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Process factors influencing spinning deformation of thin-walled tubular part with longitudinal inner ribs①

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Abstract: As a successively and locally plastic deformation process, ball backward spinning is applied for the purpose of producing thin-walled tubular parts with longitudinal inner ribs. By simplifying ball backward spinning as forward extrusion mechanics model, slab method is used in order to solve spinning force. Based on plastic mechanics, the influence of the process parameters involved on formability of inner ribs as well as the quality defects of spun parts is analyzed so as to present an approach to acquire the desired parts. The quality of inner ribs is one of the critical tasks in obtaining the desired spun workpieces and the height of inner rib depends greatly on spinning material, ball diameter, feed ratio, and wall thickness of tubular blank. The knowledge of the influence of process variables such as ball diameter, feed ratio, and wall thickness of tubular blank on the spinning process is essential to prevent the quality defects of the spun parts and obtain the desired spun parts.

Key words: ball spinning; power spinning; slab method; spinning force; spinning
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1 INTRODUCTION

Thin-walled tubular parts with longitudinal inner ribs emerge in order to adapt to the development of aeronautic industry, aerospace industry and military industry. Traditional plastic working processes have been unable to meet the demand of producing thin-walled tubular parts with longitudinal inner ribs. As a successively and locally plastic deformation process, ball backward spinning plays a significant role in forming thin-walled tubular parts with longitudinal inner ribs. The attractiveness of ball backward spinning comes from its ability to manufacture spun parts with excellent properties so that it can be more efficient in forming thin-walled tubular parts with longitudinal inner ribs. However, mechanism of power spinning deformation of thin-walled tubular parts with longitudinal inner ribs is pretty complex and the height of inner ribs is difficult to control. Forming the desired height of inner ribs is one of the most critical tasks in obtaining the desired spun workpieces. It is evident that the height of inner ribs depends mainly on spinning material, ball diameter, feed ratio, and wall thickness of tubular blank. Without the knowledge of the influence of process variables such as ball diameter, feed ratio, and wall thickness of tubular blank on spinning formability of thin-walled tubular parts with longitudinal inner ribs, the process parameters cannot be matched rationally, so it would not be possible to obtain the desired spun parts or to predict and prevent the occurrence of defects. Therefore, based on the plastic mechanics, the knowledge of the influence of process variables such as ball diameter, feed ratio and wall thickness of tubular blank on the spinning process is essential to obtain the desired spun parts[1-15].

2 EXPERIMENTAL

Ball backward spinning (As shown in Fig. 1) is more efficient in forming thin-walled tubular parts with longitudinal inner ribs (Fig. 2).

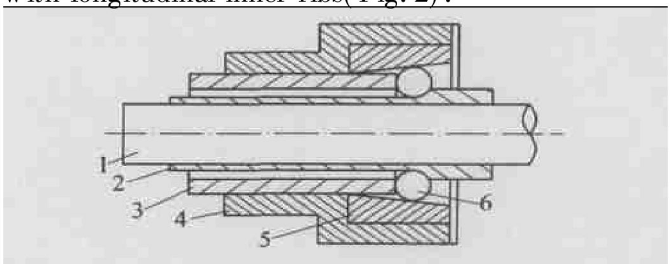

Fig. 1 Schematic diagram of ball backward spinning
1—Mandrel; 2—Spun part; 3—Screw tube; 4—Outer cylinder; 5—Inner ring; 6—Ball

In the course of spinning, the spinning head, which consists of screw tube, outer cylinder and inner ring, is fixed in the chuck of the lathe and turns with the principal axis of the lathe, at the same time, the

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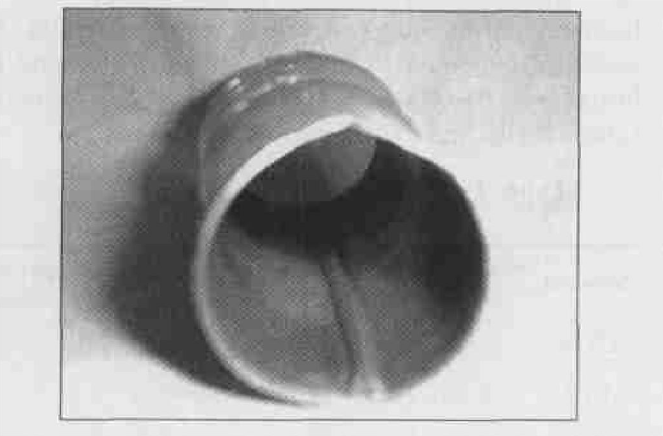

