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To cite this article: R Y Guan *et al* 2020 *J. Phys.: Conf. Ser.* **1507** 102035

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# Optimization design of spinning process of titanium alloy cylinder based on numerical simulation technology

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**Abstract.** Power spinning is a very complicated plastic forming process, and its processing quality involves many and complicated process parameters. The simufact.forming software is used to simulate the power spinning of the titanium alloy cylindrical parts. The effects of technological parameters such as attacking angle, roller nose radius, feed rate, spinning temperature, etc. on cylindrical parts accuracy, spinning force, and stress-strain distribution are systematically studied. The causes of spinning process defects are analyzed, and the sensitivity of process parameters that affected spinning quality is ranked. Through orthogonal test analysis, it is determined that a set of optimal process parameters for the titanium alloy cylindrical part spinning process: attacking angle is attacking angle  $20^\circ$ , the roller nose radius is 10mm, feed rate is 1mm/r, spinning temperature is  $850^\circ\text{C}$ . The spinning process of titanium alloy cylindrical parts is initially formed, which lays the foundation for the subsequent spinning process tests of titanium alloy cylindrical parts.

## 1. Introduction

Titanium alloys because of their high strength, low density, high temperature resistance, corrosion resistance, etc., have been increasingly used in aerospace, automotive, medical and other fields, and has become essential metal materials for new equipment and new technologies. However, titanium alloy materials are expensive, and rods are used for machining during the preparation of cylindrical parts. This forming method has low material utilization and causes a lot of waste. Spinning technology can effectively improve the utilization rate of materials. However, the spinning of titanium alloys at room temperature has difficulties in processing such as large deformation resistance and poor plasticity. And the influencing factors of spinning forming are complicated. In this paper, a numerical simulation study is carried out for the spinning forming process of titanium alloy cylindrical parts. Effectively improve the development cycle, reducing the cost of test, try to optimize the process parameters before the spinning test. Combined with the process test, the test effect is verified.

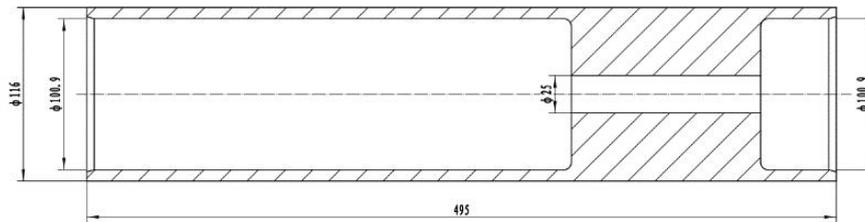
## 2. Foundation of finite element model

### 2.1. Spinning blank parts dimensions

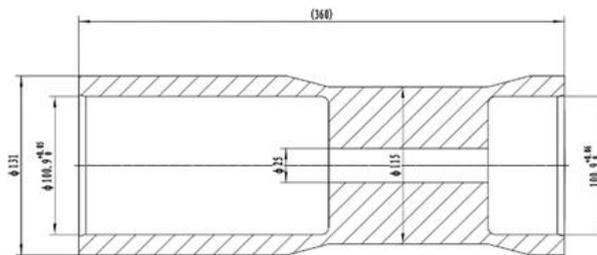
According to the structure of the cylindrical part, it is processed by forward flow forming, that is, the blank flows in the feed direction following the movement of the spinning roller, and the blank is designed in the form with a bottom. Calculate the required volume of the workpiece after spinning, and design the corresponding blank structure. According to the principle of constant volume [1], the



volume of the titanium alloy cylinder spinning blank should not be less than 2.4kg. The dimensions of the titanium alloy cylindrical part and the spinning blank are shown in figures 1 and 2. The specific dimensions of the blank are: outer diameter  $D = \Phi 131\text{mm}$ , inner diameter  $d = \Phi 100.9\text{mm}$ , and length  $L = 350\text{mm}$ .



