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Thickness improvement and calibration pressure reduction of stepped tubular components using axial hydro-pressing method

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Abstract: A new tube axial hydro-pressing method was proposed to solve the problems of high forming pressure and severely uneven wall thickness distribution of traditional tube hydroforming methods to form stepped tubular components. The forming pressure of the traditional hydroforming and the tube axial hydro-pressing method is studied theoretically, the mechanical model of the fillet area is established, and the forming pressure calculation formula is given. Based on this, an investigation of the tube axial hydro-pressing method is carried out by numerical simulation and experimental methods, and compared with the traditional tube hydroforming method. The key to the tube axial hydro-pressing method is to precisely control the relationship between the protrusion height and the axial feed, which is achieved by precisely controlling the feeding pressure and the axial displacement. Therefore, the constant pressure device in the experiment was used to eliminate the influence of the pressure rise caused by the volume compression on its cooperation relationship, to achieve accurate control of the loading path, eliminate wrinkles and flash defects. A qualified workpiece is successfully manufactured when the internal pressure is 18.0 MPa and the feed on each side is 15.0 mm. The forming pressure is reduced by 88.0\%, and the feed is increased by 6.5\%, which reduces the wall thickness reduction by 9.0\%. The wall thickness difference of the workpiece can be controlled within 7.0\%. The tube axial hydro-pressing method is suitable for forming stepped tubular components, which can achieve more replenishment at lower pressures, thereby effectively improving the uniformity of wall thickness and significantly reducing the forming pressure.

Keywords: Hydroforming; axial hydro-pressing; calibration pressure; thickness distribution; stepped component

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1 Introduction

Tube hydroforming is an advanced forming technology developed for lightweight component manufacturing in recent years. It has been widely used in the automotive and aerospace fields due to its light weight, good performance, good structural stiffness and fatigue performance, especially reducing the number of parts and subsequent machining and welding and it has a very broad market potential and application trend [1,2]. Tube hydroforming technology can be divided into three categories according to the different product shapes: variable diameter tube hydroforming, curved axis tube hydroforming and multi-pass tube hydroforming [3]. Variable diameter components have been widely used as typical structures for automotive exhaust systems and aerospace joints [4]. Variable diameter components are traditionally manufactured by stamping and welding. However, it is difficult to control the welding deformation caused by thin plate welding, which makes it difficult to ensure the forming accuracy and consistency of the product. Therefore, Tube hydroforming technology was invented and successfully used in the integral forming of the variable diameter components, which solved the problems of stamping and welding of sheet metal [5]. Variable diameter components generally have the same characteristics, and the diameter is continuously or discontinuously changed along the axis. Considering the sealing and the initial diameter of the tube, when designing the hydroforming process of the variable diameter components, the larger diameter part is usually placed in the middle area, and the ends are basically the same as the original tube diameter. In this way, the material at the tube end needs to be fed to the middle area during the forming process. However, it is difficult to completely supply the material required in the middle area by the end feeding due to the friction between the tube blank and the die surface, which will inevitably cause the following typical characteristics: the wall thickness of the tube end is thickened, the wall thickness of the middle area is thinned, and the wall thickness invariant line appears at the tube end and the middle area. Especially for stepped tubular components, the effect of the friction is more prominent and the characteristics are more obvious [6,7]. The wall thickness of the transition area near the corners was severely thinned and even cracked on the straight walls of the steps. It is hard to supplement the material of the tube end to the straight wall portion, only the bulging will exacerbate the material thinning in the transition area instead of the rounded corners because of the friction effect [8]. However, uniform wall thickness distribution is one of the important indicators to ensure the mechanical properties of the hollow components, so it is very important to control the wall thickness distribution of the formed workpiece.

