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ORIGINAL ARTICLE

Incremental forming characteristics of hollow parts with grooves

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Abstract

Incremental profile forming (IPF) is a new plastic processing technology developed in recent years. The new profile manufacturing technology is mainly used to produce tubular parts with variable cross sections along the axis of tube. The parts with different cross sections produced by this technology satisfy the lightweight and high strength requirements of the tubular parts. The IPF method is very flexible and can form diverse complex-shaped parts. Because no special machine is available for this technology, depending on the shapes of formed tubular parts, the forming tool and forming method should be designed. Thus, this study proposes a new method to form the annular groove and tube wall groove. Using a special tool and servo drive system of spinning machine, it is possible to form an annular groove and tube wall groove on the surface of tubular part. This is a typical IPF method for tubes. The process of different grooves on the surface of tubes was systematically studied in this paper. Through experiments and finite element simulations, different process parameters influencing the forming quality of groove were studied. It was concluded that the tool's single feed and spindle speed significantly affect the forming quality and forming limit.

Keywords Incremental forming · Tubular parts · Grooves · Simulation

1 Introduction

Undoubtedly, lightweight design of materials has become an important issue in the field of plastic forming. Although many methods are used to achieve lightweight materials, component lightweight design is the most important [1–3]. Hydroforming is the main method for forming complex-shaped parts. Hydroforming technology is widely used for forming lightweight or complex components in the automotive and aerospace industries [4, 5]. Hydroforming requires special molds. Therefore, for a small number of parts, it is not only expensive but also requires a long production cycle of hydroforming. The incremental profile forming (IPF) is suitable for the manufacturing of complex-shaped tubular parts using simple and flexible tools [6]. The IPF method is a flexible plastic processing method, producing tubular parts with variable cross sections along the axis of tube [7, 8]. Unlike the typical tube spin forming method [9, 10], the IPF tools are more versatile, and the forming method is also more flexible. To reduce the IPF force, different forms of tools were invented by Goran Grzancic [11]. Furthermore, the studies of Goran Grzancic and Christoph Becker in ref. [12] focused on the factors influencing the forming force of IPF. According to the shape of forming material, IPF is divided into two types, incremental tube forming (ITF) and incremental sheet forming (ISF). ISF is a mature technology, including single-point incremental forming (SPIF) and double-sided incremental forming (DSIF) [13, 14]. The research on ITF is at a preliminary stage and important for plastic manufacturing technology. Many researchers have systematically studied the theory of tube radial deformation [15–17]. Based on the theory, some studies have been conducted on the forming quality, forming limit, and forming equipment of IPF in this paper.

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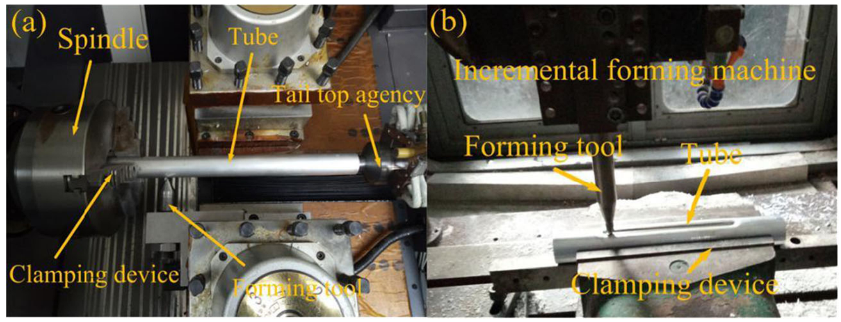

Fig. 1 **a** and **b** IPF equipment

2 Forming mechanism of IPF

2.1 IPF equipment and forming principle

At present, German scholars have already started studying the incremental forming equipment for tubular parts. The equipment for ISF has been relatively mature in the domestic region, but incremental forming equipment for tubular parts has not been systematically studied. The development of tube forming equipment is based on the spinning machine. The specific components of the equipment for IPF are shown in Fig. 1.

The annular and spiral grooves are shaped by the design of equipment as shown in Fig. 1a. During the formation, the tube is fixed by a clamping device and tail top agency. Through the rotation of spindle and axial movement of forming tool, an annular groove or a spiral groove can be precisely formed on the tube surface. The maximum processing axial length achieved by the design of forming equipment shown in Fig. 1a is 300 mm. In addition, a straight groove can be formed by the incremental forming machine shown in Fig. 1b. First, the tube is fixed by a clamping device. Next, the forming tool is pressed down and moves along the axial direction of tube. The experimental results show that the design of forming tools and forming method is relatively reasonable. The principle of IPF is shown in Fig. 2.

2.2 Typical strain analysis of IPF

This section presents a typical strain analysis model for IPF. During the progressive incremental forming of tube, the strain analysis of position where the tool head contacts the tube is very important. The strain analysis is shown in Fig. 3.

