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Influence of Process Parameters on 6061 Aluminum Alloy Tube in Stagger Spinning

Xiaokai Zhao[a,*], Haopeng Zhao[b], Zheyuan Mu[c]

College of Mechanical and Electrical Engineering, Shaanxi University of Science & Technology, Xi'an, China
[a]zhaoxk2017@sust.edu.cn, [b]zhaohaopeng@sust.edu.cn, [c]muzheyuan@sust.edu.cn
**Corresponding author*

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Abstract: In this paper, a three-dimensional finite element model of staggered spinning of 6061 aluminium alloy thick-walled tube is established based on Abaqus simulation software. The influence of stagger distance, thinning rate and feed ratio on the forming quality of tube is analysed. The optimal process parameters were obtained as follows: stagger distance is 7mm, thinning rate is 20%, and feed ratio is 2.5mm/r. The multi-pass stagger spinning process experiment was carried out. The as-spun tube was obtained with good dimensional accuracy and mechanical properties. The average wall thickness deviation of the as-spun tube is 0.11 mm. Compared with the initial tube blank, the circumferential and axial tensile strengths of the tube formed by multi-pass stagger spinning are increased by 35MPa and 38MPa (19.13% and 20.21%), and the circumferential and axial yield strengths are increased by 69MPa and 94MPa (69.7% and 98.95%), respectively. The mechanical property of the tube was enhanced both in axial and circumferential directions by stagger spinning.

1. Introduction

Power spinning is a near-net forming process and an important method for forming thin-walled tubes and hollow tubes [1]. It has the characteristics of high forming precision, high material utilization, good surface quality and mechanical properties [2-3]. Therefore, spinning is widely used in aviation, aerospace and military industries [4]. In the process of spinning thick-walled tubes, two or more rollers are staggered in the axial direction, and different thinning distributions are set in the radial direction, which is the multi-roller stagger spinning process [5]. When the thinning rate is large, the stagger spinning can effectively avoid the vibration of the tube. Compared with the traditional mandrel spinning, the dimensional accuracy of the tube is higher [6].

Aluminum alloy has low density, high specific strength, good plasticity, strong electrical and thermal conductivity, excellent processing performance and corrosion resistance, so it is widely used in aerospace, weaponry, transportation, energy and other fields [7-8]. Aluminum alloy materials can meet the needs of lightweight, large-scale and complex structure of products, and have a very broad application prospect.

In the spinning, the complex state of deformation is closely related to the process parameters, and the optimization of process parameters is a research hotspot. A large number of FE simulations and experiments have studied the metal flow and process conditions optimization during the stagger spinning process. Cao et al. [10] studied the dimensional accuracy of ultra-thin-walled tube in stagger spinning process by combining finite element simulation and experiment. Cheng et al. [11] studied the variation of dimensional accuracy of tube in stagger spinning forming by orthogonal design method. Hamid et al. [12] studied the effect of thinning rate on the mechanical properties and forming accuracy of 7075-O aluminum alloy tubes by experiments. Although the research on spinning forming has been widely reported, there are many studies on thin-walled tubes, and there are few studies on tubes with larger initial thickness.

In this paper, the influence of staggered distance, thinning rate and feed ratio on the forming accuracy of 6061 aluminum alloy thick-walled tube is investigated by FE simulation. Subsequently, multi-pass stagger spinning experiments were carried out on the initial thick-walled tube. The dependence of spinning process on processing parameters was studied, by analyzing the results of experiments and simulations. The experimental and simulation results are helpful to understand the deformation of the tubular workpiece during the stagger spinning process and provide a theoretical basis for the actual processing.

2. FEA Models and Experimental Procedure

2.1 Establishment of FEA Models for Stagger Spinning

A 3D elastic-plastic finite element model of backward tube spinning was established based on ABAQUS simulation software. The spinning model includes a tube blank, a mandrel, and three rollers that are evenly distributed in 120° along circumferential, as shown in Figure 1. The free end of the tube blank is chamfered by 15° according to the forming angle of the roller, which can improve the stability of the contact between the roller and the tube in the initial stage of spinning, and reduces the flaring of the tube blank. It also can effectively improve the distortion of the tube blank, and reduces the impact vibration generated by the contact between the roller and the tube. The geometric parameters are shown in Table 1.

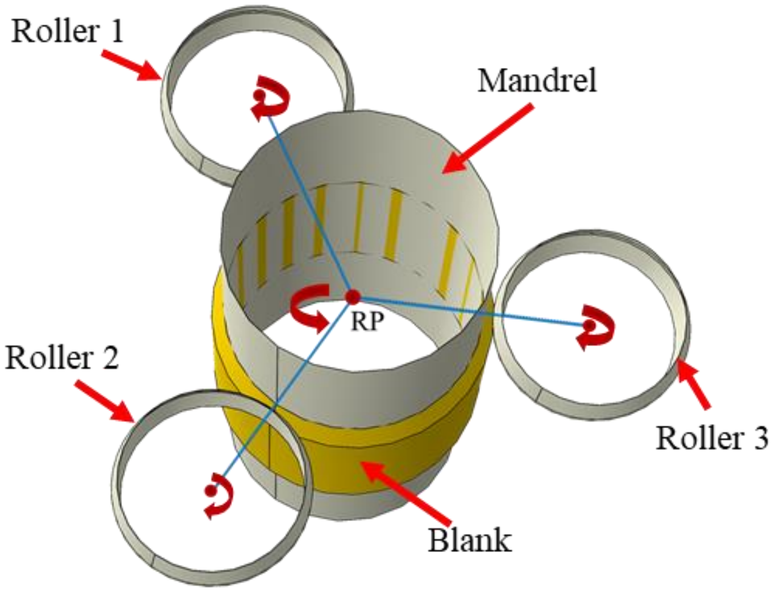

Figure. 1: 3D elastic-plastic FE model of three rollers stagger spinning.