There are many methods to control the wall thickness of the hydroformed variable diameter components in addition to selecting a large fillet radius and avoiding stepped features as much as possible in the design [9]. Firstly, it is one of the effective measures to reduce the friction between the tubular blank and the die surface to improve
the thickness uniformity distribution. In industrial production, lubricants are often used to improve the surface quality of dies. Abir Abdelkefi et al. compared the wall thickness distribution of hydroformed square, rectangular, trapezoidal parts with or without lubricant. Regardless of the shape formed, the lubricant can greatly improve the uniformity of the wall thickness [10-12]. Secondly, the "beneficial wrinkles" is a subversive process method. Wrinkles are generally considered to be defects in the traditional sense. Yuan et al proposed the concept of "useful wrinkle" to obtain workpieces with large expansion rates by using beneficial wrinkle through accumulating materials in the middle area. In general, wrinkles with specific types of characteristics are obtained by controlling the loading path, that is, the relationship of the axial displacement and the internal pressure, thereby effectively accumulating material from the tube end to the middle area, and then the wrinkles are flattened by high pressure during the subsequent calibration process [13,14]. On this basis, it is also an effective method to increase the preforming process to realize the forming of parts with non-rotating features. There will be no beneficial wrinkles, if there are large differences in the shape characteristics of the workpiece or uneven friction during the forming process because of the different contact sequence. Preforms with rotating characteristics are first obtained by adding a preforming process, which can effectively utilize beneficial wrinkles. Then the preform is clamped by the die and calibrated by the high internal pressure in the subsequent calibration process. It is also an effective method to improve the uniformity of wall thickness [15]. Third, it is also an effective method to improve the wall thickness distribution by controlling the contact sequence of the die and the tube blank in the circumferential direction. "Petal-like" preforming is one of the methods to adjust the contact sequence when the cross-sectional shape of the part is polygonal, which effectively reduce the friction and improve the uniformity of wall thickness [16,17]. For parts that need to be bent in advance, the wall thickness inside and outside the bending position is not uniform due to the bending, resulting in heterogeneous in the bending area. Therefore, not only the contact sequence between the fillet corner and the straight side, but also the contact sequence between the inside and the outside of the curved area must be considered [18]. Fourthly, it is also beneficial to improve the uniform distribution of the wall thickness by selecting a tube blank with a large n value. Thickness distribution is a function of the hardening index n of the tube blank material, and a larger n value is beneficial to improve the wall thickness distribution [19,20]. In addition, it is also a method to improve the uniformity distribution of the wall thickness by changing the die structure. Bihamta proposed a method for hydroforming a complex shaped part by using a three-part die instead of a two-part die, where the fillet is no longer formed solely by hydraulic pressure, but by a combination of hydraulic pressure and mechanical extrusion, thereby effectively reduces wall thickness thinning.
Hwang Y M et al. used a movable die to eliminate the effect of axial friction, thereby achieving the formation of parts with large expansion [22].

A tube axial hydro-pressing method was proposed for the variable diameter components with stepped features, based on the previous research. The conventional tube hydroforming device generally includes only an upper die and a lower die. However, the device of the new method of tube axial hydro-pressing includes two end dies composed of left and right side portions besides the middle die composed of the upper and lower portions. And the left and right end dies and punches are respectively fixed, so that the left and right end dies and punches are fed simultaneously, thereby eliminating the effect of friction on the feed. The forming pressure of the traditional hydroforming and the tube axial hydro-pressing method is studied theoretically, the mechanical model of the fillet area is established, and the forming pressure calculation formula is given. Based on it, an investigation of the tube axial hydro-pressing method is carried out by numerical simulation and experimental methods, and compared with the traditional tube hydroforming method. A volume pressure compensation mechanism is proposed, which reveals the forming shape accuracy and wall thickness distribution law.

2 Specimen dimensions and material

The numerical simulation and experimental methods are used to study the process of axial hydro-pressing. The sample is shown in Figure 1. It is a variable diameter component with step features, and its shape is symmetrical along the axial direction. The axial length of the sample is 165.0 mm, the end section A-A of the sample is circular, and the outer diameter is 60.0 mm. The cross-sectional shape and size do not change from the end to the fillet area. In the fillet area, the cross-sectional shape transitions from a circle with an outer diameter of 60.0 mm to a circle with an outer diameter of 80.0 mm, that is, the section B-B, and then gradually decreases to a circular cross section with an outer diameter of 60.0 mm. The minimum fillet radius of the fillet part is 3.5 mm, the middle of the sample is slightly concave for positioning, the middle section D-D is a circle with an outer diameter of 60.0 mm, and the sample is a typical axisymmetric stepped variable diameter part.

