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Analysis and Control of Cracking and Wrinkling at the End of Seamless Steel Tube with Multi-Pass Large Deformation Diameter-Reducing

Heng Liu ^{1,2}, Liandong Wang ^{1,2,*}, Xiaodi Wang ³ and Qiying Tan ²

¹ Hebei Key Laboratory of Special Delivery Equipment, Yanshan University, Qinhuangdao 066004, China; lh@stumail.ysu.edu.cn

² School of Vehicle and Energy, Yanshan University, Qinhuangdao 066004, China; tanqiying@stumail.ysu.edu.cn

³ School of Mechanical Engineering, Yanshan University, Qinhuangdao 066004, China; wangxiaodi@stumail.ysu.edu.cn

* Correspondence: wangld@ysu.edu.cn; Tel.: +86-0335-8074682

Abstract: Axial cracking and circumferential wrinkling are found at the end of seamless steel tubes during multi-pass large deformations pushing diameter-reducing (PDR), which seriously affects product quality. However, the cracking and wrinkling mechanism of PDR has not been elucidated yet. In this paper, the Equation of circumferential residual stress at the end was deduced from the warping deformation and shear stress. It is revealed that the circumferential residual stress in the end warping area from the inner to outer surface is tensile, and the generation mechanism of circumferential wrinkling on the inner wall at the end was revealed through the deformation analysis of PDR. The geometric model of the tube with periodic alternating variation of wall thickness was established to reveal the generation and development of circumferential wrinkling. In addition, the four-pass PDR experiments and simulations were developed to reveal the influence of reducing pass and wall thickness deviation on the end warpage, unevenness and circumferential residual tensile stress. The pushing-pulling diameter-reducing (PPDR) method was proposed to control the wrinkling and cracking. The simulation and experimental results showed that the end warpage, unevenness and circumferential residual tensile stress are all greatly decreased, and the risk of axial cracking and circumferential wrinkling is eliminated.

Keywords: pushing diameter-reducing; axial cracking; end wrinkling; residual stress; unevenness



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1. Introduction

PDR refers to the cold forming method that consists of reducing the tube diameter by a conical die [1,2]. It has the advantages of high production efficiency, low manufacturing cost and simple die structure and has been widely used in the manufacturing of reducing tubes in automobiles, engineering machinery and aerospace [3–5].

There are many studies on diameter-reducing deformation and force. Rumiński et al. [6] presented the influence of different die shapes on the strain field distribution of the reducing tube by simulation and hardness measurements. Lu [7] obtained the approximate calculation method of the reducing ratio and loading rate by using the volume invariant condition and Mises equation. Zhao et al. [8] established the strain velocity field of tube drawing, and the drawing force was solved based on the inner product integral of strain rate vector. Ogbeyemi et al. [9] revealed the stress and pressure fields of the reducing tube by using Bubnov-Galerkin finite element model. Sadok et al. [10] analyzed the strain state of the reducing tube by finite element simulation and carried out the hardness measurement; the results showed that the reducing deformation is uneven, and the maximum effective strain is on the tube's inner surface.

Due to the uneven reducing deformation, the residual stress exists in the reduced tube [11]. Vollert et al. [12] researched the residual stress of medium carbon tube with hollow and fixed mandrel drawing and revealed that the circumferential residual stress on the inner and outer surface is compressive and tensile, respectively. Gattmah et al. [13] developed the fixed mandrel drawing residual stress of AISI 1010 tube with the different reduction of the area by an X-ray method. The results showed that the circumferential residual stress near the outer and inner surface at the small reduction of the area is compressive and tensile, respectively. Kishimoto et al. [14] elucidated the mechanism causing the excessive thinning of the outer diameter during microscale hollow drawing by considering the size effect and plastic anisotropy.

Different from the tube drawing, the tube is subjected to the pushing force during the PDR, and it is not affected by external force after reducing it, while the end of the reduced tube is warped. Liu et al. [15] studied the residual stress of one-pass PDR tube without wall thickness deviation by the X-ray method and simulation, the results showed that the circumferential residual stress is tensile from the inner to outer surface at the end, and it is compressive and tensile at the inner and outer surface of sizing area, respectively.

The axial buckling and wrinkling may occur in the middle area of the PDR tube due to the excessive reducing force. Liu et al. [16] investigated the influence of temperature on the axial instability of the hot extrusion transmission shaft and provided the optimal forming parameters without axial instability. Teng et al. [17] studied the influence of die cone angle on the wrinkling of reducing thin-walled cylindrical cup, and presented that the larger the cone angle, the easier the wrinkling.

