Numerical Analysis of Multi-pass Cold Spinning of Superalloy of Cylindrical Part

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Abstract. In view of the poor plasticity and easy cracking of superalloy at room temperature, the multi-pass cold spinning of cylindrical part was studied. Firstly, the tensile test of superalloy GH3030 is carried out, and the true stress-strain curve is obtained. Then, the numerical models of 250 and 87.5 diameter-thickness ratio blank are established, and the stress and strain field, wall thickness distribution and tool force distribution of the cylindrical part are analyzed and compared. The wrinkle model of 250 diameter-thickness ratio blank was analyzed, and the experiment of 87.5 diameter-thickness ratio blank was carried out. The results show that the wall thickness of the cylindrical part has metal accumulation at the flange, and the thickness of the waist is very small, which is easy to crack under the repeated forming of the roller; the wall thickness distribution of the large diameter-thickness cylindrical part is more uniform, but it has a great challenge to the equipment force and the equipment stiffness. The main reason for the flange wrinkle is staggered distribution of the tangential tensile and compressive stress of the whole flange.

1. Introduction
Metal spinning process, as a complex rotary forming process, can be traced back to hand-made pottery technology of thousands of years ago. With the continuous development of various technologies, spinning technology is developing on new material, new technology, such as dieless spinning, non-circular spinning, and new method, such as using artificial intelligence to optimize the process parameters and so on[1-3].

At present, most of the experimental materials selected for spinning are aluminum alloy with high formability, which have good plasticity at room temperature and are not easy to crack after annealing. However, for fields such as aerospace, the aluminum alloy cannot meet the working conditions. The superalloy material, which takes iron, nickel, cobalt as the base, therefore can work under the high temperature above 600 °C for a long time. At present, the research on superalloy mostly focuses on hot spinning process, Xu et al. [4] adopted spinning process to form a superalloy aeroengine casing to replace the original forging process. By studying the mechanism of the temperature effect on the spinning deformation behavior of superalloy, the relationship between temperature and the process parameters such as the mandrel rotation velocity and the roller feed velocity is obtained, and the key technologies such as temperature control and forming quality control in hot spinning are solved, the mechanical properties of the parts are improved. Hot Spinning of Ni-Cr-W-Mo superalloy was studied by Sun et al. [5-6] at temperature of 1050 °C and 1100 °C, and qualified spinning parts were obtained.
Chen et al. [7] found the microstructure evolution of TA15 titanium alloy during hot spinning of cylindrical part. And the influence of wall thickness thinning ratio on microstructure evolution of TA15 was discussed. Shan et al. [8] investigated the effect of microstructure on the deformation behavior of Ti-6Al-2Zr-Mo-1V alloy tube by hot reverse spinning process. Wang et al. [9] found the effects of the process parameters on the dimensional accuracy of the cylindrical part by using stagger spinning method of GH4169 superalloy. Miu et al. [10] formed a large thin-walled complex revolving shell casing with GH3536 superalloy and studied the plastic deformation behavior of complex physical field in multi-pass spinning process. Xiao et al. [11] found the process parameters optimization and shape control of Haynes230 tube based on processing map. Niklasson [12] studied the heat treatment temperature and recrystallization of shear spinning for the manufacture of superalloy 718 aeroengine casing. The method of complete recrystallization was found. Most of the previous researches focus on the hot spinning process of the difficult-to-deformation metals, which is mainly due to the great difference of the plasticity of the superalloy at room temperature and high temperature. However, the workpiece surface is easy to be oxidized in the hot spinning process at high temperature, and the oxide scale is grown on the metal surface. So the surface quality is rough, and the cutting amount needs to be reserved. In contrast, there are few studies on cold spinning of superalloy, the main reasons are that the plasticity of superalloy is poor at room temperature, on the one hand, the material is easy to crack, on the other hand, the material is easy to crack, in addition, it has a great challenge to the force and rigidity of spinning equipment, and as the superalloy at the top of the whole pyramid, blind test without theoretical foundation not only results in material waste, but also the huge experimental cost, so it is necessary to study the cold spinning of superalloy.