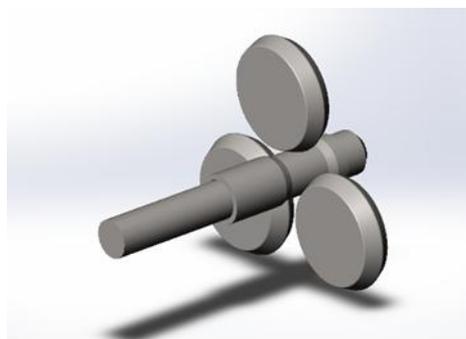
**Figure 1.** Titanium alloy cylinder dimensions.



**Figure 2.** Dimensions of spinning blanks of titanium alloy cylindrical part.

## 2.2. Model assembly

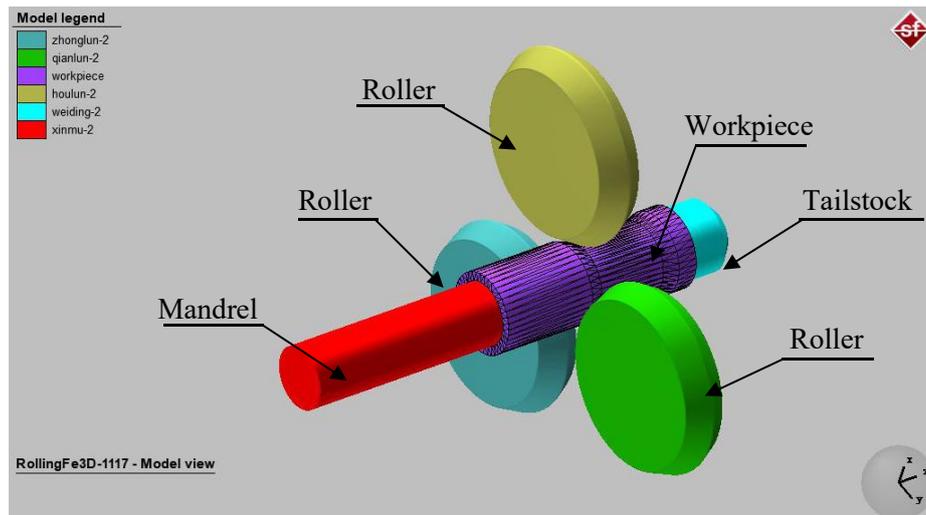
After modeling the parts in the Solidworks software, perform the overall assembly of the spinning model according to the plan. The cylindrical part will generate a large amount of spinning force during the spinning process. In order to maintain balance, prevent eccentricity of the mandrel due to uneven force, and avoid vibration caused by uneven force on the spinning equipment. The three spinning rollers adopt a spinning method of  $120^\circ$  uniform distribution. The distance between the axis of the spinning roller and the axis of the blank is determined by the percent thickness reduction, which is an important process parameter for the power spinning. According to the results of spinning experiments on cylindrical parts in foreign literatures, it can be known that when the percent thickness reduction fluctuates within the range of 30% or less, the wall thickness deviation and inner diameter size deviation results of spinning parts are better [2]. The assembled 3D solid model is shown in figure 3.