Different from the PDR, the circumferential buckling and wrinkling exist in the middle deformation area of the tube with outer pressure necking in a viscous or solid particle medium. Many studies have researched the circumferential wrinkling of thin-walled alloy tube with outer pressure necking. Zhao et al. [18] analyzed the wrinkling of thin-walled tube with outer pressure necking and researched the influence of forming factors on the anti-wrinkle of outer pressure necking tube. Zhang et al. [19] revealed the effect of the buckling mode and uneven thickness defect on the wrinkling of outer pressure necking tube by finite element simulation.

In the engineering practice of the multi-pass large deformation PDR of a seamless steel tube, it is found that the end of reduced tube is warped, and there is axial cracking and circumferential wrinkling at the end of individual reduced tube, which seriously affects the quality of the products, as shown in Figure 1. However, the cracking and wrinkling mechanism of PDR has not been reported yet.



Figure 1. Axial cracking of reduced tube end.

In this paper, for the seamless steel tube with the multi-pass large deformation PDR, the Equation of circumferential residual tensile stress at the end was deduced, and the generation mechanism of circumferential wrinkling on the inner wall at the end was revealed through theoretical analysis. The influence of wall thickness deviation and reducing pass on circumferential residual stress, end warpage and unevenness were revealed by finite element analysis (FEA) and the experiment (EXP). In order to control the axial cracking

and circumferential wrinkling, a new method of PPDR was proposed, which improves the forming quality of the reduced tube and provides a reference for engineering application.

2. Geometric Model of Seamless Steel Tube

2.1. Wall Thickness Measurement

Hot-rolled seamless steel tube is generally adopted in large deformation PDR processes. Due to the run-out and wear of rolling mandrel and the uneven heating of the tube, the unavoidable wall thickness deviation defects exist in the tube [20,21]. The hot-rolled seamless steel tube Q345B selected for the bulging-pressing-formed automobile axle housing [22] with a load of 6.5 tons is taken as the research object. For the initial tube, the length L_0 is 1350 mm, the outer diameter d_0 is 219 mm and the nominal wall thickness is 7.5 mm. The chemical composition and mechanical properties of the Q345B seamless steel tube is shown in Tables 1 and 2, respectively. The true stress-strain curve of the initial tube is shown in Figure 2.

Table 1. Chemical composition of the Q345B seamless steel tube (%).

C	Si	Mn	P	S	Cr	Mo
0.18	0.39	1.54	0.017	0.01	0.01	0.09

Table 2. Mechanical properties of Q345B seamless steel tube.

Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Elongation (%)	Elastic Modulus (GPa)	Poisson's Ratio
418.61	589.42	31.46	210	0.30

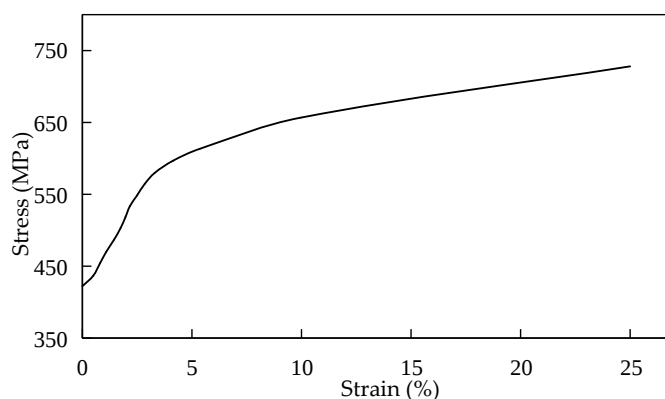


Figure 2. Stress-strain curve of the initial tube.

On the tube's outer surface, the circles are drawn with equal spacing of 145 mm and the axial lines are drawn with an equal circumferential interval angle of 15° . Accordingly, the intersection of the circle and axial lines is the wall thickness measuring point, the sections where the circles are located are designated as cross-section P_1 to P_{10} , respectively, as shown in Figure 3.

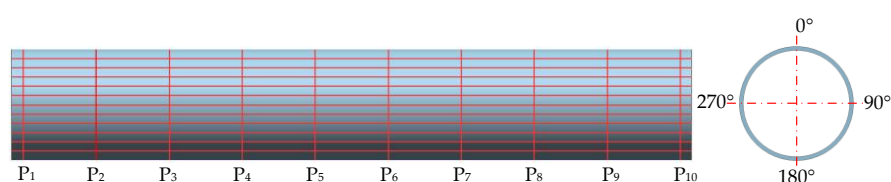


Figure 3. Schematic diagram of wall thickness measurement.