The material of the tube blank used in the experiment was 321 stainless steel, the outer diameter of the tube blank was 60.0 mm, and the thickness was 1.5 mm. It can be known that the maximum expansion rate of the cross section of the sample during the deformation process is 33.3%. The engineering stress-strain curve was obtained by one-way tensile method, and the mechanical properties were obtained. The yield strength is based on the stress at 0.2% tensile strain. The detailed mechanical performance parameters are shown in Table 1.
Table 1 Mechanical properties of 321 tubular blanks

| Elastic modulus | Yield strength | Ultimate strength | Elongation |
|-----------------|----------------|--------------------|------------|
| E(GPa)           | σy (MPa)       | σu (MPa)           | δ (%)      |
| 194.0            | 317.0          | 380.0              | 49.0       |

3 Principles of two forming methods

3.1 Traditional tube hydroforming method

Generally, the stepped variable components can be formed by the traditional tube hydroforming method. The forming device generally includes upper and lower dies and left and right punches, and the die cavity is divided into three typical areas, which are a feeding area, a bulging area and a transition area, as shown in Fig.2. The forming process is as follows: firstly, the upper and lower dies are closed, and the left and right punches are sealed. Secondly, the inside of the tube is filled with liquid medium and pressurized. After the internal pressure reaches a certain value, the left and right punches feed to the middle to push the material of the tube end to the bulging area, which accumulates in the bulging area to form beneficial wrinkles. Finally, the internal pressure in the tube blank is increased to calibrate, so that the tube blank fills the bulging area to obtain a workpiece. It is difficult to make the material flow to the bulging area due to the friction between the tube blank and the die surface, which causes...
the local thickening of the feeding area and the excessive thinning of the bulging area. As a result, the wall thickness distribution is very uneven of the workpiece after hydroforming.

3.2 New tube axial hydro-pressing method

The author proposes a tube axial hydro-pressing method to solve these problems of stepped parts. The die structure of the tube axial hydro-pressing method generally includes upper and lower dies, left and right movable dies, and left and right sealing punches, in which the sealing punch on each side and the ends of the movable die are constrained as a whole, as shown in Fig. 3. The forming process is as follows: firstly, the tube blank is fixed by the upper and lower dies, and the left and right dies are pressed against the tube blank to achieve sealing. Secondly, the liquid medium is filled inside the punch on one side through the replenishing channel. After pressurizing to a certain value, the movable dies on the left and right sides feed to the middle. In this process, a constant pressure device is used to ensure that the liquid pressure in the tube does not change sharply due to volume compression, and the control of feeding and internal pressure is performed according to a certain loading curve. When the middle fixed die contacts the left and right movable dies, the bulging height of the rounded corner reaches a predetermined height at the same time. The fillet is formed by the supporting force of the liquid internal pressure and the axial force of the left and right movable dies to obtain the required workpiece.
Compared with the traditional tube hydroforming method, the feeding die and the punch move simultaneously, eliminating the axial friction between the tube blank and the die surface. In addition, the feeding die and the middle die reserve more deformation space at the bulging position. The combined force of internal liquid and axial feeding die makes it easy for the tube blank to accumulate materials in the fillet area and avoid excessive thinning. At the same time, the feeding of the end die matches the change of the internal pressure. As the distance between the end die and the middle die is shortened, the bulging height of the fillet area is continuously increased. When the middle die and the end die are in contact, the fillet area bulges to a predetermined height at the same time. The fillet is formed under the combined action of the internal pressure support force and the axial compression force of the feeding die, which greatly reduces the forming pressure.

4 Forming process and mechanical analysis of fillet

4.1 Mechanical analysis of fillet by traditional tube hydroforming method

The process of forming a sample with step features by the traditional tube hydroforming method is analyzed, as shown in Fig. 4. Considering the symmetry of the step variable diameter sample and the die structure, only a quarter is taken for analysis. The forming process includes two stages of low-pressure feeding and high-pressure shaping. First, the die is closed, and the inside of the tube blank is filled with liquid to provide pressure support. Then the left and right punches start to feed axially, pushing the tube material to the rounded area. At this time, the tube is subject to the axial force $F$ of the punch, the internal support pressure $P$, and the friction force $F_{f1}$. There is a non-negligible friction force $F_{f1}$ between the tube and the die surface due to the internal pressure inside the tube blank. During the process of the punch pushing the tube material to the fillet area, the friction force $F_{f1}$ is opposite to the direction of movement of the tube material, which prevents the tube material from accumulating in the fillet area. At this time, the axial pressure $F$ and the internal pressure $P$ of the punch work together, and the tube in the fillet area begins to bulge. Because of the hindrance of the friction force $F_{f1}$, the fillet cannot be completely filled during the low pressure feeding process, and the tube wall is inevitably thinned during the bulging process. After the feeding is completed, the internal pressure needs to be greatly increased to form the fillet, that is, the calibration stage. The punch remains stationary, and the tube is subjected to the calibration pressure $P_c$ and the friction force $F_{f2}$. At this time, the calibration pressure required to form the fillet area is [23]:

$$P_c = \frac{t}{r_c} \sigma_f$$  \hspace{1cm} (1)

Where $r_c$ is the minimum fillet radius of the formed part, $t$ is the wall thickness of the formed part, and $\sigma_f$ is the material flow stress during shaping. In general, $\sigma_f = \frac{\sigma_s + \sigma_b}{2}$ is used for estimation.
In this example, the corresponding shaping pressure is calculated to be 149.4 MPa. The high calibration pressure causes the frictional force $F_{f2}$ to increase significantly compared to $F_{f2}$, and it is more difficult for the tube material to flow to the fillet area, resulting in excessive thinning of the fillet area. Therefore, it is difficult to solve the problems of high forming pressure and serious wall thickness thinning no matter how to adjust the axial feeding and the internal pressure by the traditional tube hydroforming method.

![Fig.4 Schematic diagram of force analysis of traditional tube hydroforming method](image)

4.2 Mechanics analysis of fillet by new tube axial hydro-pressing method

Similarly, the process of forming a step sample by the axial filling method is analyzed, as shown in Fig. 5. First, the middle die is closed, and the tube blank is filled with a liquid medium to provide internal pressure support. Then the movable dies at the left and right ends are fed axially. At this time, the tube is subjected to the axial force $F$ of the end die and the internal support pressure $P$. Because the tube end and the die move at the same time, the frictional resistance between the tube blank and the die surface is eliminated. Between the end die and the middle die, deformation space is reserved, so the tube blank is easily accumulated in this area. With the bulging of the fillet area and the feeding of the end die, the tube blank in the fillet area gradually comes into contact with the end die and the middle die. Because the die and the tube are moving relative to each other, the direction of the friction force $F_f$ points to the fillet area, and the friction force further promotes the flow of the tube material to the fillet area. The left and right dies are precisely matched with the internal pressure. When the end die and the middle die are just in contact, the rounded corners of the blanks just reach the design size. The fillet is formed by the combination of the die mechanical pressure $F$ and the internal pressure $P$.

For the tube axial hydro-pressing method, the forming pressure is reduced sharply because the direction of the friction force is directed to the fillet area. Figure 5 is a schematic diagram of the stress in the fillet area. Only a section of the unit width along the ring direction is taken for analysis. The AB segment is selected for force analysis due to the symmetry of the rounded corners. The AB segment is subjected to the internal pressure $P$, the sliding friction force $F_f$, and the acting force $F_B$ for balancing the friction force generated by the BD segment. Let the friction coefficient be $\mu$, and balance equations along the AB direction:

$$F_B = F_f = \mu l AB P$$  \hspace{1cm} (2)
The AB segment acts on BD with a thrust force $F_B$ pointing to the fillet area, which helps to push the material toward the fillet area and reduce the forming pressure of the fillet.

From the geometric relationship, it can be seen that when the angle between the AB segment and the axial direction of the tube is $\varphi$, the angle between the fillet area is $2\varphi$, and the BD segment is subjected to a force analysis. The BD segment is supported by the internal pressure $P$, and the left and right straight arm segments are opposite to the BD. Segment thrust $F_B$, $F_D$, die support force $F_{BB}$, $F_{BD}$. First analyze the entire BD segment and establish a balance equation along the OB direction:

\[ F_{BB} + F_{BD} \cos 2\varphi = \int_0^{2\varphi} PR \cos \varphi \, d\varphi + F_D \sin 2\varphi \]  \hfill (3)

Because the rounded structure is left-right symmetrical, there are the following

\[ F_{BB} = \frac{\sin 2\varphi \left( PR + \mu l_{AB} P \right)}{1 + \cos 2\varphi} \]  \hfill (4)