Fig. 2 Schematic diagram of spun part

tubular blank made from LF2 and LY12 aluminum alloy is mounted on the mandrel and feeds with the mandrel along the axial direction. Adjusting the relative displacement between outer cylinder and screw tube results in different gaps between balls and mandrel, so different wall thickness reductions are implemented so as to produce spun parts with various wall thickness and diameter.

Ball backward spinning has been the best plastic working process to form thin-walled tubular parts with longitudinal inner ribs up to now. The quality of inner ribs is one of the critical tasks in obtaining the desired spun workpieces. The height of inner ribs relies mainly on spinning material, ball diameter, feed ratio, and wall thickness of tubular blank.

3 CALCULATION OF CRITICAL SPINNING FORCE

The critical spinning force is defined by the force imposed on deformation zone under a critical state that the inner ribs of the spun part will be formed but cannot be formed. Slab method is used to solve the critical spinning force by combining approximate plastic condition with differential equation of equilibrium. The calculating procedure of the critical spinning force is as follows.

3.1 Simplification of mechanical model

During ball backward spinning, balls are distributed uniformly along the circumference of deformation zone and the radial forces are balanced each other. According to the characteristics of ball backward spinning, ball backward spinning can be regarded as forward extrusion model(Fig. 3) as well as axially symmetrical problem.

3.2 Calculating procedure

1) Derive a slab element in Fig. 4, and write differential equation of equilibrium along the axial direction:

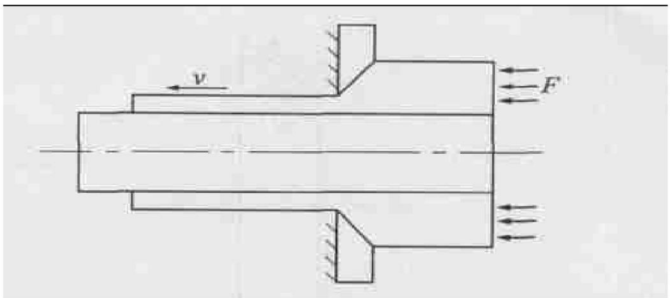

Fig. 3 Forward extrusion model of ball backward spinning

$$\sigma_x \cdot \frac{\pi}{4}(D_x^2 - d_1^2) + p\sin\alpha \cdot \pi D_x \cdot \frac{dD_x}{2} \cdot \frac{1}{\sin\alpha} + \mu_1 \sigma_s \cos\alpha \cdot \pi D_x \cdot \frac{dD_x}{2} \cdot \frac{1}{\sin\alpha} + \mu_2 \sigma_x \pi d_1 \cdot \frac{dD_x}{2} \cot\alpha - (\sigma_x + d\sigma_x) \cdot \frac{\pi}{4}[(D_x + dD_x)^2 - d_1^2] = 0 \quad (1)$$

where d_1 is the diameter of the mandrel, α the attack angle, μ_1 and μ_2 are the friction coefficients, σ_s is the yield strength, D_x is the diameter coordinate, and p is the critical spinning force.

Simplifying equation (1) and neglecting high-order differentiation result in

$$2pD_x dD_x + 2\mu_1 \sigma_s \cdot \cot\alpha \cdot D_x dD_x + 2\mu_2 \sigma_s d_1 \cot\alpha \cdot dD_x - 2\sigma_x D_x dD_x - D_x^2 d\sigma_x + d_1^2 d\sigma_x = 0 \quad (2)$$