**Figure 3.** 3D geometric model of spinning assembly.

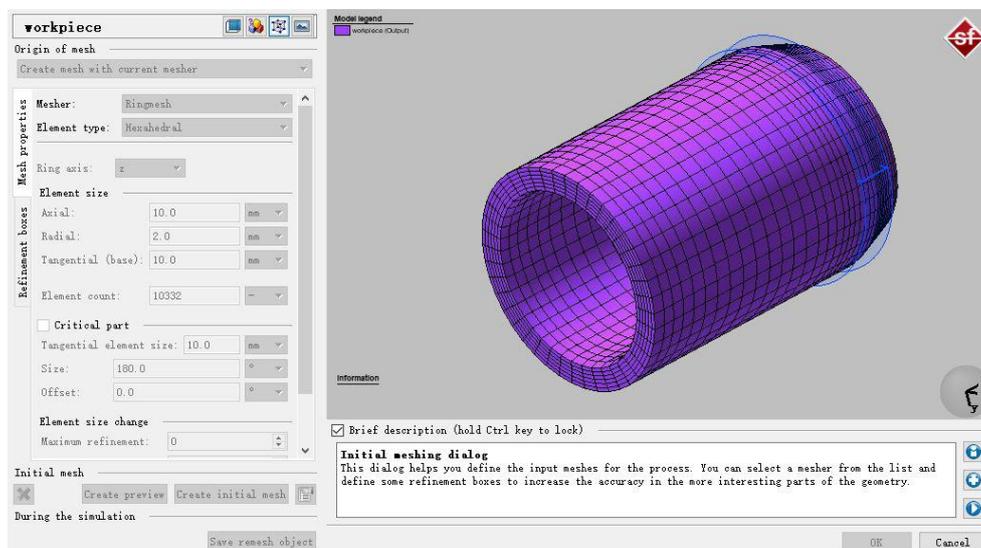
### 2.3. The finite element model

The simufact software has a powerful CAD software interface. The solid model is assembled through 3D modeling software, converted into STL format, and imported into the simufact software. The movement track of the spinning roller is given by the displacement method, and set the process parameters including spinning temperature, roller nose radius, attacking angle, feed rate, thickness reduction and offset. A numerical simulation model is established according to the process of spinning forming a cylindrical part with a cup bottom, as shown in figure 4.



**Figure 4.** Spinning model of titanium alloy cylinder.

The simufact software has a tube meshing tool (Ringmesh), which determines the thickness of the mesh by setting the axial and radial element size length. In order to transfer the nodal forces between the elements, the mesh must be fine enough to ensure contact continuity. In the 3D simulation analysis model, simplify the model accordingly to improve the calculation efficiency. Set the axial unit size to 10mm, the radial unit size to 2mm, and the tangential unit size to 10mm. The mesh refinement is performed at the chamfer, that is, the turning position of the spinning roller, to generate a three-dimensional mesh with a total of 10,332 three-dimensional elements.



**Figure 5.** Meshing of 3D models.

### 3. Simulation of orthogonal test scheme

#### 3.1. Selection of process parameters

Practice shows that under the conditions of other process parameters, the selection of process parameters such as spinning temperature, roller nose radius, and feed rate has a great impact on the forming quality, spinning force, and stress-strain distribution of the spinning process. Therefore, it is used as an optimization selection object.

The spinning temperature will directly affect the plastic deformation ability of the material. If the temperature is too low, the plastic deformation ability of the titanium alloy cannot be improved, and if the temperature is too high, the blank will be too soft, which will not only fail to produce qualified products but also waste resources.

Combining the characteristics of titanium alloy materials, according to the results of thermal simulation and empirical analysis, a suitable spinning temperature is obtained. The temperature is initially designed to be 850°C, 900°C, and 950°C for optimization analysis.

The spinning adopts three rollers, and the roller structure adopts a double-cone surface spinning roller including a forming section and an exit section. The three rollers structures and attacking angles are the same, and the attacking angle  $\alpha$  is 20°. The radius  $R$  of the three rollers are the same, and the preliminary design is 6mm, 8mm and 10mm for optimization analysis.

Titanium alloy materials are very sensitive to deformation rates. As the feed rate increases, the equivalent stress increases significantly; as the deformation rate increases, the difference between the maximum and minimum equivalent stresses in the workpiece increases significantly. The initial design feed rate is 0.8mm/r, 1 mm/r, 1.2mm/r, and the influence on the forming is studied. See table 1 for other simulation parameters.