The maximum and minimum wall thickness are expressed as t_{m0} and t_{n0} , respectively; the average wall thickness is expressed as t_0 , the difference between the t_{m0} and t_0 is defined as the positive deviation T_m , the difference between the t_{n0} and t_0 is defined as the negative deviation T_n and the difference between the t_{m0} and t_{n0} is defined as the initial wall thickness deviation T_0 . Ten tubes are randomly selected, and the wall thickness is measured by MT-160 ultrasonic thickness gauge. The measurement results of the half partial cross-section are shown in Figure 4, and the wall thickness distribution of the other half is symmetrical. The measurement results are as follows:

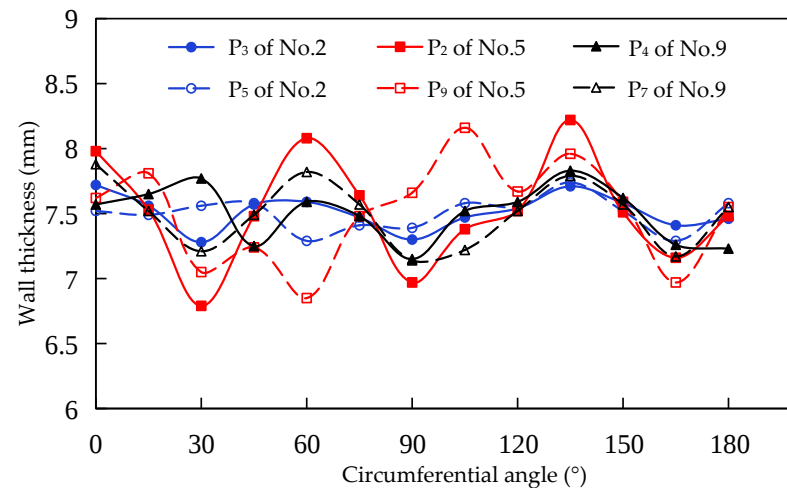


Figure 4. Circumferential wall thickness distribution.

- (1) The wall thickness along the circumferential direction is alternately thin and thick, such as the wall thickness of P_3 and P_5 cross-section of No.2 tube, P_2 and P_9 cross-section of No.5 tube, P_4 and P_7 cross-section of No.9 tube all varies alternately from 0° to 180° .
- (2) The absolute value of the maximum positive and negative deviation wall thickness on the same cross-section is close. Such as the maximum positive and negative deviation wall thickness of P_3 cross-section of No.2 tube is 0.35 mm and -0.33 mm, respectively, P_2 cross-section of No.5 tube is 0.62 mm and -0.65 mm, respectively, P_7 cross-section of No.9 tube is 0.40 mm and -0.42 mm, respectively.

2.2. Geometric Model

Based on the measurement results of seamless steel tube wall thickness, the assumptions are made as follows:

- (1) The tube's outer surface shape is a circle, and the inner surface shape is a periodic sinusoidal variation and the wall thickness on the same axis are equal.
- (2) The absolute value of the maximum positive deviation T_m and the maximum negative deviation T_n of the same cross-section wall thickness are equal.

Based on the above assumptions, the geometric model of tube with wall thickness deviation is established, as shown in Figure 5. The trough of the inner wall's sine curve is the minimum wall thickness t_{n0} , and the crest is the maximum wall thickness t_{m0} . The amplitude is $T_0/2$, the period angle is θ_n , the wave number is n .

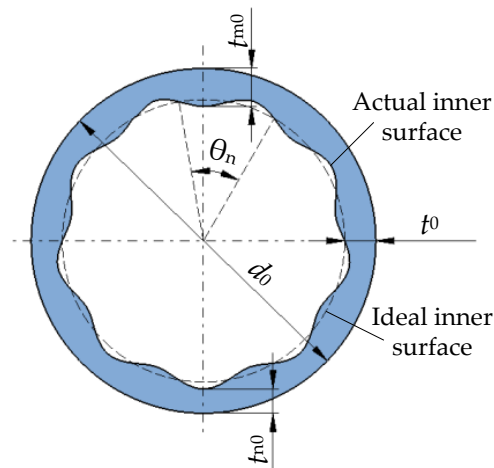


Figure 5. Geometric model of tube with wall thickness deviation.

