is 0.2 mm, and the number of elements is 2631. Material properties are based on section 2.1. Carry out two-dimensional simulation on the established blank. The simulation model is shown in Figure 6.

To form the step on the tube, the forming effects of three different roller traces are shown in Figure 6. Figure 6a shows the results of forward spinning trace. There is an obvious step on the spun part; Figure 6b shows the results obtained from the backward spinning trace. There is an area at the flange of the tube where the roller does not contact, so a small section of the flange is not deformed and has an initial wall thickness compared with other areas. This is mainly because when 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 billet wrinkle in Fig. 6b occurs at the beginning of the spinning stage. When the forward-backward spinning trace shown in Fig. 6c is adopted, that is, taking the step surface as the dividing point, the upper section formed with backward spinning while the lower section formed with forward spinning. 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 in this type of trace do not contact with the step surface, the step shape is not obvious and the step surface is not fully contacted with the mandrel, so the forming quality is poor. In conclude, the result of forward spinning trace is better and the following works are mainly based on this type of trace.

Fig. 6 (a) forward spinning (b) backward spinning (c) forward-backward spinning.

Fig. 7 shows the 2D analysis under roller E2 with forward spinning trace. It can be seen from the figure that the whole spinning process is also a straightening process because there is a certain amount of springback in the tube billet. Fig. 7a is the roller withdrawal process when forming to the upper step surface. The roller continues to feed and reshapes the step surface. Fig. 7b 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 shape of the roller. The shape of upper and lower steps obtained by using asymmetric roller is not consistent. According to our previous work [14], the wall thickness distribution is not uniform, and there is a metal accumulation phenomenon at the flange. It can also be seen from Fig. 7c that when the roller is fed to the flange, the unforming part of the billet almost completely fits with the pressing stage of the roller. However, there are certain gaps in Fig. 7a 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. 9.

Fig. 7 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.

4.2 Roller shape design and optimization

The corresponding roller parameters as mentioned in Fig.3 are shown in Table 2. The numerical simulation models are established based on these roller parameters and the maximum force of the roller in Z direction is taken as the index (it can be seen from the analysis of the process that the main force on the roller in the spinning process comes from the roller feed direction, i.e. Z direction). The influence of different roller parameters on the forming quality is studied.

Similar as Gondo et al's work [32], the roller force is also decomposed into different directions for analysis. Fig. 8 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 billet, the stress direction of a contact point is perpendicular to the contact plane. For roller 1, the direction of force P1 is related to the arc radian. For the contact point at the position shown in the figure, the force Pz1 in the Z direction is obtained after decomposing the force P1, as shown below:

$$P_{z1} = P1 \sin \alpha 1 \quad (36)$$

For roller 2, we have:

$$P_{z2} = P2 \sin \alpha 2 \quad (37)$$

Assuming that the sizes of P1 and P2 at the same height are equal, for these two Z direction components, the roller 2 has a smaller bite angle. Therefore, the smaller the Z direction component is, the smaller the deformation resistance in the feeding process is.

Table 2 Geometry parameters of the roller.

Roller shape	a-Roller width/ mm	r-Roller		α -bite angle/ °	β -exit angle/ °	straightening zone/ mm
		nose radius/ mm	R-Roller radius/ 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	-	-	-

Fig. 8 Force analysis of rollers with different geometry.

Fig. 9 The effect of installation angle on Z force of roller.

Fig. 9 shows the influence of the adjustment of the installation angle of the roller on the roller Z force. According to Fig. 9, four installation angles of -5° , 0° , 5° and 10° is selected for simulation. The first large peak value appears near area 1. At this time, the roller has just bitten into the billet, and there is a large resistance in the stretching and thinning process due to the springback and difficult-to-deform character of the billet. With the continuous feeding of the roller, the billet continues to contact with the mandrel, and the Z force of roller also decreases. When the roller feeds to the upper step surface and withdrawal (i.e. the position of area 2 in Fig. 9), 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 the roller is formed to the lower step surface, the roller bites in the billet again. But the force on the Z direction decreases again because the roller only moves in the X direction, and then the roller continues to feed, the billet is continuously thinned and elongated, and

when it is formed to the flange of the tube billet, due to the maximum springback, serious metal accumulation and large wall thickness, the Z force of roller is increasing, and the maximum force exists in the area 3 near the end of forming. Compared with different installation angles of the roller, when the installation angle is negative, the peak force in the Z direction of the spinning wheel is the smallest, and the peak force of the roller increases gradually with the gradual positive increase of the installation angle. According to the analysis of Fig. 8, 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 of the roller is very serious and the surface quality of the workpiece is poor.