**Table 1.** Spinning numerical simulation process parameters of titanium alloy cylindrical parts.

Process parameters	Value
Percent thickness reduction $\varepsilon/\%$	20
Diameter of the roller $D/\text{mm}$	300
Roller nose radius $\rho/\text{mm}$	6, 8, 10
Attacking angle $\alpha/(\text{°})$	20
Spinning temperature $T/(\text{°C})$	850°C, 900°C, 950°C
Coefficient of friction $\mu$	0.08
Spindle speed $v/\text{rpm}$	100
Feed rate $S/(\text{mm}/\text{r})$	0.8, 1, 1.2

#### 3.2. Orthogonal test analysis

The roller nose radius, spinning temperature, and feed rate are selected as orthogonal test factors, and three levels are set for each factor. The combination of each factor level is shown in table 2. In the course of the experiment, an  $L_9(3^3)$  orthogonal table is selected, and an orthogonal test scheme of 3 factors and 3 levels is designed.

**Table 2.** Factors affecting spinning.

Sequence	Roller nose radius	Spinning temperature	Feed rate
1	6mm	850°C	0.8mm/r
2	8mm	900°C	1.0 mm/r
3	10mm	950°C	1.2 mm/r

According to the material characteristics and blank size of the titanium alloy, orthogonal experimental analysis is performed on the titanium alloy spin-forming process parameters. The orthogonal experimental simulation scheme and results are shown in table 3.

**Table 3.** Orthogonal experiment simulation scheme and results.

Sequence	A	B	C	Max equivalent stress (MPa)	Thickness deviation (mm)
	$\rho$ /(mm)	T/(°C)	S/(mm/r)		
1	1(6)	1(850)	1(0.8)	394.51	0.29
2	1(6)	2(900)	2(1.0)	383.98	0.28
3	1(6)	3(950)	3(1.2)	393.98	0.36
4	2(8)	1(850)	2(1.0)	378.41	0.29
5	2(8)	2(900)	3(1.2)	394.62	0.31
6	2(8)	3(950)	1(0.8)	394.22	0.30
7	3(10)	1(850)	3(1.2)	382.52	0.23
8	3(10)	2(900)	1(0.8)	394.65	0.29
9	3(10)	3(950)	2(1.0)	384.62	0.27

### 3.3. Selection of target items

In the power spinning process of cylindrical parts, the accuracy of the spinning part is an important evaluation index. Generally, the wall thickness deviation is used to measure the accuracy of the outer diameter. The thickness deviation is the difference between the actual size of the thickness and the nominal size.

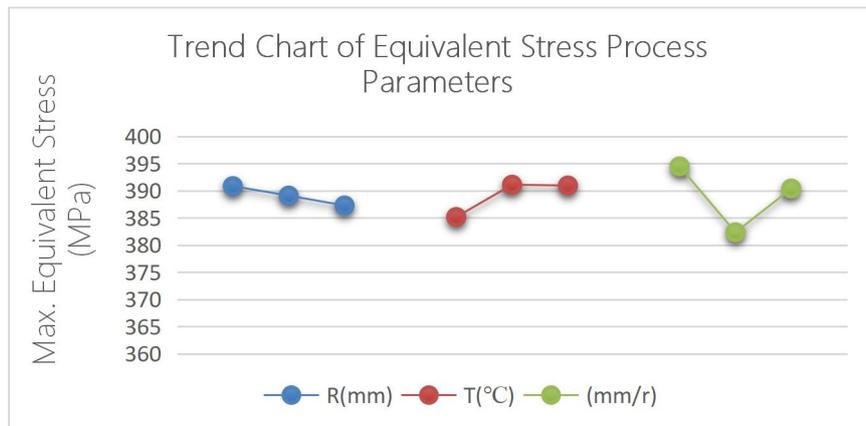
The existence of residual stress in the workpiece will reduce the stiffness and stability of the structure. It also affects the structure's resistance to brittle fracture, corrosion, high temperature creep, and resistance to cracking. Therefore, stress analysis of titanium alloy cylindrical parts after power spinning is very important.