The forming process of the fillet is regarded as the bending deformation process of the BD segment. The deformation conditions can be obtained by analysing the fillet bending moment and bending conditions. It is deduced that the bending moment at the center C of the fillet is the largest. The result is:

\[ M = F_{BB} R \sin \varphi - F_B R (1 - \cos \varphi) - \int_0^\varphi PR^2 \sin \varphi \, d\varphi \]  \hfill (5)

The yield conditions for bending deformation are:

\[ \sigma_{max} = \frac{M_{max}}{W} = \frac{F_{BB} R \sin \varphi - F_B R (1 - \cos \varphi) + PR^2 \cos \varphi - 1}{\frac{bt^2}{6}} = \sigma_s \]  \hfill (6)

Where $W$ is section modulus in bending equal to $\frac{bt^2}{6}$, and $b$ is width of micro element which is selected to 1. So, the internal pressure required to form the fillet from equations (4), (5) and (6) is:

\[ P = \frac{bt^2}{6R(R + \mu l_{AB})} \frac{\sin 2\varphi \sin \varphi + \cos \varphi - 1}{\frac{bt^2}{6} \sigma_s} \]  \hfill (7)

Generally, for the friction between metals, $\mu$ is taken as 0.1. Consequently, the fillet forming pressure is calculated from Equation (7) to be 17.51 MPa.
Fig. 5 Analysis of the force of the new tube axial hydro-pressing method: a Initial state b Free expansion c Axial charging force d Fitting with the die e Force diagram of rounded corners.

5 Simulation

5.1 Finite element model and experimental tools

The simulation was carried out by LS-DYNA, and the effect of the loading path on the hydroformed part was studied. The finite element model of traditional method used for hydroforming process is shown in Fig. 6a, which includes an upper die, a lower die, two punches and a tube. The finite element model of new method used for hydroforming process is shown in Fig. 6b, there are a left slide die and a right slide die except an upper die, a lower die, two punches and a tube. In the two cases, the dies are defined as rigid bodies, and the tube is defined as Belytschko-Tsay shell elements. The coefficient of friction between the dies and tube is selected as 0.1[16]. The loading path of the axial feeding and the internal pressure is considered in the hydroforming and applied on the internal surface.

Fig. 6 Finite element model. a Traditional tube hydroforming method. b New tube axial hydro-pressing method

There are many related reports and experiment results of the traditional tube hydroforming methods, then the relevant experiments are no longer carries out, and the relevant experimental verification is carries out for the new near-thickness wall forming method. The hydroforming process is performed by the hydroforming machine, which consists of a hydraulic press with the capacity of 20000KN, an intensifier with the capacity of 400MPa, two sealing cylinders, and a control computer. Two cylinders of 2000KN are all equipped with high precision displacement sensor that the control accuracy is 0.05mm. The pressure sensor is equipped at the outlet end of the intensifier, which is used to detect the internal pressure of the tube inside, and the precision is 0.25MPa. And the hydroforming
tool is shown in Fig. 7, which consists of an upper die, a lower die, a base plate, two-cylinder brackets, left punch and right punch, left slide die and right slide die. Among them, the left die and the punch, and the right die and the punch are respectively assembled and fixed together. Left punch and right punch can be used to realize both sealing and axial feeding. Emulsion is used as forming media, and the internal pressure is supplied by an oil-water pressure transducer. Both the internal pressure and the axial feeding can be accurately controlled by a close-hoop servo system and a computer.

![Fig. 7 Experimental tool of new tube axial hydro-pressing method.](image)

5.2 Research scheme of the loading path using trial and error method

It can be got that the initial yield pressure is 15.9 MPa, the cracking pressure is 19.0 MPa, according to the reference [3]. The axial feeding on each side of tube end is 12.5 mm according to the principle of constant volume, thus different loading paths are designed, as shown in Fig. 8. The final calibration pressure of all the schemes mentioned above is 150 MPa. In the study, the studied parameters are changed and other parameters are fixed. The effect of feeding pressure on forming defect is studied under the condition of axial feeding of 12.5 mm. In order to ensure yielding and avoid cracking, the range of the feed pressure is best controlled between the initial yield pressure and the cracking pressure. Therefore, the feeding pressure is set as 14.0 MPa, 16.0 MPa, 18.0 MPa, 20.0 MPa, and 22.0 MPa, respectively. Simultaneously the effect of axial feeding on forming defect is studied under the condition of the internal pressure of 18.0 MPa and the axial feeding is 11.0 mm, 13.0 mm, 15.0 mm, 17.0 mm, and 19.0 mm, respectively.
The scheme of loading paths for the numerical simulation. a Same axial feeding. b Same feeding pressure