2.3. Definition of Unevenness

2.3.1. Unevenness T

The difference between the maximum wall thickness t_m and the minimum wall thickness t_n of the same cross-section is defined as unevenness T , which is expressed as

$$T = t_m - t_n \quad (1)$$

2.3.2. Relative Unevenness K

The ratio of unevenness T to the average inner diameter d_i is defined as relative unevenness K , which is expressed as

$$K = \frac{t_m - t_n}{d_i} \cdot 100\% \quad (2)$$

The relative unevenness K is used as an evaluation index for whether the circumferential wrinkling produced.

2.3.3. Critical Relative Unevenness K_c

The maximum wall thickness deviation of seamless steel tube allowed by GB/T8162-2018 (China Standard) [23] is T_x . The ratio of T_x to the initial tube inner diameter d_{i0} is defined as the critical relative unevenness K_c , which is expressed as

$$K_c = \frac{T_x}{d_{i0}} \cdot 100\% \quad (3)$$

When the relative unevenness K of reduced tube is greater than the critical relative unevenness K_c , it is evaluated as the circumferential wrinkling.

3. Mechanical Analysis

During the PDR, the upper and lower clamping die is used to fix the middle area of the tube, and the reducing die is reduced from the tube's end to the inner side. The cavity of the reducing die is divided into the reducing area, the rounded corner area and the exit area, as shown in Figure 6. Based on the deformation characteristics in each area of the reducing die, the PDR deformation process can be divided into reducing stage, bending stage and warping stage. The mechanical model of the PDR tube with a wall thickness deviation is established, the upper and lower sides of the tube are defined as the thick and thin wall side, respectively. For the reducing die, the half-cone angle is α , the inner diameter of the exit area is d_m and the rounded corner radius is R . For the initial tube, the

diameter is d_0 , the intermediate layer radius of the thick and thin wall side is R_{m0} and R_{n0} , respectively, and the corresponding wall thickness is t_{m0} and t_{n0} , respectively.

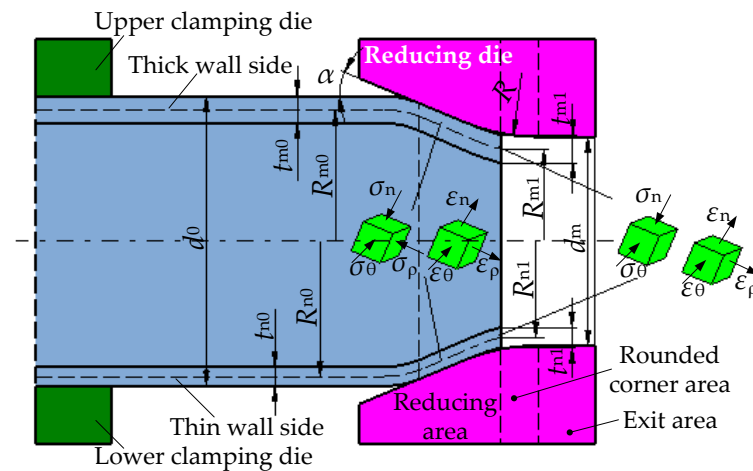


Figure 6. Reducing stage.

3.1. Reducing Stage

After the tube is deformed in the reducing stage, the intermediate layer radius of the thick and thin wall sides decreases to R_{m1} and R_{n1} , respectively, and the corresponding wall thickness increases to t_{m1} and t_{n1} , respectively, as shown in Figure 6.

In the reducing stage, the tube wall thickness is increased while the diameter is reduced, and the length is elongated along the axial direction. The circumferential compressive strain is the main deformation, so that the thick wall side metal flows to the adjacent thin wall side, which is beneficial to decrease unevenness. The normal compressive stress is smaller than the circumferential compressive stress. The axial stress of the end is approximately zero, and on the inner side of the end it is compressive.

3.2. Bending Stage

After the tube is deformed in the reducing stage, it flows into the rounded corner area of the reducing die and continues to undergo axial bending deformation, as shown in Figure 7. Furthermore, after the tube is deformed in the bending stage, the intermediate layer radius of the thick and thin wall side is R_{m2} and R_{n2} , respectively, the corresponding wall thickness is t_{m2} and t_{n2} , respectively, and the tube end diameter d_{02} is less than the inner diameter d_m of the reducing die exit area.