Table 1: Geometric parameters of three rollers stagger spinning.

Process parameters	values
Internal diameter of tube (mm)	300
Wall thickness of tube (mm)	15
Length of tube(mm)	220
Diameter of mandrel (mm)	300
Diameter of the rollers (mm)	240
The fillet radius of the rollers (mm)	10
Forming angle of roller(°)	15

In the finite element simulation, 6061 aluminum alloy is selected as the material of the tube blank. The density of the material is ρ=2700 kg/m^3, the elastic modulus E=71 GPa, and the Poisson's ratio v=0.33. The tensile test was carried out at room temperature, and the true stress-strain curve was measured. The stress-strain curve of the 6061 aluminum alloy material is shown in Figure 2, and the constitutive relationship model is defined as follows:

$$\sigma = \sigma_s + k\varepsilon^n \quad (1)$$

Where strengthening coefficient is K=373.2 MPa, hardening exponent is n= 0.381, yield stress is σ_s=101.3MPa.

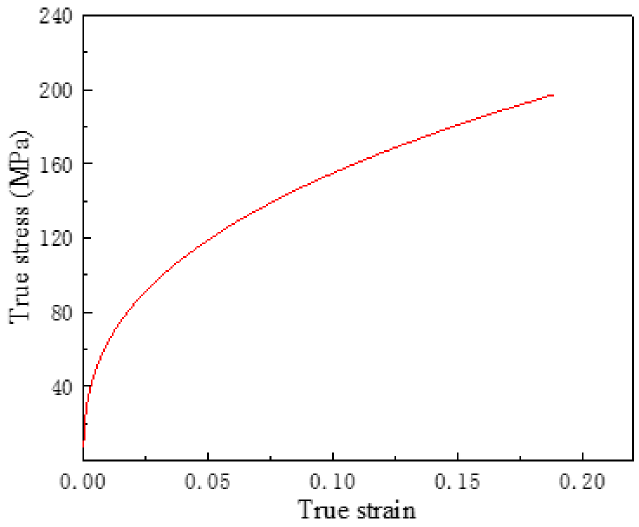

Figure. 2: Stress-strain curve of 6061 aluminum alloy.

When the finite element model contains a large number of meshes, the rotation of the tube blank may lead to huge volume changes and numerical errors. In order to improve the calculation speed of the model, a certain mass amplification coefficient is set, which will lead to a sharp increase in the rotational inertia of the tube. The bottom of the tube is prone to distortion, and the top of the tube will also be distorted due to the lack of radial and circumferential constraints. Therefore, in the simulation of stagger spinning, the rotation of the tube blank and the roller is different from the actual stagger spinning experiment. The bottom of the tube is fixed, and the three rollers are synchronized and controlled by the connector to make a planetary rotation motion around the tube blank. The free rotation of the three rollers is released, so that the roller can rotate passively when in contact with the tube [9].

The friction coefficient between the outer surface of the three rollers and the outer surface of the tube is set to 0.05. The friction coefficient between the outer surface of the mandrel and the inner surface of the tube is set to 0.2. The mass magnification factor selected is 10000, which effectively reduces the time of calculation.

The hexahedral mesh is not prone to excessive distortion in the process of large deformation. Therefore, the mesh of tube adopts the type of 8-node hexahedral linear reduced integral element (C3D8R). The number of seeds divided is 580 in the circumferential direction, 110 in the axial direction, and 5 in the radial direction. The total number of meshes is 319,000. The mesh division of the tube is shown in Figure. 3. The local coordinate system is defined to describe the deformation state and material flow. The Arbitrary Lagrangian Eulerian (ALE) adaptive meshing technique was adopted to control mesh distortion during spinning.

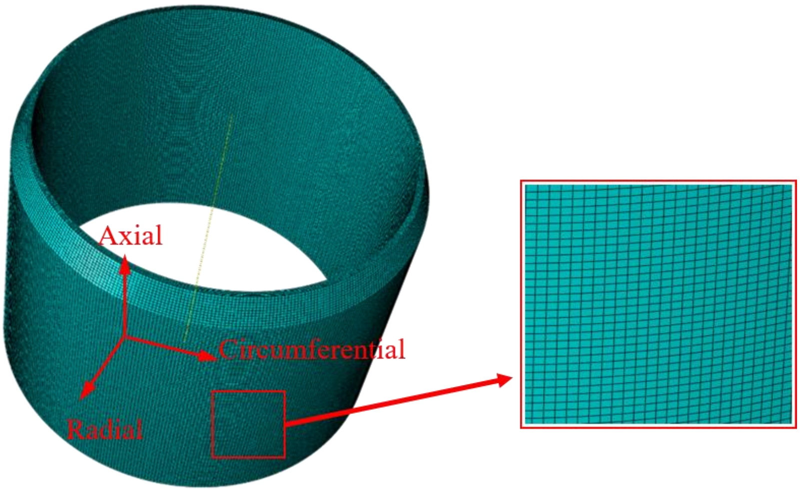

Figure. 3: Meshing of tube.