To simplify the analytical model, it is assumed that the lubrication between forming tool and tube surface is an ideal condition, and the coefficient of friction is zero. The principle of IPF process of tube shows that when forming the i layer, the angle of contacting area between the forming tool and tube satisfies the following formula:

$$\cos\frac{\alpha_i}{2} = \frac{r - i\cdot\Delta h}{r} \tag{1}$$

where α_i is the angle between the contact area of forming tool and tube when forming the i layer, Δh is the amount of feed for each floor, i is the number of forming layers, and r is the radius of tool head.

After the forming of $i-1$ layer is completed, the contacting area between the tube and forming tool and its neighboring area are a, b, c, and d. Because the feeding amount is small, the actual ab and cd parts are small and tend to be linear, assuming that a b and c d are linear. After the forming tool has pressed the area for i layer time, the straight line a b, the arc b c, and the straight line cd become arcs. According to the geometric relationship shown in Fig. 3:

$$AL_{\acute{a}\acute{b}} = r\cdot\alpha_i \tag{2}$$

$$L_{\acute{a}\acute{b}} = 2r\cdot\sin\frac{\alpha_i}{2} \tag{3}$$

$$AL_{bc} = r\cdot\alpha_{i-1} \tag{4}$$

$$L_{bc} = 2r\cdot\sin\frac{\alpha_{i-1}}{2} \tag{5}$$

$$L_{ab} = L_{cd} = \frac{L_{\acute{a}\acute{b}} - L_{bc}}{2\cos\frac{\alpha_i}{2}} = \frac{r\cdot\sin\frac{\alpha_i}{2} - r\cdot\sin\frac{\alpha_{i-1}}{2}}{\cos\frac{\alpha_{i-1}}{2}} \tag{6}$$

where $AL_{\acute{a}\acute{b}}$ is the arc length of arc $\acute{a}\acute{b}$, $L_{\acute{a}\acute{b}}$ is the length of line $\acute{a}\acute{b}$, AL_{bc} is the arc length of arc bc; L_{bc} is the length of line bc,

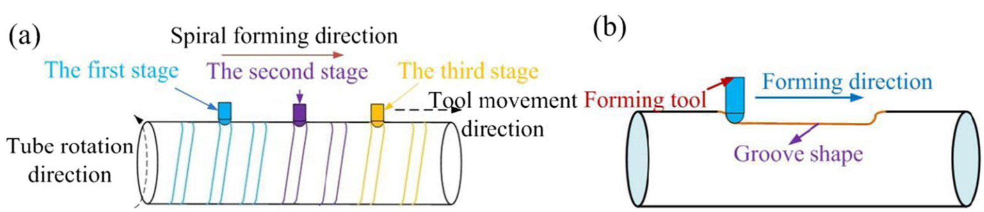

Fig. 2 **a** and **b** Principle of IPF

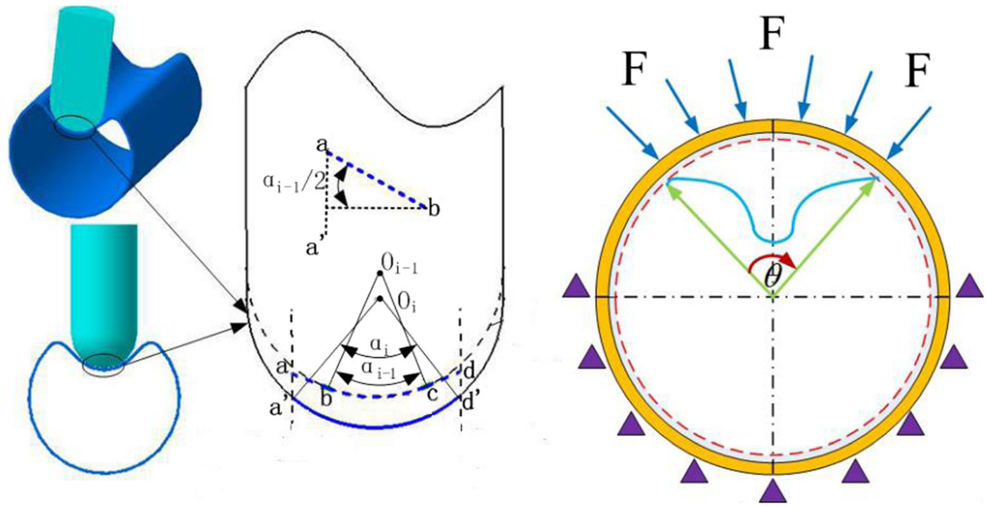

Fig. 3 Strain analysis of IPF

L_{ab} and L_{cd} are the lengths of lines *ab* and *cd*, and α_{i-1} is the angle between forming tool head and contact area of tube when forming the *i*-1st layer.