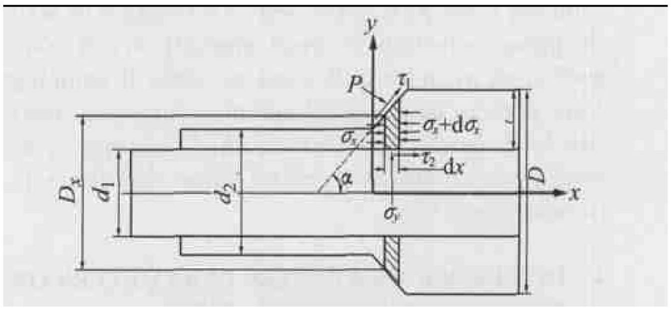

Fig. 4 Analysis of stress in deformation zone

2) Obtain a slab element(Fig. 5) by the cylinder of which diameter is equal to D_x, and write differential equation of equilibrium along the radial direction:

$$\sigma_y \cdot \pi D_x \cdot dx + \mu_1 \sigma_s \sin\alpha \cdot \frac{\pi D_x \cdot dx}{\cos\alpha} - p\cos\alpha \cdot \frac{\pi D_x \cdot dx}{\cos\alpha} = 0 \quad (3)$$

Simplification of equation (3) results in

$$p = \sigma_y + \mu_1 \sigma_s \operatorname{tg}\alpha \quad (4)$$

3) Approximate plastic condition

$$\sigma_y - \sigma_x = \sigma_s \quad (5)$$

Substitution of equation (5) into equation (2) with the help of equation (4) results in equation (6)

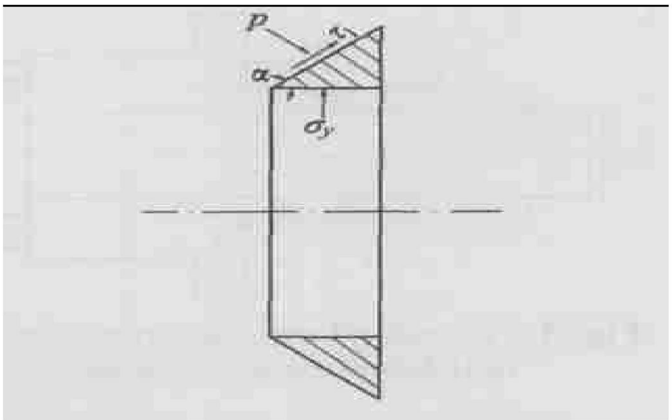

Fig. 5 Analysis of stress of slab element

$$p = \left[(A + B)\ln\frac{D_x - d_1}{2(t - \Delta t)}\right]\sigma_s + (1 + \mu_1 \mathrm{tg}\,\alpha)\,\sigma_s \tag{6}$$

where $A = 1 + \mu_1 \mathrm{tg}\,\alpha + \mu_1 \cot\alpha$, $B = \mu_2 \cot\alpha$, t is the wall thickness of tubular blank, and Δt the reduction in a pass.

In the end, we obtain the expression for the average critical spinning force as

$$p_0 = \frac{1}{2\Delta t}\int_{d_1 + 2t - 2\Delta t}^{d_1 + 2t} p\,\mathrm{d}D_x = \left[(1 + \mu_2 \mathrm{tg}\,\alpha + (\mu_1 + \mu_2)\cot\alpha)\frac{1}{\phi}\ln\frac{1}{1 - \phi} - (\mu_1 + \mu_2)\cot\alpha\right]\sigma_s \tag{7}$$

where ϕ is the wall thickness reduction ratio.

Seen from equation (7), the average critical spinning force p_0 is expressed as a function of wall thickness reduction ϕ, yield strength σ_s, friction coefficient μ, and attack angle α. Only if spinning force is more than critical spinning force can inner ribs be formed. Any factors which increase spinning force or decrease critical force contribute to forming inner ribs.

4 INFLUENCE OF PROCESS PARAMETERS ON FORMABILITY OF INNER RIBS

4.1 Influence of spinning material

Yield strength of metal material and plasticity of metal material have a significant influence on plastic deformation of the spun part. The former determines whether or not metal material is capable of having plastic deformation under a given spinning force. The latter is concerned with deformation degree of metal material. Aluminum alloys LF2 and LY12 are used as spinning materials in the experiment so as to investigate the influence of yield strength and plasticity of metal material on formability of spun parts. It is well known that LF2 has a better plasticity and lower yield strength than LY12. It is seen from Table 1 that the height of inner ribs formed using LF2 is obviously larger than that of LY12. The facts above show that the higher yield strength of metal material has an adverse influence on formability of inner ribs and the better plasticity of metal material contributes to forming the higher inner ribs.