2.2 Reliability Verification of Model

It is necessary to verify the reliability of the model. Generally, the values of RKI and RAI must be less than 10% and 5% [13]. The energy-based stability analysis of the FE model has been conducted. Figure. 4 shows the variations in the ratio of kinetic energy to internal energy (RKI) and artificial strain energy to internal energy (RAI) in the simulation. It can be seen that the values of both are less than 5% in the stable forming stage, which can prove the model is reliable.

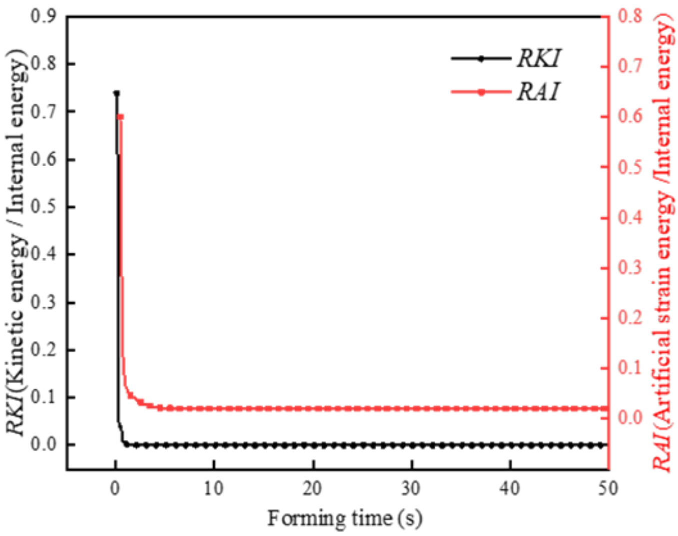

Figure. 4: Reliability verification of the FE model based on energy variation.

2.3 Selection of Spinning Process Parameters

In the stagger spinning forming process, the axial stagger distance between the rollers, the feed ratio and the thinning rate have an important influence on the forming of the tube. Generally, the thinning rate is less than 30%~40%, which can ensure the high dimensional accuracy of the parts in the spinning [14]. Therefore, the thinning rate is selected as 15%, 20%, 28% and 35% in the finite element simulation of this paper. The feed ratio of 6061 aluminum alloy is generally selected in the range of 0.3~3mm/r. The feed ratio is selected as 1.5 mm/r, 2.5mm/r and 3.5mm/r. According to the calculation method of the stagger distance between the rollers reported by Gao et al. [15], the appropriate stagger distance in this paper is about 7mm, and the radial thinning distribution ratio of the three rollers is 50%, 25% and 25%. Therefore, the stagger distance is selected as 0mm, 5mm, 7mm and 9mm.

The single factor experiment can clearly reflect the influence law of single variable factor on the experimental results, and can analyze the influence law of process parameters in the process of stagger spinning. In this paper, the effects of the axial stagger distance of the roller, the feed ratio and the thinning rate on the stagger spinning are studied respectively. The specific process parameters are shown in Table 2.

Table 2: Process parameters of spinning in single factor numerical simulation scheme.

Process parameters	values
Stagger distance of rollers (mm)	0, 5, 7, 9
Feed ratio (mm/r)	1.5, 2.5, 3.5
Thinning rate (%)	15, 20, 28, 35

3. Results and Discussion

3.1 Influence of Stagger Distance on Spinning

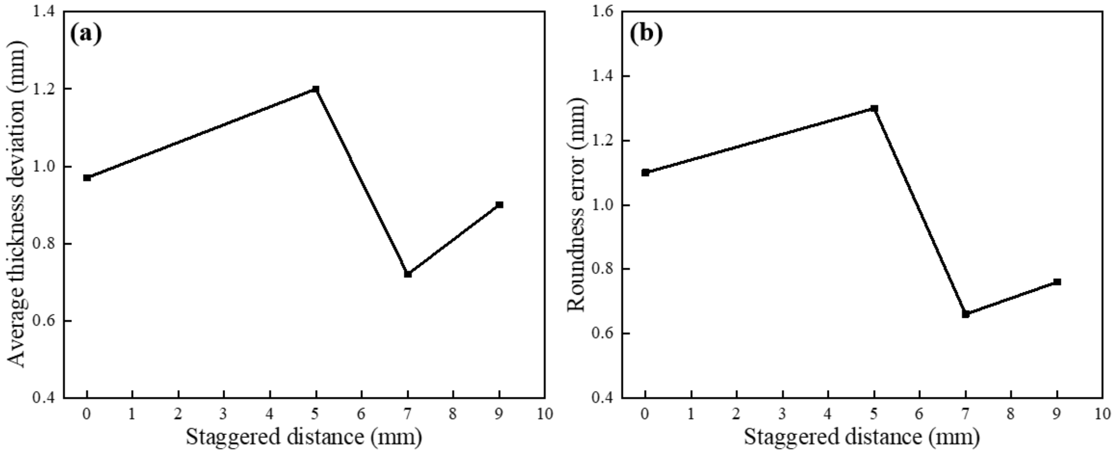

Figure. 5: Variation of dimensional accuracy of the as-spun tubes with different stagger distances. (a) Average thickness deviation of the tubes. (b) Average roundness error of the tubes.