Fig. 10 The effect of roller nose radius on Z force of roller.

Fig.10 shows that different roller nose radius also has a great impact on the maximum roller force. The action of the roller with smaller nose radius is closer to the tool, and it is easier to realize the effect of material flow during feeding process. If the roller nose radius is small and the feeding velocity is large, the nose part is very easy to bite into the blank, resulting in bump of the billet 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. 10). In power spinning process, the roller with large nose radius is more like thinning the billet 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 increase of the roller nose radius which may cause the billet instability. Therefore, it is very important to reasonably design and select the roller nose radius.

For the step roller, the straightening zone of the roller 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 of the material. The existence of the straightening zone can further reduce the roller nose radius and improve the forming accuracy of the workpiece. Fig. 11 shows the influence of the roller with and without straightening zone on Z force of the roller under same other process parameters. It can be seen from the figure that when there is no straightening zone on the roller, the force is slightly less than the roller with straightening zone. However, the peak force difference between the two is small, about 0.15 kN

Fig. 11 The effect of straightening zone on Z force of roller.

Fig. 12a shows the influence of the bite angle on the Z force of roller. The force increases with the increase of the bite angle, which also confirms the influence of the aforementioned roller shape on the forming force. Therefore, the design of the bite angle is also very important to the power spinning process. For the roller radius, as an index affecting the circumferential forming of spinning process, its size mainly affects the contact area between roller and the billet on the circumferential direction. The larger the roller radius, the larger the contact area with the billet, but at the same time, the heavier the weight of the roller and the higher the cost. Yang et al. [33] pointed out that the smaller the roller radius, the smaller the deformation force. They verified this conclusion by comparing the experimental measurements of 74 mm and 30 mm rollers. However, in the simulation results of this paper, when selecting the roller with radius of 50 mm and 100 mm and comparing the force in Z direction (see Fig. 12b), 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. Fig. 12c shows the impact on the Z force of roller when the billet wall thickness is 2 mm and the maximum thinning rate is 25%, 30% and 35% respectively. As can be seen from the figure, the greater the thinning rate, the greater the deformation resistance, and the greater the forming force required.

Fig. 12 The effect of (a) bite angle (b) roller radius (c) max thinning ratio on Z force of roller.

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. The billet is meshed by sheetmesh, and the element size is 2 mm, the number of element is 22005, the feed ratio of the roller is 0.48 mm / r, and the mandrel velocity is 300 rpm.

Fig. 13 The forming height comparison of 2D and 3D simulation model.

The 3D simulation results after spinning are compared with the 2D simulation model under the same process and roller parameters, as shown in Fig. 13. The forming height shown in Fig. 13 is about 70.5 mm. It can be seen from the observation of the 3D model that the flange is more likely the curve. One reason is because the anisotropy of the material, another is because the flange has seriously metal accumulation phenomenon and has a certain springback. When the roller is feeding to the flange, the process equals to reducing diameter and necking process, which may cause the non-uniform deformation at the flange. However, the forming height of the two models is basically close, and the 3D model can reflect the real dimension variation of the tube.

Fig. 14 shows the wall thickness distribution of the spun tube with the step, in which the gray area is the wall thickness value of the step surface, as also shown in the simulation model, and the value ranges from 1.4 to 1.6 mm. In the first stage, the roller has just bitten into the billet, 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 the lower step surface formed in the third stage. The metal accumulation and the springback of the experimental part is similar as 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. 14, the roller b has a bite transition section which has the characteristics of large fillet and gentle slope. It has a pre-forming function before the roller bites into the billet, which makes the forming process more gentle. The forming effect of roller c is more like a 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 the Fig. 14. 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 billet. Based on the wall thickness distribution in Fig. 14, the optimized roller trace that to obtain more uniform wall thickness can be designed.

Fig. 14 The wall thickness and effective plastic strain distribution of cylindrical sheet metal casing under power spinning and the spinning process analysis in five stages.