Table 1 Contrast of inner rib height of different metal materials

Material	Wall thickness/ mm	Pass number	Wall thickness change/ mm	Height of inner rib/ mm
LY12	2.00	2	2.0—1.5—1.0	1.20
LF2	2.00	2	2.0—1.5—1.0	1.56
LY12	2.50	2	2.5—2.0—1.5	1.12
LF2	2.50	2	2.5—2.0—1.5	1.68

4.2 Influence of ball size

Fig. 6 shows that increasing ball diameter can increase the height of inner ribs, and at the beginning stage, the height of inner ribs grows sharply, but later slowly.

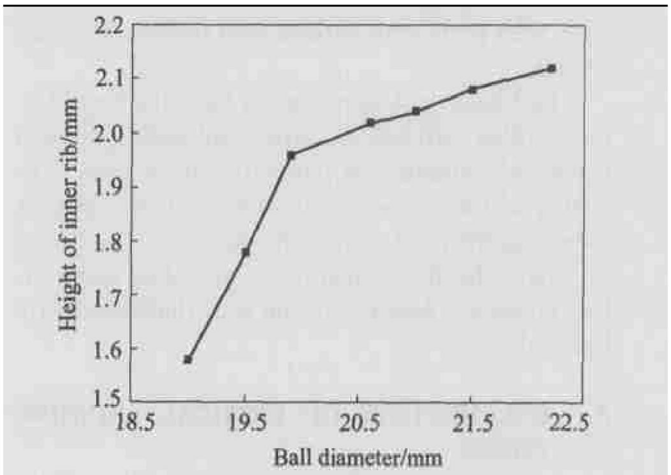

Fig. 6 Influence of ball diameter on height of inner ribs

Ball size has an important effect on power spinning deformation of thin-walled tubular parts with longitudinal inner ribs. On one hand, ball size is directly relevant to the magnitude of spinning force imposed on deformation zone so as to further determine the occurrence of plastic deformation of metal material. On the other hand, ball size is directly pertinent to the magnitude of attack angle so as to further influence stable flow of metal material. In general, increasing ball size is able to increase the spinning force and contributes to the stable flow of metal material. Experiments have proved that on the condition of the other process parameters being constant, ball size influencing spinning deformation has two critical values, which are expressed by d_1 and d_2, respectively. 1) When ball diameter $d < d_1$, tubular blank has no elongation but surface stack, in other words, metal material continuously stacks forward but has no flow along the tangent, axial and radial direction. 2) When ball diameter $d_1 < d < d_2$, tubular blank wall becomes thin and long but unable to form inner ribs. 3) When ball diameter $d > d_2$, tubular blank becomes long and thin as well as forming inner ribs. The height of inner ribs increases with the increase of ball size. However, if ball size is big enough to offer the sufficient spinning force to meet the demand of plastic deformation, increasing the ball size can only increase the height of inner ribs slightly. Therefore, on the condition that the inner ribs can be formed stably, it is unnecessary to use too large balls, which increase the size of tool and equipment.

The two critical values depend mainly on wall thickness of tubular blank and reduction in a pass.