5.3 Hydroformed part of traditional method

The numerical simulation results of traditional hydroforming are analyzed, as shown in Figures 10 and 11. Fig. 10 is a wrinkle defect obtained under an internal pressure of 18.0 MPa and a feeding amount of 15.0 mm. It accumulates in the fillet area, and wrinkle defects occur near the outside of the step. In the subsequent calibration process, the internal pressure was continuously increased to 150.0 MPa, and wrinkles could not be completely eliminated. Fig. 11 is a qualified workpiece obtained under an internal pressure of 18.0 MPa and a feeding amount of 12.5 mm. In the subsequent calibration process, the internal pressure was increased to 150.0 MPa, and the filleted area was completely fitted to the die, and a qualified part that met the requirements was obtained.
5.4 Hydro-pressed part of new method

The results of the numerical simulation of the axial charge and hydraulic deformation are analyzed. The main defects include wrinkles and flashes, which are mainly affected by the loading path. When the loading path is reasonable, the manufacturing of qualified workpieces can be successfully completed.

5.4.1 Wrinkle defect

Wrinkling is one of the main defects in tube axial hydro-pressing process. There are wrinkle defects in the formed parts obtained by the loading path 1 and the loading path 9. Figure 12 shows the forming limit diagram (FLD) for these two typical loading paths. As shown in Fig.12a, the feed pressure is 14.0 MPa and the feeding is 15.0 mm. Fig. 12b is a forming limit diagram at a feeding pressure of 18.0 MPa and a feed amount of 19.0 mm. When the feeding pressure is too small or the feeding amount is too large, wrinkling will occur due to the excessive axial force.
5.4.2 Flash defect

The flash at the apex of the fillet is another major defect form of the tube axial hydro-pressing method. The flash defects occurred in the formed parts by the loading paths 4 and 5. This is mainly due to the excessive expansion of the fillet area, as shown in Figure 13. When the feeding pressure is 20.0 MPa and the feeding amount is 12.5 mm, the simulation results show that the raised height of the blank at the fillet portion exceeds the die cavity. When the end die is closed, a flashing defect is generated at the fillet vertex position.

5.4.3 Qualified workpiece

When the feeding pressure is 18.0 MPa and the feeding amount is 15.0 mm, that is, the loading path 3, a good formed part is obtained because of well match between the feeding pressure and the feeding amount, as shown in Fig. 14.
6 Experiments of new tube hydro-pressing methods

In view of the fact that the traditional tube hydroforming method is more common for forming stepped parts and the forming rules are clear, this article only conducts experimental verification of the tube axial hydro-pressing method. Figure 15 shows the wrinkle defects obtained in the experiment. Among them, Figure 15a is an experimental piece obtained at 14.0 MPa and 15.0 mm feed by consistent feeding. Wrinkles appear on the outside of the step, which is mainly due to the low feeding pressure. Fig. 15b is an experimental part obtained under the parameters of 14.0 MPa and feed 15.0 mm with inconsistent feeding. The difference from the former is that the wrinkling position only appears outside the right step of the part. This is mainly because the tube blank has been shifted to the right in the axial direction during the clamping process of the middle die. As a result, the feeding amount at the right end is larger than a predetermined value of 15.0 mm, and the feeding amount at the left end is less than 15.0 mm. Consequently, the workpiece wrinkled at one end and unfilled fillet cavity at the other end leading to the protrusion height than the design value.

The occurrence of flashing is often caused by excessive internal pressure, and the bulging height exceeds the cavity when the end die and the middle die have not yet contacted. The internal pressure was set to 18.0 MPa in the experiment according to the simulation results in order to avoid the occurrence of flash. However, it is worth noting that in the experiment, when the tube blank is filled with pressurized liquid, the lumen volume gradually
decreases during the axial feeding of the left and right punches, and the liquid volume in the tube cavity is compressed, which causes the internal pressure of the tube blank uncontrollable rise.