4.4 Parameters optimization of power spinning process based on the RSM with catorgic 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 in the RSM mentioned above, Brenneman and Myers [34] proposed 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 as 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 experimental design. The detailed parameters of each factor are shown in Table 3. Among them, the roller shape as a discrete factor is a categoric parameter, which is divided into E1, E2 E3 three types (see Fig. 3). Detail roller parameters are shown in Table 4.

Table 3 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	-

Table 4 Parameters of roller shape.

Roller shape	a-Roller width/ mm	r-Roller nose radius/ mm	R-Roller radius/ mm	α -Bite angle/ °	β -Exit angle/ °
E1	20	1.2	62-75	25	25
E2	9.6	0.5	62-75	30	60
E3	44	2	62-75	-	-

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, which take the maximum roller force R4 as the response and take four continuous variables and one discrete variable as the factors, as shown in Table 5. Because the long calculation time of 3D multi-step simulation, the 2D simulation is taken as the experimental design object.

Table 5 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

4.4.2 Model set up and reliability test

According to the analysis of the results in Table 5. Figure 15 shows the disturbance distribution diagram of various factors. For R4 as small as possible, under the action 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 action of roller E2, when the factors A, B, C and D are close to - 1 level, R4 decreases to about 3 Kn. Under the action 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.

Fig. 15 Factors disturbance distribution (a) E1 (b) E2 (c) E3.

Adopting 2FI model and fitting the data, the fitting equation considering roller E1, E2 and E3 is shown as follows:

$$\begin{aligned}
 R4 = & 3.39 + 0.12A + 0.12B + 0.035C + 0.092D - 0.063E1 - 0.27E2 \\
 & + 0.16AB - 0.045AC - 0.017AD + 0.00838AE1 + 0.041AE2 - 0.022BC \\
 & + 0.04BD + 0.02BE1 + 0.022BE2 - 0.033CD - 0.003509CE + 0.092CE2 \\
 & - 0.13DE1 + 0.2DE2
 \end{aligned} \quad (38)$$

The analysis of variance of each factor is shown in Table 6, 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.

Table 6 Variance analysis of regression equation for R4.

Source	Sum of Squares	DF	Mean Square	F	Pr>F	Significance
Model	4.172976	20	0.208649	5.73535	0.0053	Significant
A-A	0.340826	1	0.340826	9.368639	0.0136	Significant
B-B	0.406722	1	0.406722	11.18001	0.0086	Significant
C-C	0.036571	1	0.036571	1.005278	0.3422	
D-D	0.210811	1	0.210811	5.794774	0.0394	Significant
E-E	1.98383	2	0.991915	27.26582	0.0002	Significant
AB	0.526151	1	0.526151	14.46287	0.0042	Significant
AC	0.039165	1	0.039165	1.076567	0.3265	
AD	0.005712	1	0.005712	0.157013	0.7012	
AE	0.031666	2	0.015833	0.435221	0.6600	
BC	0.009707	1	0.009707	0.26683	0.6179	
BD	0.032932	1	0.032932	0.905241	0.3662	
BE	0.020302	2	0.010151	0.279027	0.7628	
CD	0.022455	1	0.022455	0.617238	0.4523	
CE	0.119136	2	0.059568	1.637402	0.2475	
DE	0.510929	2	0.255465	7.022229	0.0145	Significant

4.4.2 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. Only the minimum R4 distribution of different factors is analyzed below.

According to Fig. 15, when using roller E1 to find the influence of factors A and B on the maximum roller force, the variation of factors C and D are coincided with the maximum roller force. Therefore, the influence distribution of factors A and B is obtained by horizontal adjustment of the two factors (see Fig. 16). When both C and D are at level 1, the blue area in the figure is large, and the maximum roller force in this area is small; While C and D are in 0 level, the blue area is the smallest, and the distribution range of R4 is wide. Therefore, at this level of C and D, R4 is more sensitive to the changes of factors A and B.

Fig. 16 Interaction effect of factor A and B on R4 under E1 roller effect **(a)** factor C and D on -1 level **(b)** factor C and D on 0 level **(c)** factor C and D on +1 level.