According to the definition of strain:

$$\varepsilon_{i_1} = \frac{\ln \mathrm{AL}_{\acute{a}\acute{b}}}{\ln(L_{ab}+\mathrm{AL}_{bc}+L_{cd})} = \frac{\ln r \cdot \alpha_i}{\ln\left(\frac{2r\cdot\sin\frac{\alpha_i}{2}-2r\cdot\sin\frac{\alpha_{i-1}}{2}}{\cos\frac{\alpha_{i-1}}{2}}+r\cdot\alpha_{i-1}\right)} \tag{7}$$

The principle of forming process and ideal lubrication state shows that:

$$\varepsilon_{i_3} = -\varepsilon_{i_1} = -\frac{\ln r \cdot \alpha_i}{\ln\left(\frac{2r\cdot\sin\frac{\alpha_i}{2}-2r\cdot\sin\frac{\alpha_{i-1}}{2}}{\cos\frac{\alpha_{i-1}}{2}}+r\cdot\alpha_{i-1}\right)} \tag{8}$$

The Mises equivalent strain definition leads to:

$$\varepsilon_{i_e} = \sqrt{\frac{2}{3}\left(\varepsilon_{x_1}{}^2+\varepsilon_{x_2}{}^2+\varepsilon_{x_3}{}^2\right)} = \frac{2}{\sqrt{3}}\frac{\ln r \cdot \alpha_i}{\ln\left(\frac{2r\cdot\sin\frac{\alpha_i}{2}-2r\cdot\sin\frac{\alpha_{i-1}}{2}}{\cos\frac{\alpha_{i-1}}{2}}+r\cdot\alpha_{i-1}\right)} \tag{9}$$

where ε_{i_1} is the momentary first principal strain in the contact zone when forming the *i* layer, ε_{i_2} is the momentary second principal strain in the contact zone when forming the *i* layer, ε_{i_3} is the momentary third principal strain in the contact zone when forming the *i* layer, and ε_{i_e} is the instantaneous equivalent strain in the contact zone when forming the *i* layer.

3 Experimental analysis

Based on the incremental forming equipment described in Section 2, the experimental analysis section focuses on the formation of straight and spiral grooves on the surface of tube. The study focused on the effect of single feed on forming quality and forming limit, and the feasibility of incremental forming methods for tubes is demonstrated experimentally.

In general, straight grooves can be formed by the IPF method. During the formation, 6061 aluminum alloy tubes were used as the experimental material. The outer diameter of tube is 40 mm, and the wall thickness is 1 mm. The relevant parameters of aluminum alloy tubes are shown in Table 1.

In the experiment of forming a straight groove, the tool radius *R* is 10 mm and the length of forming part is 200 mm. The effect of single feed and friction coefficient of forming tool on the quality of the straight grooves formed in the tube was studied. The single feed of tool head is *h*, and the friction coefficient is η. The formation of a single straight groove and three straight grooves is shown in Fig. 4.

The process of forming a single groove by the incremental forming method was studied. To study the effect of different single feeds on the wall thickness of formed tube, seven feature points at equal distances were considered in the deformation zone. The selected feature points are shown in Fig. 5.

Table 1 Relevant parameters of 6061 aluminum alloy

Density ρ (g/cm^3)	Young's modulus E (Gpa)	Yield strength σs (Mpa)	Work-hardening exponent *n*	Strength coefficient K(Mpa)	Poisson's ratio *u*
2.74	78.24	234.6	0.114	365.3	0.33

Fig. 4 Forming of straight groove parts of IPF

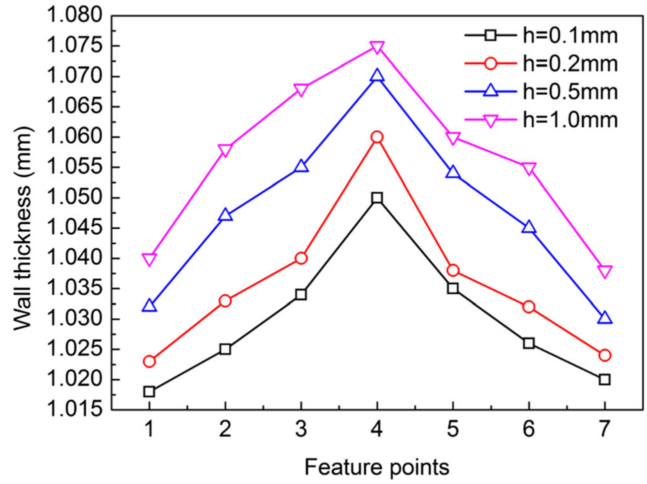

Fig. 6 Wall thickness variation

In the experiment, the single feed of forming tool is 0.1 mm, 0.2 mm, 0.5 mm, and 1 mm. The total amount of feed is 5 mm. In addition, the friction coefficient between the tube and forming tool head is a fixed value. The axial movement speed of forming tool is a constant. By measuring the wall thickness distribution of tubes at different feature points, the results obtained are shown in Fig. 6.