The influence of stagger distance on spinning was analyzed in this section while the thinning rate is set to 28% and the feed ratio is 2.5 mm/r. Figure. 5 shows the average thickness deviation and roundness error under different stagger distance. It can be seen that the stagger distance of the roller has a significant effect on the dimensional accuracy of the as-spun tube. When the stagger distance is 5mm, the wall thickness deviation and roundness error of the tube are the largest, which are 1.2mm and 1.3mm respectively. When the stagger distance increases to 7mm, the dimensional accuracy is the best, and the wall thickness deviation and roundness error are 0.72 mm and 0.66 mm, respectively. This may be due to the interference between the rollers when the stagger distance is small, which leads to the overlap of the contact area between the roller and the tube during the spinning, and the repeated uneven rolling leads to the increase of wall average thickness deviation and roundness error.

Figure. 6 shows the spinning force under different stagger distance of the rollers in the spinning. It can be seen that when the stagger distance is 0mm, the three rollers are evenly distributed along the circumferential direction, the spinning force of the three rollers is close, and the spinning force gradually increases and tends to be stable with the contact between the roller and the tube. The spinning force is relatively stable during the spinning process, indicating that the metal flow is stable and uniform. When the stagger distance is 5mm, 7mm and 9mm, the roller contacts the surface of the tube in turn. The three rollers are thinned according to the radial distribution of the rollers, resulting in different spinning force and the force becomes relatively stable during the spinning. When the stagger distance is 5mm, the three rollers change the original radial distribution ratio (50%, 25% and 25%), causing the actual thinning of roller 2 and roller 3 to increase, resulting in a significant increase in spinning force, especially the spinning force of roller 3 increases sharply. When the stagger distance is 7mm, the force of the three rollers is relatively stable in the spinning process. When the stagger distance increases to 9mm, the force of the three rollers becomes uneven, and the force of the roller 1 increases significantly during the whole spinning process. This shows that when the stagger distance of the rollers is small, the roller will destroy the distribution ratio of radial thinning and interfere with each other. However, when the stagger distance is large, the force of the rollers will become uneven, and the forming process is unstable, resulting in a decrease in dimensional accuracy.

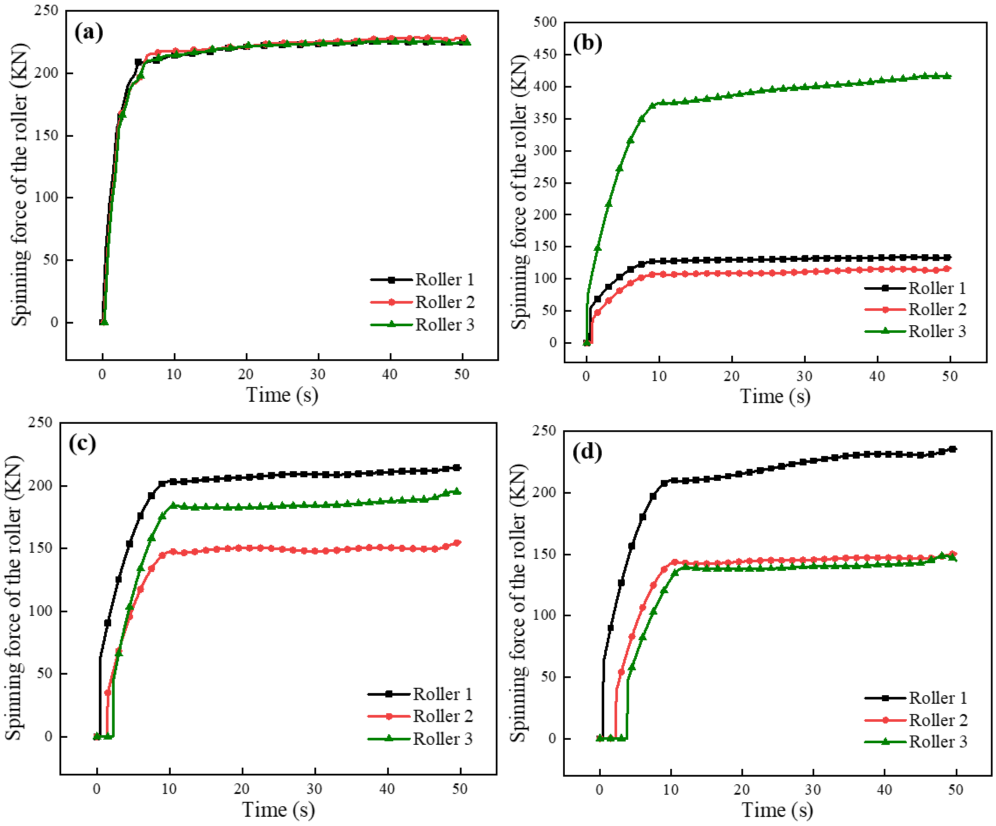

Figure. 6: Variation of spinning force during spinning. (a) Stagger distance 0 mm. (b) Stagger distance 5mm. (c) Stagger distance 7 mm. (d) Stagger distance 9 mm.