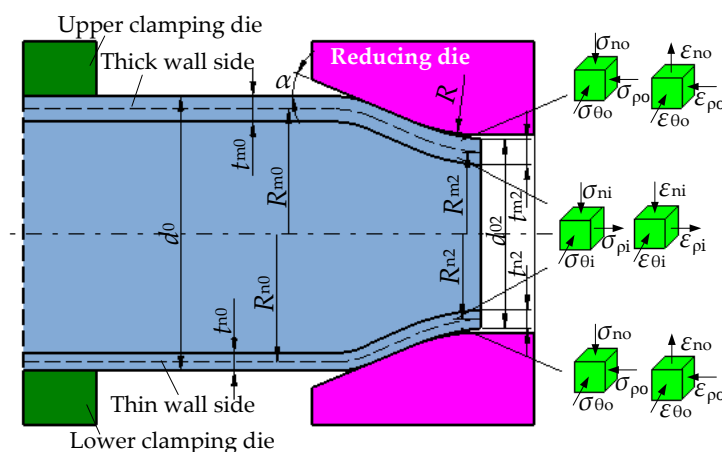


Figure 7. Bending stage.

3.2.1. Basic Assumptions

- (1) The intermediate layer of tube wall coincides with the neutral layer.
- (2) The axial compressive stress on the outside of the intermediate layer acts on half of its thickness with equivalent compressive stress. The axial tensile stress on the inside of the intermediate layer acts on half of its thickness with equivalent tensile stress. In addition, the absolute value of equivalent axial stress on the inside and outside is equal.
- (3) On the same cross-section, the torque caused by the axial stress on the inside and outside of intermediate layer on circumferential unit angle micro-plane is equal.

3.2.2. Deformation Analysis

The element body including inner and outer surface of the tube is intercepted in the bending deformation area, as shown in Figure 8. The axial length is dl , the circumferential length is dy and the wall thickness is t_e . On the right surface, the axial equivalent compressive stress on the outside of intermediate layer is σ_{pe1} , the axial equivalent tensile stress on the inside of intermediate layer is σ_{pe2} and the value of σ_{pe1} and σ_{pe2} is equal. The torque dM on the right surface is

$$dM = \frac{1}{8} t_e^2 dy \sigma_{pe2} \quad (4)$$

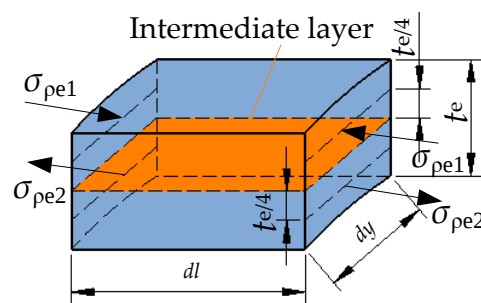


Figure 8. Element body of bending deformation area.

In the bending stage, the outside metal of the intermediate layer is shortened along the axial direction and the thickness is increased, while the inside metal of the intermediate layer is elongated, and the thickness is decreased. Based on the basic assumptions and the wall thickness of the thin and thick wall side, it can be known from the Equation (4) that the axial tensile stress on the inside of the intermediate layer of the thin wall side is greater than that of the thick wall side. So, the axial deformation and thinning at the inside of the intermediate layer of the thin wall side is larger than that of the thick wall side, which results in the unevenness is increased on the inner wall of the end.

3.3. Warping Stage

After the tube end is deformed in the bending stage, the axial elongation of the inside metal of the intermediate layer is greater than that of the outside, so that the end warped upward to form end warping area. As shown in Figure 9, there is shear deformation in the end warping area, which results in the shear stress τ_{np} on the lower surface of unit body pointing from left to right, and the shear stress τ_{pn} on the right surface of unit body pointing from top to bottom. After the tube end deformed in the warping stage, the intermediate layer radius of the thick and thin wall side is increased to R_{m3} and R_{n3} , respectively, the corresponding wall thickness is decreased to t_{m3} and t_{n3} , respectively.