When roller E2 is adopted and factors C and D are at the - 1 level, the maximum roller force 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. 17). When factors C and D are at the - 1 level, all the areas in the figure are blue, and the maximum roller force in this area is small. When C and D are at level 1, there is no blue area distribution, and the distribution range of R4 is wide. Therefore, at this level of C and D, R4 is more sensitive to the changes of factors A and B.

Fig. 17 Interaction effect of factor A and B on R4 under E2 roller effect **(a)** factor C and D on -1 level **(b)** factor C and D on 0 level **(c)** factor C and D on +1 level.

When roller E3 is adopted and factors C and D are at the 1 level, and the maximum roller force 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 the Fig. 18 that no matter which level C and D are located, almost all areas in the figure are red, and the maximum roller force in this area is large. Therefore, the roller E3 is not suitable for power spinning process.

Fig. 18 Interaction effect of factor A and B on R4 under E3 roller effect **(a)** factor C and D on -1 level **(b)** factor C and D on 0 level **(c)** factor C and D on +1 level.

When C and D are at level 1, the rollers E1 and E3 have smaller R4. At this level, the roller E2 does not have any advantages. 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. 19. It can be seen by comparing Fig. 19a and Fig. 19d, roller E2 has obvious advantages under power spinning process, and its shape is more conducive to reduce the maximum roller force and improve the performance of the equipment under the same roller trace and thinning rate.

Fig. 19 Interaction effect of factor A and B on R4 when factor C and D on +1 level **(a)** under E1 roller effect **(b)** under E2 roller effect **(c)** under E3 roller effect **(d)** factor C and D on -1 level, under E2 roller effect.

It can be seen from Fig. 19 that R4 is small when AB is at - 1 level for the three types of rollers. So Fig. 20 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 the roller force of E2 is the smallest and the blue area is the largest.

Fig. 20 Interaction effect of factor C and D on R4 when factor A and B on -1 level **(a)** under E1 roller effect **(b)** under E2 roller effect **(c)** under E3 roller effect.

4.4.3 Model optimization and simulation verification

Experiment 14 in Table 3 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 is, the greater the roller feeding velocity is, the smaller the installation angle (negative angle) is, and the smaller the roller radius is. 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 from in Fig. 3 and Table 2 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. In order to further verify the influence of the roller width on the maximum roller force, 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 used for simulation, and the force distribution in Z force of roller is compared, as shown in Fig. 21. It can be seen from the figure that under the action of the same roller width, the stress distribution of roller E2 is still the smallest. Therefore, this roller shape can be preferred.

Table 7 Optimization design scheme.

A	B	C	D	E	$R1_{pre}$	$R1_{act}$
-1	1	-1	-1	E2	2.44018	2.448

Fig. 21 Roller force comparison of three shapes of roller under same roller width.

Fig. 22 Optimized process comparison under 0° and -5° installation angle (a) wall thickness (b) maximum roller force.

The 3D simulation results of the same process with 0° installation angle and -5° installation angle are compared in Fig. 22. 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, 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 parameters optimization in power spinning process of difficult-to-deform material GH3030. The main conclusions can be drawn as follows:

(1) The traditional calculation method of forming height is based on the equal volume principle of regular shape billet. For the multi-step process of conventional spinning and power spinning, the section of billet is an irregular shape with non-uniform wall thickness and springback which cannot be calculated by the traditional method. Therefore, the length change of deformation zone of symmetrical (cone and arc) and step rollers is deduced. The accurate forming height and step surface position can be obtained through the calculation, which can be used for roller trace optimization of power spinning process.

(2) When the installation angle is negative, the metal at the front of the roller feed direction is pressed into a small slope due to the bite angle. The smaller the slope, the easier the roller feeding and the smaller the roller force on the feed direction. However, when the negative angle is too large, the material removal of the roller is very serious which may cause surface defect and crack. The roller nose radius also has a great impact on the maximum roller force. Small roller nose radius is easier to realize the material removal effect when contacting with the billet. While the roller radius has little effect on the force on the maximum roller force.

(3) The uneven flange of the workpiece is mainly due to the serious metal accumulation at the flange of the tube billet, the springback and the non-uniform deformation at the fifth stage. 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 is adopted to optimize the power spinning process parameters with discrete factor roller shape. The results 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.

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Author contribution

Zixuan Li: Conceptualization, Simulation, Experiments, Writing-original draft, Funding acquisition

Xuedao Shu: Review, Funding acquisition

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