3.2 Influence of Feed Ratio on Spinning

When simulating the influence of feed ratio on spinning, the fixed stagger distance is 7mm and the thinning rate is 28 %. Figure 7 shows the average wall thickness deviation and roundness error under different feed ratios. It can be seen that as the feed ratio increases, the roundness error and the wall thickness error increase first and then decrease. When the feed ratio is 2.5, the average roundness error and the average wall thickness deviation reach the minimum value.

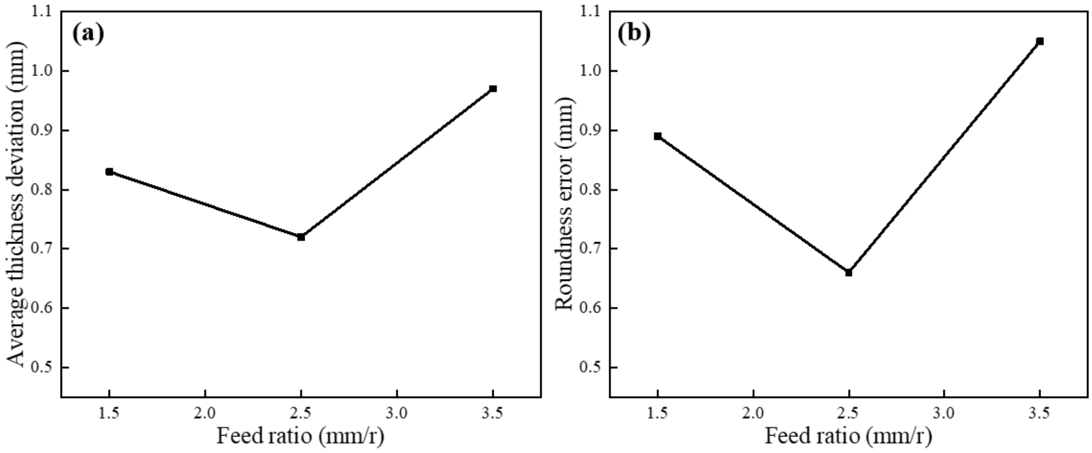

Figure. 7: Variation of dimensional accuracy of the as-spun tubes with different feed ratio. (a) Average thickness deviation of the tubes. (b) Average roundness error of the tubes.

When the feed ratio is small, the spiral trajectory of the roller has more overlap, and the repeated extrusion reduces the dimensional accuracy. On the contrary, when the feed ratio is large, it will cause the pileup of metal in front of the roller and the obvious spiral folds on the surface of the tube, as shown in Figure 8(a) and (b). Severe wrinkling will cause the surface of the tube to break, resulting in reduced dimensional accuracy. Therefore, selecting the appropriate feed ratio is the key to improve the production efficiency and ensure the forming accuracy.

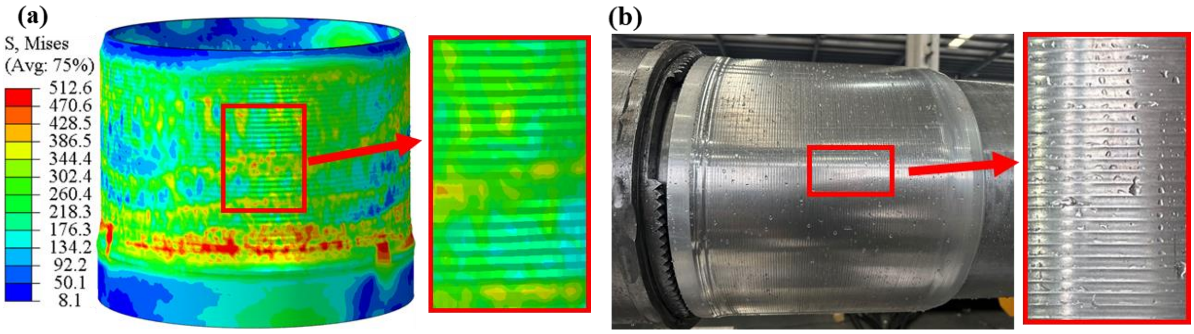

Figure. 8: Wrinkling in stagger spinning. (a) FE simulation (thinning rate is 20%, feed ratio is 3.5 mm/r). (b) Spinning experiment (thinning rate is 20%, feed ratio is 2.5 mm/r).

3.3 Influence of Thinning Rate on Spinning

When simulating the influence of thinning rate on spinning, fixed the stagger distance is 7mm and the feed ratio is 2.5mm/r. The thinning rate reflects the degree of deformation of the tube during the spinning, which directly affects the accuracy of the as-spun tube. The influence of different thinning rates on the dimensional accuracy of the tube is shown in Figure 9. It can be seen that as the thinning rate increases, the average thickness deviation and roundness error gradually increase.