For this experiment, a certain relationship existing between the total feed and wall thickness at point P_4 is shown in Fig. 7. In the experimental process, the single feed of forming tool is 0.2 mm. The groove depth increases from 0 to 3 mm, and the wall thickness at point P_4 gradually increases. The groove depth increases from 3 to 5 mm, and the wall thickness at point P_4 almost remains unchanged. The groove depth increases from 5 to 10 mm, and the wall thickness at point P_4 gradually decreases. The reasons for this phenomenon can be explained by Vasiliki's theory [15] (Fig. 8).

Two movable plastic hinges are located at two points B and B′ and a fixed plastic hinge is initially located at point A. The length of arc BAB′ starts to shorten; thus, the wall thickness starts to increase. As point A continues to move downwards, the hoop stress of tube shell becomes tensile stress. Therefore, the wall thickness starts to decrease.

Undoubtedly, spiral grooves can also be formed by the IPF method. In the experiment, the material parameters of tube are the same as those of previous experiment. The total length of spiral groove on the surface of tube is 200 mm, and the distance between two grooves is 40 mm. In addition, the single feed of forming tool is 0.1 mm, and the total feed is 4.5 mm. The formed tube is shown in Fig. 9.

4 Numerical simulation

To verify the above experiment, ABAQUS/explicit was used for numerical simulation of forming process. Based on ABAQUS/explicit, an elastic-plastic finite element (FE) model for IPF was established. The stress and strain