The increase in liquid pressure due to volume compression was measured in the experiment. First, the tube blank is sealed and filled with a liquid medium, and then the internal pressure is increased to 10.0 MPa, and then the pressure maintains at 10.0 MPa. Then the left and right dies are fed in the axial direction until they fit with the middle die. In this process, the real-time pressure of different feeds is recorded, and the final result is shown in Figure 16. It can be seen from the figure that the pressure increases from 10.4 MPa to 25.8 MPa from the start of the left and right dies to the stop of the feed. The sharp rise in liquid pressure is caused by volume compression, which accelerates the rate of bulging. When the left and right dies and the middle die are not in contact, the bulging height has exceeded the height of the fillet area, resulting in flash defects, as shown in Fig. 17. A pressure-stabilizing device was used in the experiment to avoid the pressure rise caused by the compression of the liquid volume in order to solve this problem. The internal pressure is stabilized at 18.0 MPa. When the axial feed of the left and right dies is in contact with the intermediate die, the tube just bulges to the height of the fillet area. Flashing is effectively avoided by controlling the exact coordination between the bulging height and the axial feed of the left and right dies. As shown in Fig. 18, under the condition of the internal pressure of 18.0 MPa and the axial feed of 15.0 mm, a qualified part is obtained.

Fig.16 Measured and compensated loading path of tube axial hydro-pressing.
This section gives the contour shape of the qualified part obtained under the condition of the optimal loading path using the tube axial hydro-pressing method, and compared with the traditional tube hydroforming method, as shown in Figure 19. When the internal pressure is 18.0 MPa and the feed amount is 15.0 mm, the fillet corner can be realized by using the tube axial hydro-pressing method, and a workpiece with a shape and contour that meets the design requirements can be obtained. The same internal pressure and feed volume were also selected in order to compare the two methods. However, material accumulation occurred in the fillet area and wrinkle defects were formed during the traditional tube hydroforming method. Even if it is pressurized to 150.0 MPa for calibration, wrinkles cannot be completely eliminated, and a workpiece with a shape that does not meet the requirements is obtained. In order to eliminate wrinkling, the internal pressure is kept constant at 18.0 MPa, and when the feed amount is reduced to 13.0 mm, a shaped part that meets the requirements can be obtained. Because the frictional resistance between the die surface and the blank in the feeding area is too large, the axial feeding is difficult, and
the blank fails to effectively flow and fill the fillet area. The fillet area is mainly formed by bulging, so that the wall thickness is seriously thinned.

When using conventional hydroforming methods to form stepped variable diameter components, the material in the feeding area cannot be fully fed to the fillet area because the space in the fillet area is small and friction prevents the material from flowing. When the feed amount is large, it will cause the tube material to accumulate in the round corner area, resulting in dead wrinkles. After numerical simulation analysis, it can be known that the maximum feed amount allowed by this method is 13.0 mm. For the axial tube hydro-pressing process, the fillet area is open. During the feeding process, there is a lot of space between the end dies and the middle die. And friction promotes the flow of material to the fillet area, so more feed can be achieved. For the parts described in the article, the traditional forming method can only use a 191.0 mm tube blank to form a workpiece without defect, and the axial filling hydraulic shape can use a 195.0 mm tube blank to form a workpiece without defect, which increases the feed by 6.5%.

Fig.19 Shape accuracy comparison of two forming methods.

8 Wall thickness distribution of two forming methods

Similarly, the wall thickness distribution of the formed parts obtained by the conventional tube hydroforming and tube axial hydro-pressing methods is analyzed. The forming parts under the optimal loading path for the forming effect of the two forming processes were selected respectively. Because the shape of the formed part is symmetrical, only half of the formed part is selected for measurement. Fifteen measurement points are selected along the axial direction at equal intervals on the upper side of the workpiece, and the wall thickness of each point is measured to obtain the wall thickness distribution of the workpiece in the axial direction, as shown in Fig. 20. In the figure, the results of the feeding stage and the final forming part of the traditional tube hydroforming method, the bulging stage and the final forming part of the axial tube hydro-pressing under the optimal loading path are shown. The wall thickness distribution is given in the form of the wall thickness change rate. Define the maximum
and minimum wall thickness difference $\Delta t = t_{\text{max}} - t_{\text{min}}$, and the change rate of the wall thickness difference is $\eta = \frac{\Delta t}{t_0} \times 100\%$.