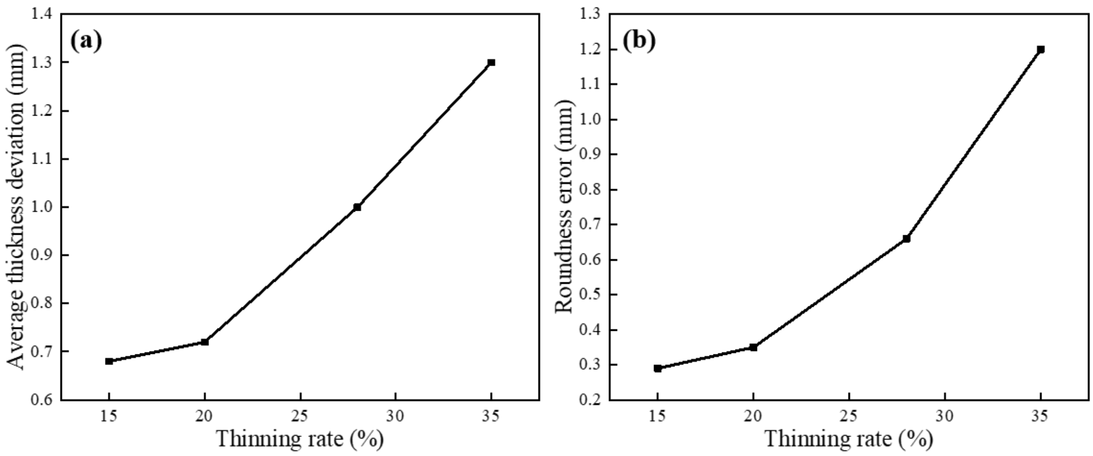

Figure. 9: Variation of dimensional accuracy of the as-spun tubes with different thinning rate. (a)Average thickness deviation of the tubes. (b) Average roundness error of the tubes.

Figure. 10(a) and (b) show the equivalent stress distribution of the whole tube and the thickness direction section at the same position in the finite element simulation. Figure. 10(c) shows the flash and pileup defect in the stagger spinning experiment. It can be seen from Figure. 10(a) and Figure. 10(b) that if the single-pass thinning amount is too large, the material will bulge in front of the roller, and the equivalent stress on both sides of the contact area between roller and tube shows a banded distribution. With the feed of the roll, the pileup increases continuously, and the metal flow is unstable, which leads to the defects of flash and pileup in the Figure. 10(c), resulting in a decrease in the forming accuracy of the as-spun tube.

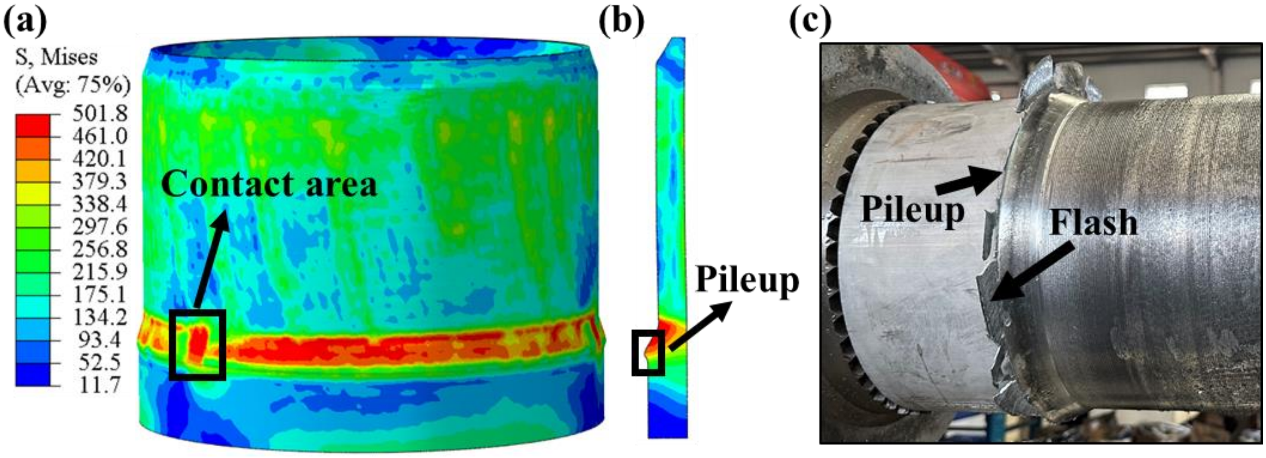

Figure. 10: Pileup defect of tube in spinning. (a) Stress distribution of stagger spinning (thinning rate 35%). (b) Stress distribution of the axial section in the contact area. (c) The bulge instability defect in the spinning experiment.

Therefore, when the thinning rate increases, the plastic deformation of the tube is also greater, which cause a decrease in the dimensional accuracy and stability. This indicates that the thinning rate should be selected within a reasonable range. Combined with the influence of the thinning rate on the average wall thickness deviation and the average roundness error in Figure. 9, it can be seen that the appropriate thinning rate should be selected in 15% ~ 20% when forming the tube with a larger initial thickness.