### 3.4. Analysis of orthogonal test results

The numerical calculation results in table 3 are analyzed. Establish equivalent stress range analysis table, table 4, and wall thickness deviation range analysis table, table 5. The first number corresponding to the row of  $K_l$  indicates the sum of the index values of each test result when the level of factor 1 is 1, and is recorded as  $K_l$ . The first number in the subscript represents the level, and the second number represents the factor. The first number corresponding to the row of  $K_l$  is recorded as  $K_{1l}$ .  $\bar{K}_{1l}=K_{1l}/3$ , and so on. Range  $R_i = \max\{\bar{K}_{ni}\} - \min\{\bar{K}_{ji}\}$ , where  $\bar{K}_{ji}$  is the index average value of the  $i$ -factor and  $j$ -level. The larger the range  $R$  of a factor, the more significant the effect of the factor on the objective function. Conversely, the smaller the range  $R$ , the less significant the effect of the factor [3].

**Table 4.** Equivalent stress orthogonal test results.

Equivalent stress	A	B	C
	$\rho$ /(mm)	T/(°C)	S/(mm/r)
$\bar{K}_1$	390.823	385.146	394.460
$\bar{K}_2$	389.083	391.083	382.337
$\bar{K}_3$	387.263	390.940	390.373
$R$	3.56	5.937	12.123



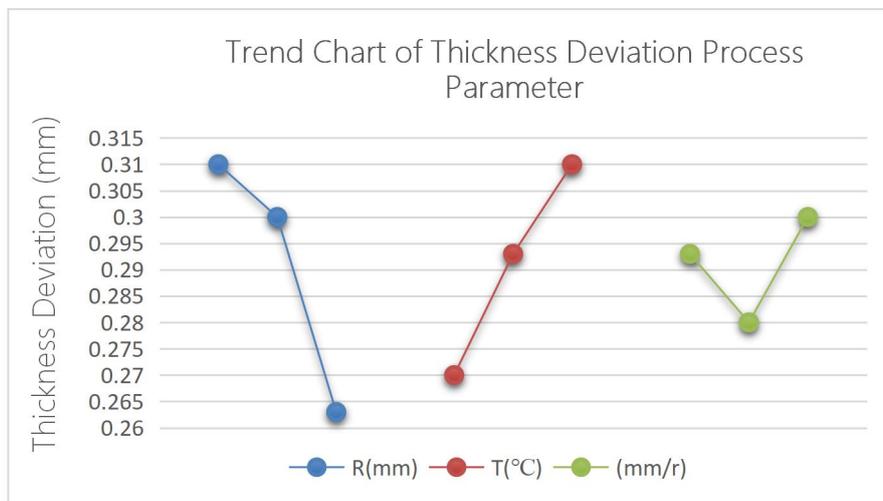
**Figure 6.** Trend chart of equivalent stress process parameters.

According to the orthogonal test results, it can be seen that the range result  $R_C > R_B > R_A$ , the factor that has a greater effect on the equivalent stress of the workpiece is the feed rate > spinning temperature > roller nose radius. Based on the results of orthogonal analysis of the equivalent stress, the optimal process combination is selected as follows: the roller nose radius is 10mm, the spinning temperature is 850°C, and the feed rate is 1mm/r.

In the same way, the influencing factors of thickness deviation of titanium alloy cylinder are analyzed.