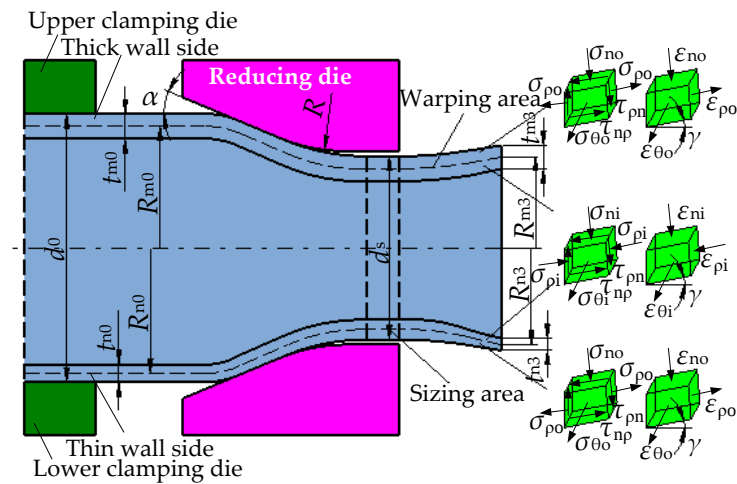


Figure 9. Warping stage.

3.3.1. Basic Assumptions

- (1) Due to the PDR deformation is axisymmetric, the circumferential stress is main stress, the shear stress components related to the circumferential direction are all zero.
- (2) Axial residual stress on the cross-section of reduced tube is self-balanced from the inner to outer surface.

3.3.2. Analysis of End Residual Stress

The element body including the inner and outer surface of the tube is intercepted in the end warping area, and the left surface of the element body is the interface between warping area and sizing area, as shown in Figure 10. For the element body, the front side is thin wall side with the wall thickness t_n , the rear side is thick wall side with the wall thickness t_m , the circumferential angle between the front and rear surface is $d\theta$, the outer circumferential curvature radius of the left and right side is $d_1/2$ and $d_2/2$, respectively, the axial curvature radius and included angle of the upper side is r_ρ and β , respectively. The right, upper and lower surface are all free surfaces. On the left surface, the shear stress $\tau_{\rho n}$ pointing from bottom to top, and there is axial tensile stress $\sigma_{\rho o}$ and compressive stress $\sigma_{\rho i}$ on the outer and inner layer, respectively, the axial resultant force is zero. The circumferential stress on the front and rear surface is $\sigma_{\theta m}$ and $\sigma_{\theta n}$, respectively.

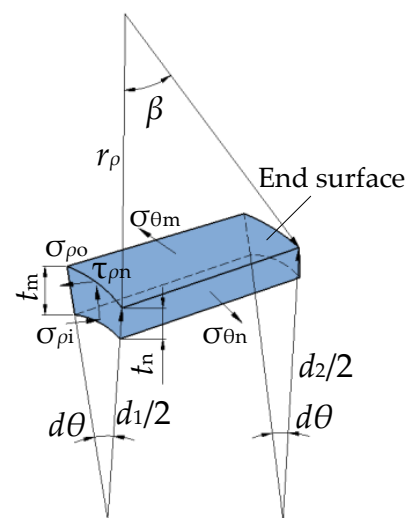


Figure 10. Element body of end warping area.

According to the equilibrium condition of force in the wall thickness direction, it can be obtained as

$$\sigma_{\theta n} t_n r_\rho \beta \sin \frac{d\theta}{2} + \sigma_{\theta m} t_m r_\rho \beta \sin \frac{d\theta}{2} - \tau_{\rho n} \frac{t_n + t_m}{2} \frac{d_1}{2} d\theta \cos \frac{\beta}{2} = 0 \quad (5)$$

Since $d\theta$ is very small, and $\sin(d\theta/2) = d\theta/2$ is approximated, the above Equation (5) is simplified as

$$\sigma_{\theta n} t_n + \sigma_{\theta m} t_m - \frac{d_1(t_n + t_m)}{2r_\rho \beta} \tau_{\rho n} \cos \frac{\beta}{2} = 0 \quad (6)$$

Based on the geometric analysis, the approximate Equation is

$$r_\rho \beta = \frac{d_2 - d_1}{2 \sin(\beta/2)} \quad (7)$$

Substituting the Equation (7) into (6) to obtain

$$\sigma_{\theta n} t_n + \sigma_{\theta m} t_m = - \frac{d_1(t_n + t_m) \sin \beta}{2(d_2 - d_1)} \tau_{\rho n} \quad (8)$$

According to the equilibrium condition of force in the tangential direction, it can be obtained as

$$\sigma_{\theta m} t_m - \sigma_{\theta n} t_n = 0 \quad (9)$$

Substituting the Equation (9) into (8) to obtain

$$\sigma_{\theta n} = \frac{d_1(t_n + t_m) \sin \beta}{4(d_2 - d_1)t_n} \tau_{\rho n}, \sigma_{\theta m} = \frac{d_1(t_n + t_m) \sin \beta}{4(d_2 - d_1)t_m} \tau_{\rho n} \quad (10)$$