3.4 Multi-Pass Stagger Spinning Experiment

3.4.1 Experimental Procedure

According to the results of FE simulation, the multi-pass stagger spinning experiment was carry out on the three-roller CNC spinning machine with the 6061 aluminum alloy tube. Before the experiment, the tube is cutting to make the inner and outer surfaces smooth, and a 15 ° chamfer is processed at the top of the tube to reduce the vibration caused by the contact between the roller and the blank. The geometric parameters of the blank are consistent with the simulation. 3 passes stagger spinning is carried out and the as-spun tube is shown in Figure. 11. The spinning process parameters are shown in Table 3.

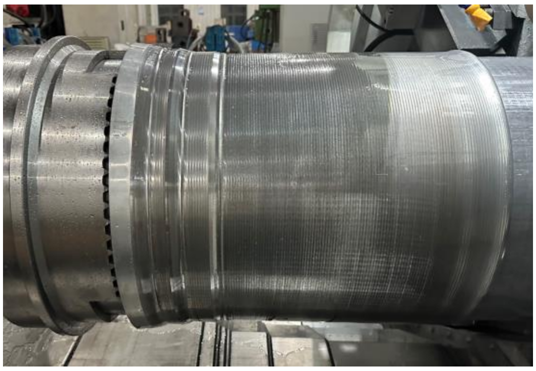

Figure. 11: 6061 aluminum alloy as-spun tubes formed by 3 passes stagger spinning.

Table 3: Process parameters of spinning.

Process parameters	Values
Stagger distance of rollers (mm)	7
Feed ratio (mm/r)	2.5
Thinning rate per pass (%)	20
Radial distribution of roller (%)	50, 25, 25
Diameter of roller (mm)	240
Fillet radius of roller (mm)	10
Forming angle of roller (°)	15
Spindle speed (rpm)	80

3.4.2 Dimensional Accuracy

After the spinning experiment, the thickness of the as-spun tube was measured by DAKOTA PZX-7 ultrasonic thickness gauge. The thickness was measured every 30 ° along the circumferential direction for each pass. Figure. 12 shows the thickness deviation curve of each pass of the as-spun tube and the finite element simulation. It can be seen that the thickness deviation is the largest as the actual thinning amount of the first pass is the largest, and the difference between the maximum and minimum values is 0.043 mm. With the increase of passes, the thickness deviation decreases gradually. In the first and second passes, due to the large amount of thinning, the metal rebound is obvious, resulting in a large thickness deviation. After two passes, due to the decrease of the actual thinning amount, the increase of work hardening and the decrease of metal springback, the thickness is more uniform and close to the theoretical value. The thickness error of the experiment and simulation in the first pass is about 3 %, which can verify the reliability of the FE model.

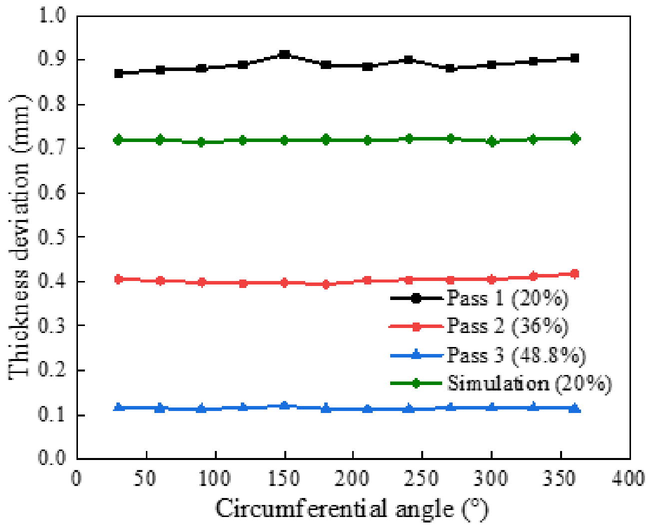

Figure. 12: Thickness deviation of the cross-section of the as-spun tubes in each pass.

3.4.3 Tensile Test

The tensile specimens were cut along the circumferential and axial directions of the as-spun tube. The specimen with a gauge width of 3.0 mm, a thickness of 1.5 mm, and a parallel length of 12.0 mm. The tensile test was carried out on a UTM 5105 universal testing machine with a speed of 0.12 mm/s at the temperature. Figure. 13 shows the results of tensile test in different passes. It can be seen that the 6061 aluminum alloy tube has good ductility in both axial and circumferential directions. With the increase of thinning amount, the strength increases and the strain decreases gradually.