**Table 5.** Thickness deviation orthogonal test results.

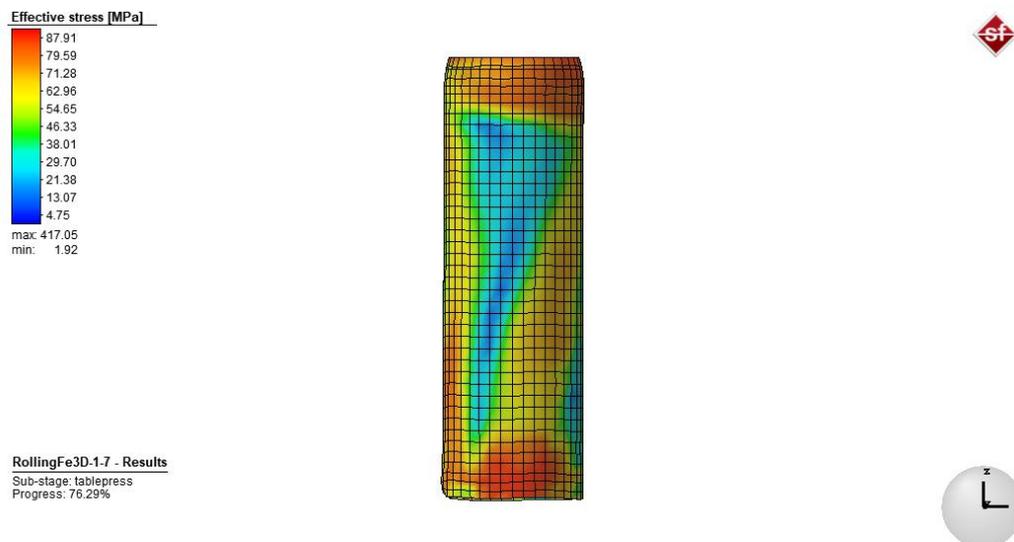
Thickness deviation	A	B	C
	$\rho/(mm)$	T/(°C)	S/(mm/r)
$\bar{K}_1$	0.310	0.270	0.293
$\bar{K}_2$	0.300	0.293	0.280
$\bar{K}_3$	0.263	0.310	0.300
R	0.047	0.040	0.020



**Figure 7.** Trend chart of thickness deviation process parameter.

According to the orthogonal test results, it can be seen that the range result  $R_A > R_B > R_C$ , and the factor that has a greater influence on the thickness deviation is the roller nose radius  $>$  spinning temperature  $>$  feed rate. Through the orthogonal analysis of the thickness deviation results, the optimal process combination is selected as follows: the roller nose radius is 10mm, the spinning temperature is 850°C, and the feed rate is 1mm/r.

In summary, the best combination of the effects of each factor on the thickness deviation is  $A_3B_1C_2$ , and the best combination of the effects on the equivalent stress is  $A_3B_1C_2$ . The results of the best combination of the two groups are the same, and the optimal spinning solution is obtained. The best solution is that the roller nose radius is 10mm, the spinning temperature is 850°C, the feed rate is 1mm/r, the attacking angle of the roller is 20°, and the diameter D of the roller is 300mm. Through numerical simulation analysis of the best process plan, the results are obtained: the maximum spinning force is 10126N, and the maximum wall thickness deviation is 0.21mm. After multiple steps of spinning, the equivalent stress of the final workpiece is 417.05 MPa. Figure 8 is the stress cloud diagram of spinning process [4].



**Figure 8.** Optimal combined multi-pass processing stress cloud diagram.

#### 4. Conclusion

The orthogonal test results show that under the same conditions of other process parameters, the size of the roller nose radius is an important factor affecting the spinning accuracy of the cylindrical part, and the effects of spinning temperature and feed rate on the spinning accuracy of titanium alloy cylinders are secondary.

According to the analysis of the equivalent stresses of the inner and outer diameters of the titanium alloy cylindrical parts after spinning, the equivalent stress distribution is not uniform. According to the analysis of the equivalent strain of the titanium alloy cylindrical parts, after three steps of spinning, the titanium alloy cylinder has a small effect on the dimensional accuracy of the cylinder as the temperature decreases.

The optimized process parameter model of spinning of a certain type of titanium alloy cylindrical part is obtained, that is, the roller radius is 10mm, the spinning temperature is 850°C, the feed rate is 1mm/r, the attacking angle is 20°, and the diameter of the spinning roller is 300mm.

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