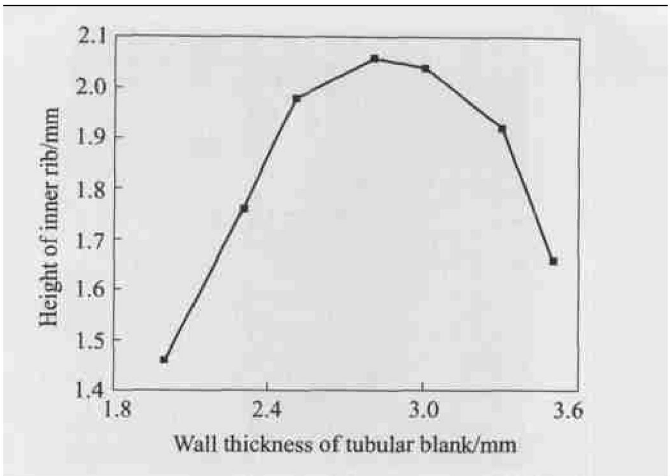

Fig. 7 Influence of wall thickness on height of inner rib

4.3 Influence of wall thickness of tubular blank

Seen from Fig. 7, the curve has a extremum point, i. e., before the extremum point, the height of inner ribs increases with the increase of wall thickness of tubular blank, and after the extremum point, the height of inner ribs decreases with the increase of wall thickness of tubular blank. The phenomenon demonstrates that there exists the best wall thickness value for forming a certain high inner rib. The reason leading to the phenomenon above is mainly that the spinning force is a function of the ball size. In the case of the constant ball size, the spinning force imparted to deformation zone is also invariable. When the wall thickness of tubular blank is very thin, the spinning force is large enough to make metal material of deformation zone yield so as to form inner ribs in per pass in the course of spinning, so the height of inner ribs increases with the increase of wall thickness of tubular blank. However, with the increase of wall thickness of tubular blank, the ball cannot offer the spinning force which plastic deformation needs so that the inner ribs cannot be formed in the previous several passes in spinning. Too many spinning passes lead to strain hardening and poor plasticity of metal material. Because of strain hardening, the height of inner ribs decreases with the increase of wall thickness of tubular blank.

4.4 Influence of feed ratio

Feed ratio is defined as the proportion of the feed velocity of the mandrel to the turning velocity of spinning equipment:

$$v_n = v / n \quad (8)$$

where v_n is feed ratio, v the feed velocity of the mandrel, and n the turning velocity of spinning equipment.

Feed ratio is an important process parameter influencing power spinning deformation of thin-walled tubular parts with longitudinal inner ribs. It is seen from Fig. 8 that increasing feed ratio can increase the height of inner ribs. Feed ratio has an effect on deformation velocity (strain rate) as well as spinning force imposed on deformation zone. Experiments have proved that increasing feed ratio contributes to enhancing not only strain rate but also spinning force imposed on deformation zone. It is evident that though increasing feed ratio can increase the height of inner ribs, but too large feed ratio can affect surface quality of spun parts adversely.

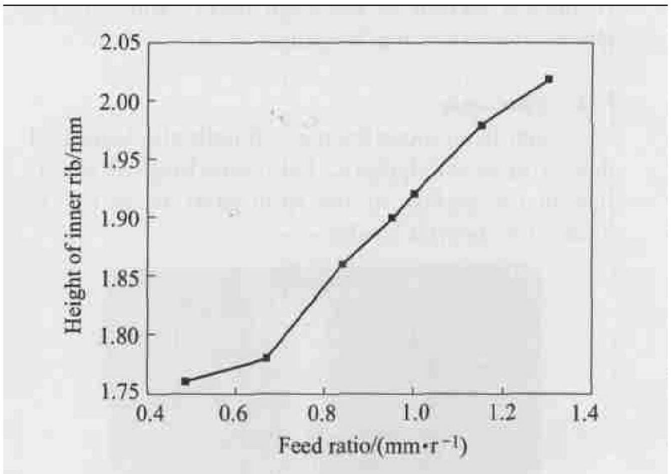

Fig. 8 Influence of feed ratio on height of inner rib

5 QULITY DEFECTS OF SPUN PARTS

5.1 Elliptical end

Elliptical end (Fig. 9) is a serious defect in power spinning deformation of thin-walled tubular parts with longitudinal inner ribs. The main reason to lead to the defect is due to uneven flow of metal material along the axial direction. In the course of power spinning deformation of thin-walled tubular parts with longitudinal inner ribs, the metal of deformation zone flows simultaneously along the radial, axial and tangent directions. However, the metal of inner ribs

Fig. 9 Schematic diagram of spun part with elliptical end

flows more slowly along the axial direction than the metal of the other section, namely, deformation velocity (strain rate) of inner ribs is less than the other along the axial direction so as to cause appended stress, which results in elliptical end. Elliptical end is an unavoidable defect due to objective law of deformation. The only approach to solve the problem is to impart a certain redundant section to the spun parts, which is removed after spinning forming.

5.2 Fish scale

Seen from experiments, though the height of inner ribs is satisfactory, fish scale (Fig. 10) can arise on the surface of the spun parts so as not to obtain the desired workpieces.