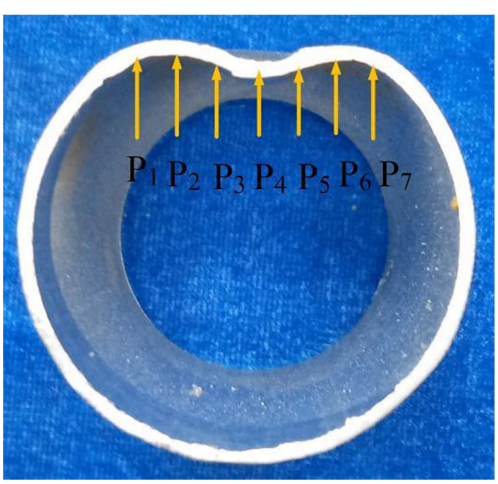

Fig. 5 Feature points

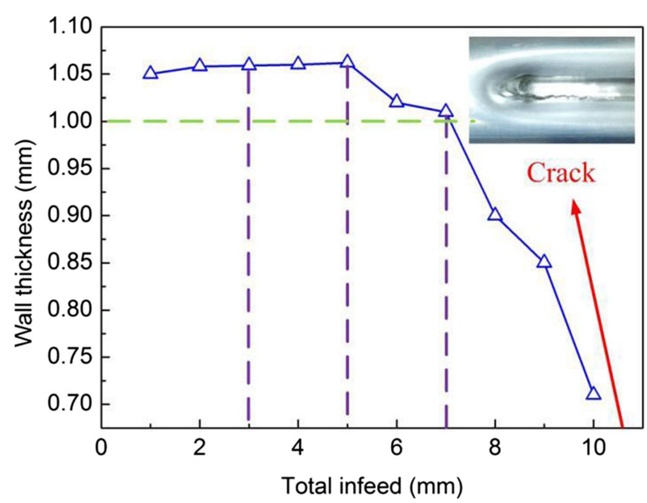

Fig. 7 Wall thickness of the lowest point of groove

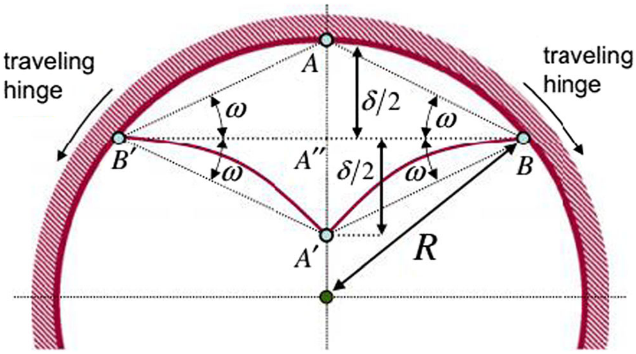

Fig. 8 Vasiliki's theoretical model

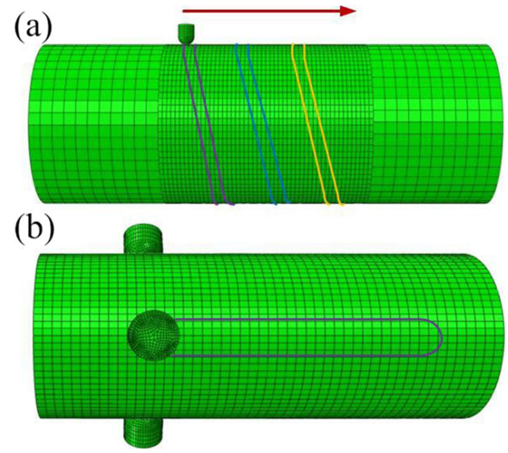

Fig. 10 **a** and **b** FE model of IPF

distributions during the IPF were analyzed. To ensure the accuracy and reliability of simulation, FE models were established for the formation of straight and spiral grooves. During the FE simulation, the multiple of mass scaling is 100,000. In addition, the material model is a power enhancement material model. This material model is suitable for many metals. The power enhancement material model is suitable for plastic problems with a large strain. The contact between forming tool and tube was modeled with different friction coefficients. The FE model of forming spiral grooves is shown in Fig. 10a, and the FE model of forming straight grooves is shown in Fig. 10b.

For the FE simulation of forming straight grooves, the simulation parameters should be determined. The tube diameter of 6061 aluminum alloy is 40 mm, and tube wall thickness is 1 mm. The axial speed of the forming tool is 10 mm/s. The simulation parameters are shown in Table 2.

For different simulation friction coefficients, the simulation results obtained under different conditions are shown in Fig. 11. The friction coefficients of Fig. 11a–d are 0.05, 0.08, 0.10, and 0.12, respectively.

For the FE simulation of forming spiral grooves, the simulation parameters should also be determined. The contact between forming tool and tube was modeled with a friction coefficient of $\mu = 0.02$. The spindle speed is 10 rmp, and axial speed of forming tool is 6.7 mm/s. The simulation parameters are shown in Table 3.

For different signal feeds, the simulation results obtained under different conditions are shown in Fig. 12. This has less influence on the maximum groove depth of spiral grooves.

5 Results and discussion

Through a combination of experiments and FE simulation, the results of ITF were reasonably analyzed. Through FE simulation, the forming process parameters were rationally optimized, the defects in the forming process were predicted, and the optimal parameters for the experiment were obtained, thus reducing the number of experiments. The effect of process parameters for ITF was evaluated. First, the results of forming straight grooves obtained by the IPF method are analyzed and discussed. To study the effect of different single feeds on the wall thickness of formed tube, seven feature points

Fig. 9 Components formed by the IPF method

Table 2 Simulation parameters for straight grooves

Number	The single feed (mm)	Friction coefficient	Maximum groove depth (mm)
1	0.10	0.02	10.62
2	0.20	0.02	11.53
3	0.50	0.02	10.51
4	1.00	0.02	10.47
5	0.10	0.05	10.45
6	0.10	0.08	10.43
7	0.10	0.10	10.36
8	0.10	0.12	10.28

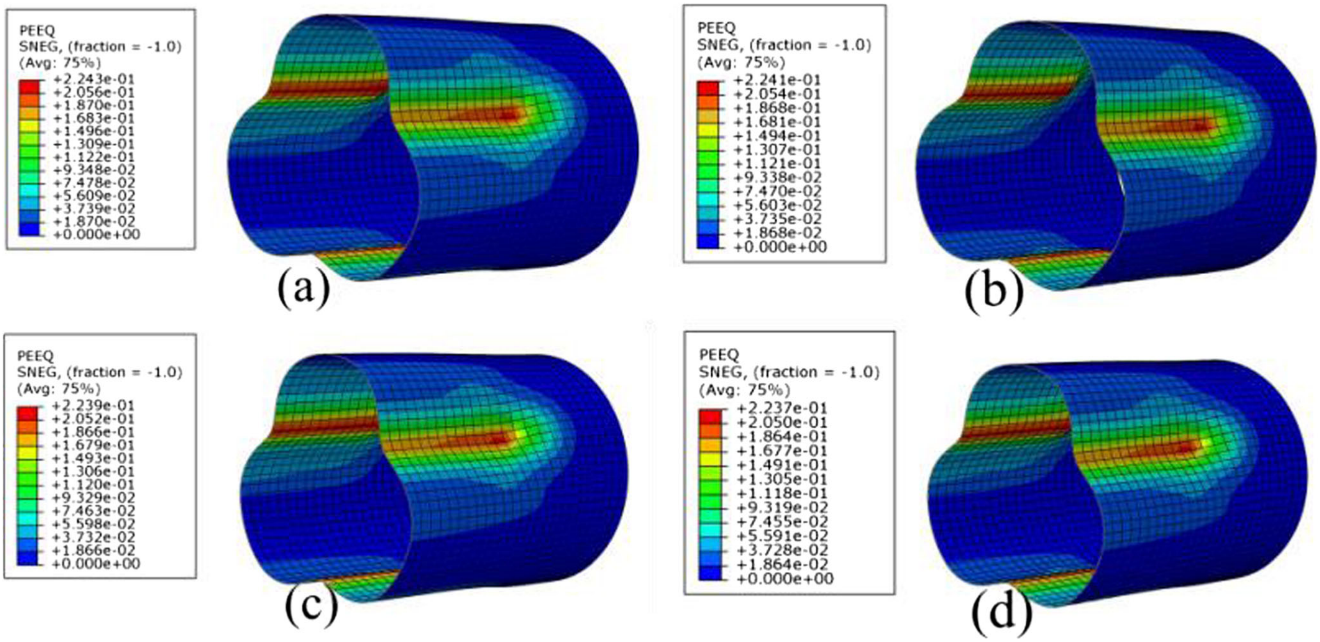

Fig. 11 **a**–**d** Strain distribution of straight grooves

at equal distances were studied in the deformation zone of FE simulation. The location of feature points is shown in Fig. 13.