According to the Equation (10), the circumferential residual stress σ_θ in the end warping area is related to end warping deformation parameters and shear stress $\tau_{\rho n}$. Since the direction of the $\tau_{\rho n}$ is upward, the σ_θ is characterized as tensile stress from the inner to outer surface and the σ_θ is verified as tensile stress by the X-ray measurement and FEA in the literature [15]. Moreover, the $\sigma_{\theta n}$ of the thin wall side is greater than the $\sigma_{\theta m}$ of the thick wall side. When the circumferential residual tensile stress of the end is greater than the ultimate tensile strength, axial cracking may occur and the axial cracking is more likely occur on the thin wall side.

3.3.3. Unevenness Analysis

The tube end is warped in the warping stage, which results in the end diameter expansion and wall thickness thinning. Due to the $\sigma_{\theta n}$ is greater than the $\sigma_{\theta m}$, the circumferential deformation and thinning of the thin wall side is larger than that of the thick wall side, which results in the end unevenness is further increased. When the relative unevenness exceeds the critical value, circumferential wrinkling will be generated. However, the inner side of the end is no longer warped, the unevenness is no longer changed as well, and the sizing area is formed. The outer diameter of the sizing area is less than the inner diameter of the exit area of the reducing die.

4. Research Methods

4.1. Research Objects

The hot-rolled seamless steel tube Q345B is selected as the initial tube with the length L_0 of 1350 mm, the outer diameter d_0 of 219 mm and the nominal wall thickness of 7.5 mm. According to the GB/T8162-2018 [23], the maximum allowable wall thickness deviation is 2.25 mm, so the critical relative unevenness K_c is 1.10%. During diameter-reducing, the middle area of the tube is clamped by clamping die, which is to keep the length of 456 mm without deformation, as shown in Figure 11. Moreover, the radius of upper and lower clamping die is 109.5 mm.

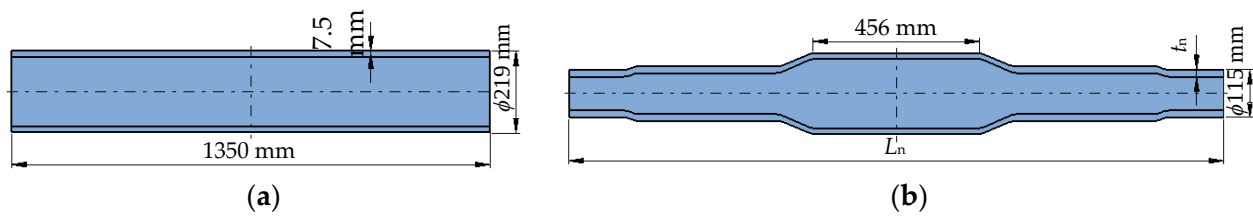


Figure 11. Process diagram of PDR. (a) Initial tube; (b) reduced tube.

4.2. PDR Experiments

The initial unevenness T_0 of 0.4 mm, 0.8 mm and 1.2 mm was selected, respectively. Four-pass PDR was carried out on the THP63-200/300/100 $\times$ 2 hydraulic press. The reducing die of each pass is shown in Figure 12, the half-cone angle α is 23° , the rounded corner radius R is 50 mm and the inner diameter of the exit area d_m is 190 mm, 162 mm, 138 mm and 115 mm, respectively.

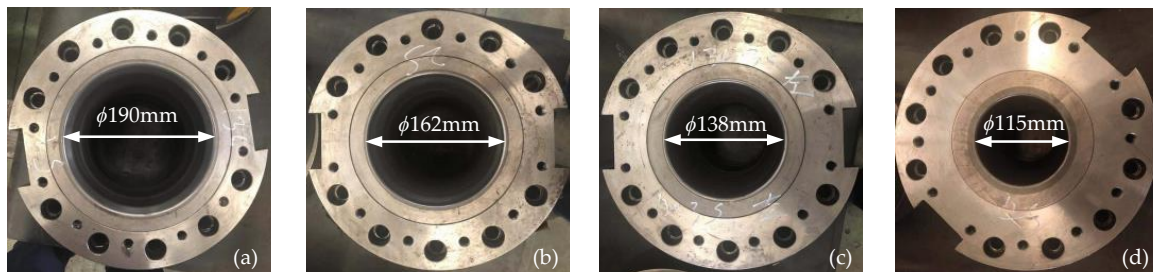


Figure 12. Reducing dies. (a) First pass; (b) second pass; (c) third pass; (d) fourth pass.