In this paper, the multi-pass (seven passes) conventional spinning process models of 250 and 87.5 diameter-thickness ratio sheet blank of superalloy GH3030 are established, and the involute roller trace is used to simulate the spinning process, and the stress, strain field, wall thickness and toolforce distribution of the workpiece are analyzed, the wrinkle defect is analyzed in detail, and then the experimental verification of the 87.5 diameter-thickness ratio sheet is carried out.

2. Experimental setup
The QX800-II spinning machine is used in this paper. As shown in Fig. 1, the dimensions and samples of the material tensile specimens are shown in Fig. 2a and 2b, the true stress-strain curves are shown in Fig. 2c, and the chemical composition is shown in Table 1.

| Table 1. Chemical composition of GH3030% |
|---|---|---|---|---|---|---|---|---|---|---|
| C  | S  | Si | Mn | P  | Cr | Fe | Al | Ti | Cu | V  |
| 0.057 | 0.0020 | 0.368 | 0.392 | 0.010 | 19.89 | 0.441 | 0.040 | 0.194 | 0.2 | 0.26 |

Figure 1. QX800-II spinning machine.  Figure 2. (a) tensile specimen size GH3030 (b) experimental specimen (c) true stress-strain curve.
3. Finite element analysis

3.1. Finite element modeling

The simulation model is set up in Simufact. Forming. Table 2 shows the comparison of process parameters between the two simulation models of 175 mm diameter and 500 mm diameter blanks. The thickness of the blanks is 2 mm. Then we can get the diameter-thickness ratio of the two models are 87.5 and 250. The mesh size of 175 mm blank is about 2 mm, and 5 mm of the 500 mm blank. As can be seen from Table 2, the process parameters also changed greatly after the diameter is changed. When the roller feed ratio and the attaching-mandrel velocity are 2 / 3 of the 175 mm blank and the mandrel velocity is increased to 500 rpm, the forming effect is better, the wall thickness is more uniform. However, when the roller feed ratio and the attaching-mandrel velocity are 5 / 9 of the 175 mm blank, the blank appears serious wrinkle in the forming process. When the mesh size is larger, thickness layers are fewer, so the calculation time is shorter. That is the reason why simulation forming time of 500 mm blank in the table is shorter than that of 175mm. When we use the same mesh size and layers in both simulations, the calculation time of 500 mm blank cannot be carried out for several months.

| Diameter-thickness ratio | 87.5 | 250 | 250 (Wrinkle) |
|--------------------------|------|-----|--------------|
| Roller feed ratio (mm/r)  | 1.17 | 0.78| 0.65         |
| Attaching-mandrel velocity (mm/min) | 200 | 133 | 111         |
| Mandrel rotation velocity (rpm) | 300 | 500 | 500         |
| Mesh size (mm)            | 3    | 5   | 5            |
| Element numbers           | 9444 | 6232| 6232         |
| Calculation time (h)      | 473.48| 317.45| Interrupt    |

3.2. Analysis of numerical results

As shown in Fig. 3, it is found that even the distribution of wall thickness in the thinnest annular region is not uniform. The flange quality of the cylindrical part with 175 mm blank is relatively good and there is no such defect (as shown in Fig. 4). Fig. 3 verified this point, for 500 mm blank, the wall thickness distribution in this region fluctuates to a certain extent, the deviation is close to 0.1 mm. From Fig. 3, the minimum wall thickness is about 1.65 mm, the maximum wall thickness is about 2.35 mm, the maximum wall thickness deviation is about 0.7 mm and the maximum thinning rate is about 35%, therefore, the axial distribution of the wall thickness is not uniform. For 175 mm blank, the results show that the minimum thickness is 1.22 mm, the maximum thickness is more than 2.4 mm, the maximum thickness deviation is nearly 1.2 mm, and the maximum thickness reduction rate is about 60%. It can be seen that when the same roller trace and the same tools are used to form the blanks of different diameter-thickness ratio with different process parameters, the deviation of the maximum wall thickness is quite different, larger diameter-thickness ratio causes more uniform wall thickness.