Firstly, the axial wall thickness distribution of the variable diameter part obtained by the traditional tube hydroforming method is analyzed. When the feed is completed, the wall thickness of the end and middle parts of the workpiece increases and the fillet area becomes thinner. During the calibration process, the wall thickness of the fillet area is seriously thinned. Since the feed is mainly concentrated in the transition area outside the fillet, the outer area of the fillet is less thinned, and the inner area of the fillet is most seriously thinned. The minimum $t_{\text{min}}$ of the wall thickness of the workpiece was 1.345 mm, and the thinning rate reached 10.3%. In the middle of the workpiece, the maximum wall thickness $t_{\text{max}}$ was 1.556 mm, and the wall thickness increased by 3.7%. The maximum and minimum wall thickness difference of the workpiece is 0.211 mm, and the variation rate of the wall thickness difference is 14.1%.

Secondly, the wall thickness of the workpiece obtained by the tube axial hydro-pressing method is analyzed. In the bulging stage, no wall thickness reduction occurred due to sufficient feed. After that, the forming of the fillet was mainly obtained by axial compression. After that, the forming of the fillet was mainly obtained by axial compression. The compression caused the tube material on both sides to be squeezed into the fillet area, and the wall thickness of the fillet area was further thickened. A small amount of thinning occurred during the transition of both sides of the fillet. Similarly, since the feed is mainly concentrated in the outer transition area of the fillet, the thinning of the outer transition area of the fillet is smaller, while the inner transition area of the fillet is larger. The minimum wall thickness of the workpiece obtained by using the tube axial hydro-pressing method is 1.480 mm, and the thickness thinning rate is only 1.3%. The wall thickness in the rounded area is the largest, reaching 1.581 mm, with a thickening rate of 5.4%. The variation rate of the wall thickness difference of the workpiece is 6.7%. The wall thickness reduction is improved by 9.0%, and the wall thickness difference is improved by 7.4% compared with the traditional tube hydroforming method. It can be seen that the wall thickness distribution law of the formed parts obtained by the tube axial hydro-pressing method is different from those obtained by the traditional tube hydroforming method. Local thinning and wall thickness uniformity are significantly improved compared to traditional tube hydroforming method.
9 Conclusion

This paper presents the tube axial hydro-pressing method for forming stepped variable diameter components, and compares it with the traditional tube hydroforming method. The conclusions are obtained as follows:

(1) The axial filling hydraulic process method adopts a block die structure, which eliminates the axial friction resistance in the feeding area, and reserves sufficient deformation space for the fillet area between the end dies and the middle die. The amount of feeding has increased by 6.5% compared to that of the traditional tube hydroforming. Fillet is formed under the combine of internal pressure and axial mechanical extrusion. The friction in the fillet region promotes the fillet forming, and the forming internal pressure is reduced by 88.0% compared with the traditional tube hydroforming.

(2) The defects in the axial hydro-pressing process are mainly wrinkles and flashes when forming stepped variable diameter components. The relatively small feeding pressure or the excessive feeding amount cause the tube to undergo instability and wrinkling under the action of axial pressure. During the die clamping process, the liquid volume compression causes the internal pressure to rise and cause flash phenomenon. Wrinkle and flashing defects can be eliminated by adjusting the internal pressure and the feeding amount. When the internal pressure is 18.0 MPa and the left and right feedings are 15.0 mm each, qualified parts can be formed.

(3) The wall thickness of the formed parts obtained by the tube axial hydro-pressing method has different distribution compared with that of the traditional tube hydroforming method. The wall thickness of the traditional hydroformed fillet area has been seriously thinned, while the axial hydro-pressed fillet area is thickened to some
extent compared to the two sides. The wall thickness of the formed part obtained by the tube axial hydro-pressing method was improved by 9.0%, and the wall thickness difference was improved by 7.4%. Local thinning and uniformity of wall thickness were significantly improved.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Availability of data and material

The datasets used or analysed during the current study are available from the corresponding author on reasonable request.

Code availability

Not applicable

Ethics approval

Disclosure of potential conflicts of interest

There is no potential conflicts of interest

Research involving Human Participants and/or Animals

Not applicable

Informed consent

Not applicable

Consent to participate

Not applicable

Consent for publication

The authors agree to transfer copyright of the article to the Publisher.

Authors' contributions
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