According to Vasiliki's theory, the wall thickness of first tube increases and then decreases with the increase in total feed. An intermediate deformation was obtained for tubes of different materials. The coefficient of friction in Fig. 14a is 0.02. When the total feed is a fixed value, the distribution of wall thickness on tube surface is shown in Fig. 14. For this 6061 aluminum alloy, the intermediate deformation is 5 mm.

With the increase in single feed, the wall thickness of tube increases. The friction coefficient slightly affects the change in wall thickness, but significantly affects the surface quality of formed tube. With the increase in coefficient of friction, the surface quality of formed tube decreases. No quantitative relationship exists between the friction coefficient and surface quality of the tube.

In addition, the results of forming spiral grooves obtained by the IPF method are also analyzed and discussed. By combining spindle rotation and axial movement of forming tool, a spiral groove can be formed on the surface of tube with high precision. Similarly, the single feed of the forming tool affects the forming limit and quality. Figure 15a shows relationship between wall thickness of tube and total feed. The results of simulation and experiment are consistent. Figure 15b shows the relationship between the calculation of spring back and single feed.

During the formation of spiral grooves on the surface of tube, with increase in total feed, the wall thickness of tube gradually decreases. When the single feed is 0.15 mm, the maximum groove depth is 4.55 mm.

The influence of the spindle speed and the forming tool axial movement speed on the forming limit was evaluated. When the single feed of the forming tool is 0.1 mm and the total feed is 3.5 mm, simulations and experiments were carried out for the case where the distance between the spiral grooves is 40 mm and 20 mm. When the distance between spiral grooves is 20 mm, the axial speed of the forming tool is 5 mm/s and the spindle rotation speed is 15 rmp. When the distance between the spiral grooves is 40 mm, the axial speed of forming tool is 5 mm/s and the spindle rotation speed is 7.5 rmp. A comparison between simulation and experiment is shown in Fig. 16.

According to the results of simulation and experiment, when the distance between spiral grooves is different, the effect of change in stress distribution and wall thickness during the formation is not significant. The strain of tube during the forming process increases as the distance between the spiral grooves increases, but the increase is not clear. Further systematic studies are needed to evaluate the influence of spindle speed on forming quality.

Table 3 Simulation parameters for spiral grooves

Number	The signal feed (mm)	Maximum groove depth (mm)
1	0.05	4.35
2	0.10	4.45
3	0.15	4.55
4	0.20	4.48