In addition, large diameter-thickness ratio cylindrical parts require very high toolforce of the equipment. Fig. 5 shows the force of mandrel and roller in the two simulation models, in Fig. 5a, the maximum Z (axial) force on the mandrel at the initial stage is more than 700 kN, nearly 7 times that on the 175 mm blank. In Fig. 5b, the maximum force on the roller is nearly 20 kN, only about 5 kN higher than that on the 175 mm blank. Therefore, it is a great challenge to the toolforce and the equipment stiffness for the superalloy cold spinning of large diameter-thickness ratio cylindrical parts.
3.3. Analysis of wrinkle defect

Wrinkle defects are very common in large diameter-thickness ratio cylindrical parts. Therefore, it is necessary to analyze the mechanism of wrinkle defects. Wang [13] thinks that the wrinkle defect is mainly caused by the shear stress on the blank. The blank mainly has a certain tangential compressive stress at the circumference of the contact area of the roller at the first forming pass and the fillet area of the mandrel and back-plate. At the end of the first pass, there is a circular shear stress area around the waist of the blank. In addition, to the front part of the roller contact area, there is also a non-uniform distribution of tangential compressive stress at the flange. The tangential compressive stress in the flange recovers to the non-uniform distribution of the tangential tensile stress, while the front part of the contact area of the roller is still in the state of tangential compressive stress, except the contact area of the roller and its circumferential area, the tangential tensile stress around the flange is not uniformly distributed, as can be demonstrated by the distribution in the red region. The final blank is heavily wrinkled at the fifth pass as shown in Fig. 6e, when the simulation is interrupted, there is a serious wrinkle on the flange.

Fig. 6a and b show that the wrinkle-free parts have a uniform tangential tensile stress distribution in the circumferential direction of the flange, however, there is a large number of non-uniform tangential compressive stress distribution in the wrinkle parts, and some tangential tensile stress mixed in it. The shear stress of the flange is analyzed and compared every 45 degree in circumferential direction. It can be seen from Fig. 6c and d that the values of the tangential tensile stress vary a little except the compressive stress in the roller contact area, and the tensile and compressive stress are staggered at the flange of the wrinkle part. Fig. 6e and f show the comparison of the shapes and shear stresses of the fifth pass wrinkle and the wrinkle-free parts. Although the flange of the wrinkle parts is also mostly in the state of tangential tensile stress at this time, the values of tensile stress in the area of serious wrinkle are obviously uniform, but the flange tensile stress distribution is uniform and the shape is smooth for the wrinkle-free part.
Therefore, it is believed that the wrinkle is mainly due to the incomplete recovery of the tangential compressive stress in the area when the roller leaves the original contact area, and the incomplete change of the tangential compressive stress into the tangential tensile stress, which results in the residual tangential compressive stress in the area, thus, the circumferential tensile and compressive stresses of the entire flange are staggered, resulting in distortion and wrinkle.

![Figure 6. Tangential stress comparison (a) wrinkle part in first pass (b) wrinkle-free part in first pass (c) tangential stress circumferential distribution of wrinkle part flange (d) tangential stress circumferential distribution of wrinkle-free part flange (e) wrinkle part in fifth pass (f) wrinkle-free part in fifth pass.](image)

3.4. Experimental verification

![Figure 7. 175 mm diameter experimental samples (a) wrinkle (b) crack (c) finished part.](image)

It is found that the wrinkle and cracking in cold spinning of superalloy can be effectively avoided by optimizing the process parameters such as the roller feed ratio, the number of forming passes and the roller trace. From Fig. 4 and 7c, we can see that the result of simulation model is reliable.

4. Conclusion

1. The wall thickness distribution of the product shows a circular distribution, which decreases at waist and then increases at the flange. The metal flows along the roller feed direction, and there has metal accumulation at the flange, and the thickness of the waist is very small, under the repeated action of the roller, it is easy to break.

2. The maximum force on the mandrel of 250 diameter-thickness ratio blank is about 7 times than that on the 87.5 diameter-thickness ratio blank, and the force of the roller is increasing about 30%. When the feed ratio of the roller and the attaching-mandrel velocity are 2 / 3 of the 87.5 diameter-
thickness ratio blank and the mandrel rotation velocity is increased to 500 rpm, the forming effect of 250 diameter-thickness ratio ratio blank is better.

(3) The wrinkle defect is mainly due to the fact that the tangential compressive stress in the area does not fully recover to the tangential tensile stress when the roller leaves the original contact area, which results in the residual tangential compressive stress in the area. The entire flange in the circumferential region is staggered with the tangential tensile and compressive stress, resulting in distortion.

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