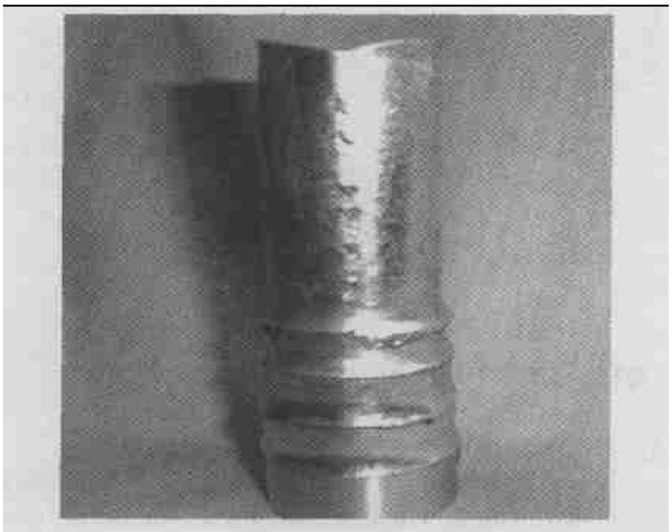

Fig. 10 Schematic diagram of spun part with fish scale

The phenomenon is mainly relevant to the process parameters besides the materials and cooling factor. In general, fish scale is easy to take place on the surface of LF2 aluminum alloy and the insufficient cooling leads to fish scale. Fish scale mainly results from too large wall thickness reduction and too large feed ratio, which contribute greatly to sharply increasing the plastic deformation and deformation rate of the metal material so that the continuity of plastic deformation can be damaged.

5.3 Surface stacking

It can be seen from experiments that surface stacking (Fig. 11) is easy to arise on aluminum alloy, such as LF2 and LY12, whereas surface stacking is easier to take place on LF2 than on LY12. The reasons why surface stacking of spun parts are formed as follows.

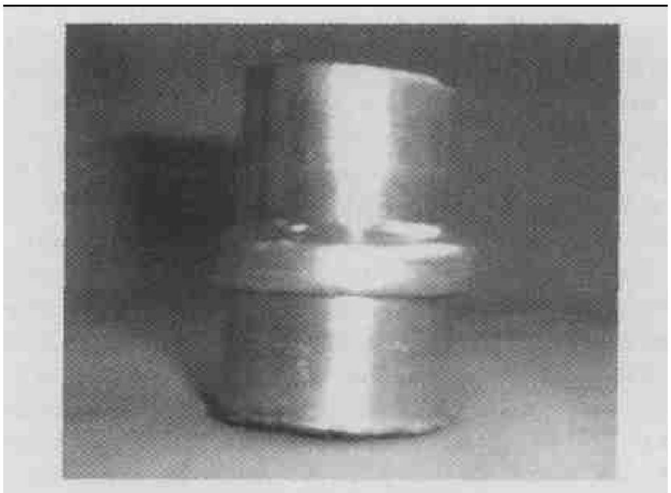

Fig. 11 Schematic diagram of spun part with surface stacking

First, in terms of metal material, surface stacking is easy to take place on the surface of aluminum alloy. Second, in terms of process parameters, surface stacking results from too large wall thickness reduction and too small ball size. Third, in terms of spinning method, surface stacking arises more easily in backward spinning than in forward spinning. Therefore, if spinning material and spinning method are determined, the best measures which are taken to avoid surface stacking are to increase ball size or to reduce reduction in a pass or to reduce feed ratio.

6 CONCLUSIONS

1) Ball backward spinning has been the best plastic working process to manufacture thin-walled tubular parts with longitudinal inner ribs up to now. The quality of inner ribs is one of the critical tasks in obtaining the desired spun workpieces.

2) The forming of the inner ribs depends on the spinning force imposed on deformation zone of the spun parts. The average critical spinning force is a function of wall thickness reduction Φ, yield strength

σ_s, friction coefficient μ, and attack angle α.

3) The height of inner ribs relies mainly on spinning material, ball diameter, feed ratio and wall thickness of tubular blank. The height of inner ribs formed using LF2 is obviously larger than LY12. It is evident that in the case of stable flow of metal, not only can increasing the ball size increase the height of the inner rib, but increasing feed ratio can do as well. If the other process parameters are constant, there will be a best wall thickness value for forming a certain height of inner rib.

4) If the three process parameters, namely, ball diameter, feed ratio, and wall thickness of tubular blank, cannot be matched rationally, the quality defects such as elliptical end, fish scale and surface stacking, will arise on the spun parts.

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