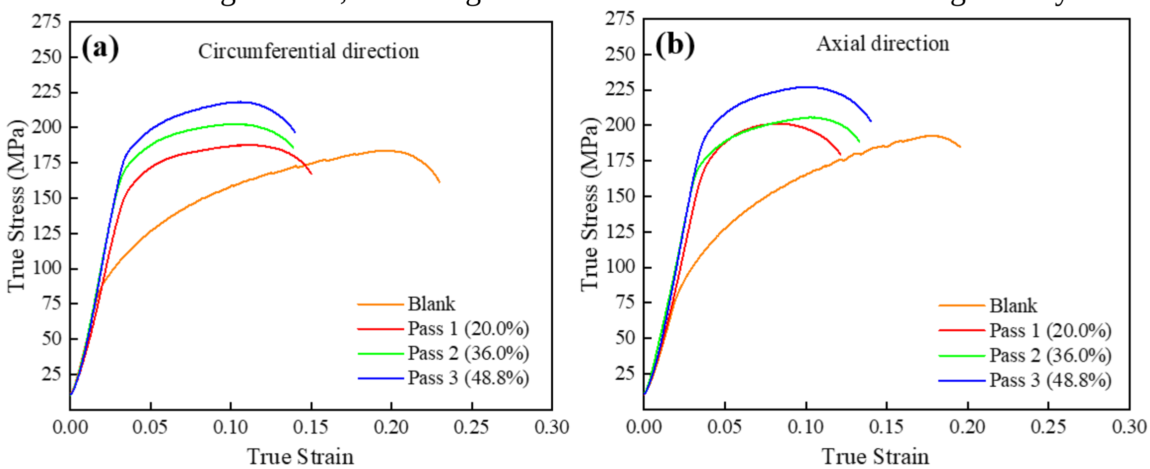

Figure. 13: Stress-strain curve of 6061 aluminum alloy as-spun tubes. (a) The circumferential. (b) The axial.

Figure. 14 shows the variation of tensile properties of the specimen with different thinning rates. Compared with the initial tube blank, the circumferential and axial tensile strength of the third pass increased by 35MPa and 38MPa (19.13% and 20.21%), and the circumferential and axial yield strength increased by 69Mpa and 94Mpa (69.7% and 98.95%), respectively. The metal flow mainly occurs in the axial direction during the spinning, so the axial tensile strength and yield strength are always larger than the circumferential direction. As the thinning rate increases, the axial strength increases more obviously.

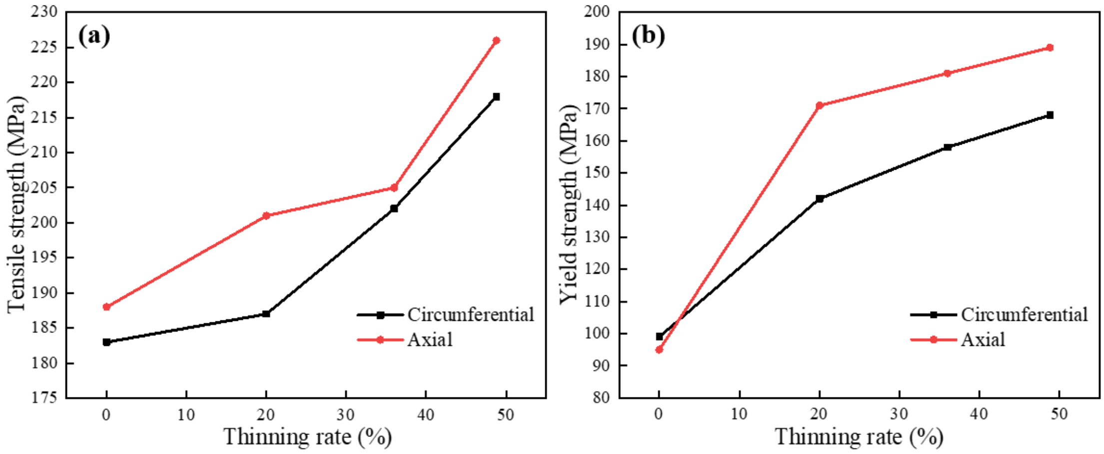

Figure. 14: The strength under different thinning rates. (a) Tensile strength. (b) Yield strength.

4. Conclusions

The FE simulation of three-roller stagger spinning of 6061 aluminum alloy tube was carried out. The effects of stagger distance, thinning rate and feed ratio on the dimensional accuracy and spinning force of the roller were studied. The multi-pass stagger spinning experiment was carried out, and the dimensional accuracy and mechanical properties of the spun tube were measured. The main conclusions are as follows.

(1) The stagger distance, thinning rate and feed ratio have an important influence on the processing quality of the stagger spinning forming process. The stagger distance has a significant effect on the spinning force of the three rollers. When the thinning rate is too large, the bulge instability defect will appear in the spinning. When the feed is relatively large, the surface of the tube will produce obvious spiral folds, and serious wrinkling will lead to surface rupture, resulting in reduced dimensional accuracy. In the model of this paper, the optimal process parameters obtained are the stagger distance of 7mm, the thinning rate of 20% and the feed ratio of 2.5mm/r.

(2) The multi-pass stagger spinning can be used to obtain an as-spun tube with better dimensional accuracy by designing reasonable multi-pass thinning parameters. After three passes of forming, the thickness deviation is about 0.11 mm.

(3) Multi-pass stagger spinning improves the mechanical properties of the tube. The circumferential and axial tensile strength of the third pass increased by 35MPa and 38MPa (19.13% and 20.21 %), and the circumferential and axial yield strength increased by 69Mpa and 94Mpa (69.7 % and 98.95 %), respectively. The mechanical property of the tube was enhanced both in axial and circumferential directions by stagger spinning, and the axial is more obvious.

Acknowledgments

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