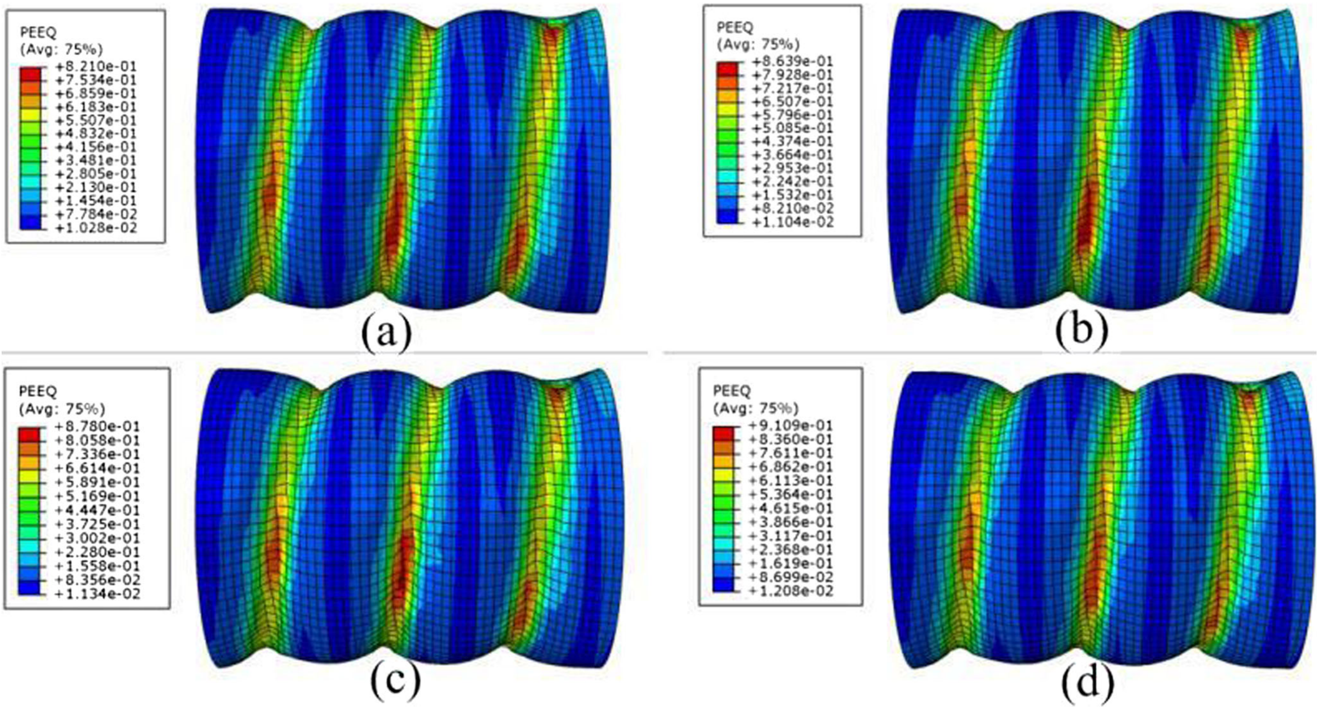

Fig. 12 **a**–**d** Strain distribution of spiral grooves

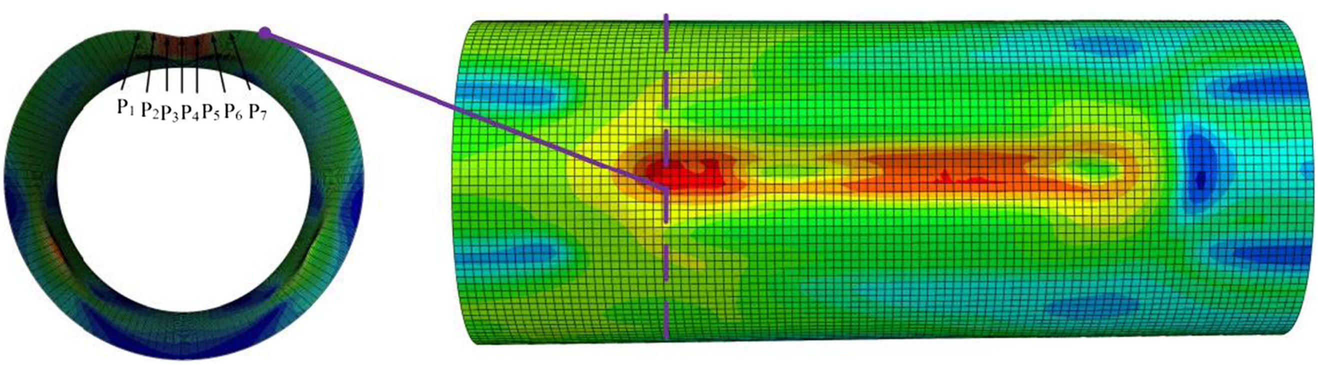

Fig. 13 Feature points of FE simulation result

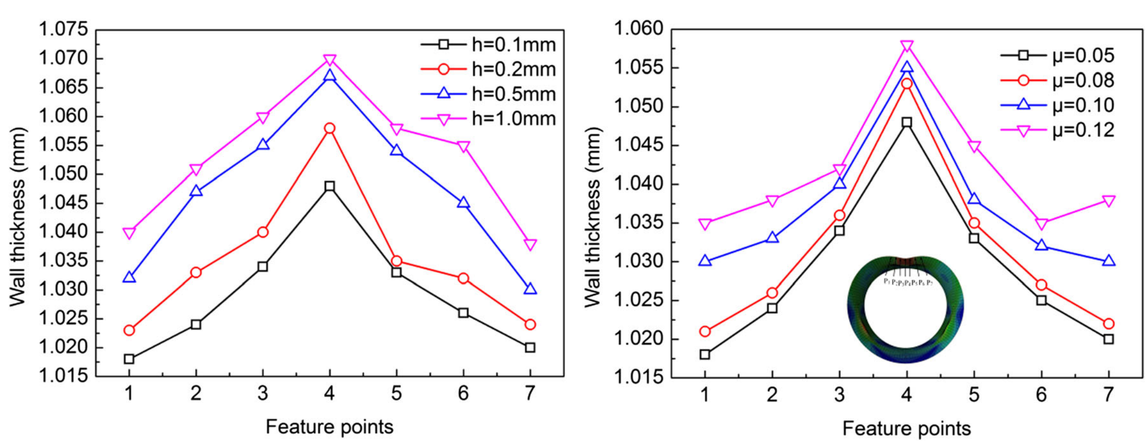

Fig. 14 **a** and **b** Distribution of wall thickness FE simulation results

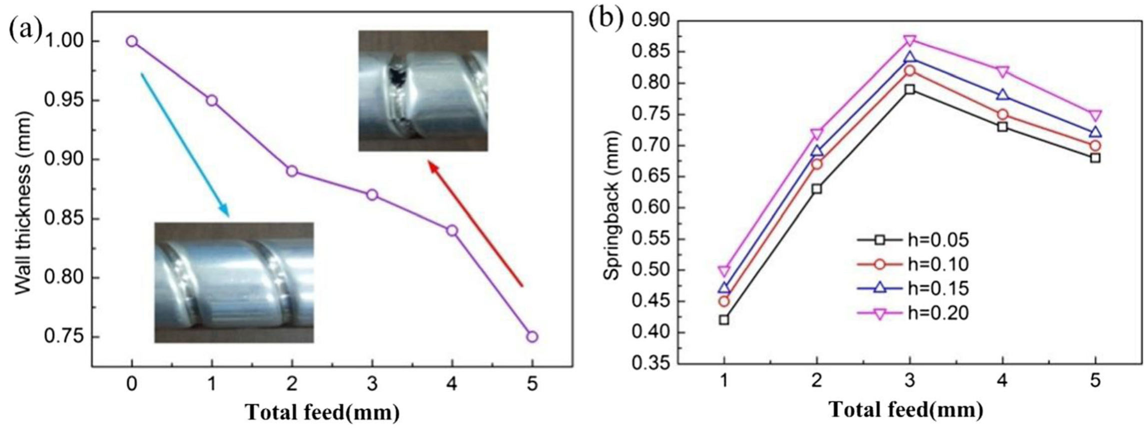

Fig. 15 **a** and **b** Relationship between spring back and wall thickness and total feed

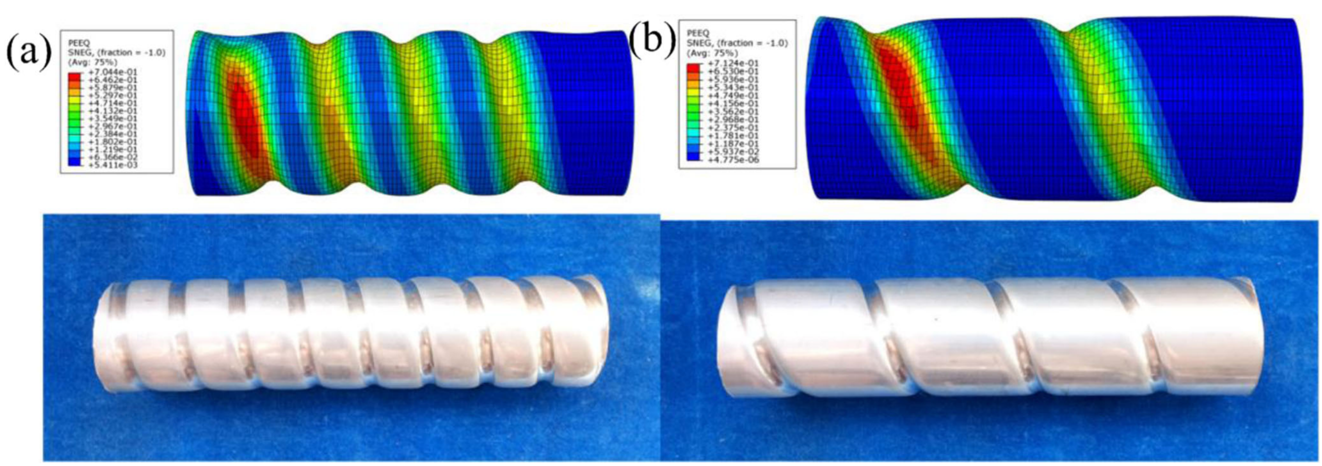

Fig. 16 **a** and **b** Simulation and experimental analysis of spiral groove distances

6 Conclusions

(1) Based on ABAQUS/explicit, a three-dimensional FE model was established for the IPF of tubes. By studying the distribution of stress and strain in the process of forming straight and spiral grooves, the area where the forming starts may cause stress and strain concentration. Wall thickness thinning and cracking often occur in this area of tube.

(2) During the formation of straight grooves on the surface of a tube by the IPF method, with the increase in single feed of forming tool, the rebound of forming part becomes larger. In addition, the increase in single feed increases the material flow of forming area, making the deformation uneven.

(3) During the formation of straight grooves, the axial movement speed of forming tool slightly affects the distribution of stress and strain. An increase in the axial movement speed of forming tool increases the forming force.

(4) When a spiral groove is formed on the surface of a tube, the combination of spindle speed and axial movement speed of forming tool should be considered. The single feed of forming tool significantly affects the forming quality. By comparing different single feeds, it was found that when the single feed is 0.1 mm, the maximum groove depth increases by 12.5%.

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