Before diameter-reducing, the outer wall of both ends of the tube and the inner wall of the reducing die are lubricated by lubricating oil, then the tube is placed into the lower clamping die and the center is aligned. During diameter-reducing, the upper clamping die is driven by the upper slider of hydraulic press to move downward to clamp the middle area of the tube, and the left and right reducing die are respectively pushed by the left and right slider of hydraulic press from the tube end to the inner side at the speed of 10 mm/s.

4.3. Stress-Strain Relationship

The tensile specimens with ASTM-E8 standard were obtained by cutting in the initial tube and the sizing area of reduced tubes along the axial direction, the geometry and dimensions of each pass tensile specimen is shown in Figure 13 and Table 3. The uniaxial tensile tests were carried out on the Inspekt-Table100 (Hegewald & Peschke, Nossen, Germany) electronic universal testing machine at room temperature, and the test speed was 5.0 mm/min. The contact extensometer was used, and the original gauge length of the extensometer is 25 mm. The true stress-strain curve is obtained, as shown in Figure 14.

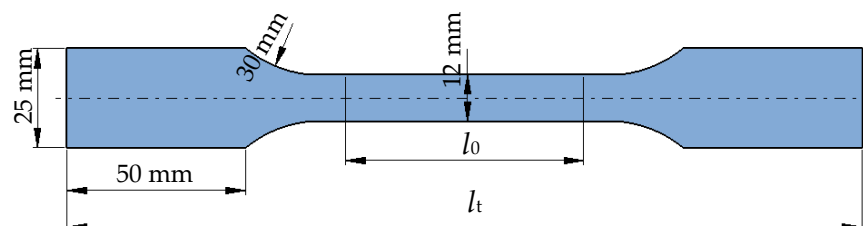
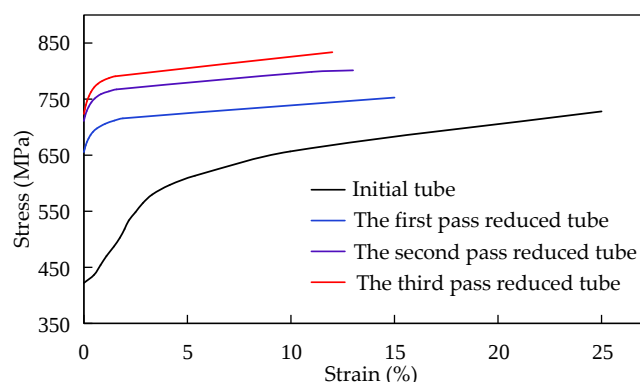


Figure 13. Tensile specimen.

Table 3. Dimensions of each pass tensile specimen (mm).

Reducing Pass	0	1	2	3
l_0	54	57	60	63
l_t	198	202	206	210

**Figure 14.** Stress-strain curve.

The stress-strain relationship of the initial tube and the first, second, third pass reduced tube is respectively obtained by power function fitting as

$$\sigma_{00} = 901.9\epsilon_{00}^{0.15}, \sigma_{01} = 783.7\epsilon_{01}^{0.02}, \sigma_{02} = 835.3\epsilon_{02}^{0.02}, \sigma_{03} = 869.6\epsilon_{03}^{0.02} \quad (11)$$

The uniaxial tensile test results are shown in Table 4, and it can be found as follows:

Table 4. Results of uniaxial tensile test.

Reducing Pass	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Elongation (%)	Section Shrinkage (%)
0	418.61	589.42	31.46	71.35
1	651.22	697.59	18.44	69.89
2	706.08	749.92	16.65	65.90
3	718.42	773.20	14.30	62.75

- (1) The yield strength and ultimate tensile strength of each pass reduced tube are significantly higher than that of the initial tube. Both the yield strength and ultimate tensile strength are increased with the increase of reducing pass.
- (2) Both the elongation and section shrinkage are gradually decreased with the increase of reducing pass, which indicates that the plastic deformation ability of the reduced tube is gradually decreased, and axial cracking may occur.

4.4. FEA of PDR

The geometric models of tube with the wall thickness deviation T_0 of 0 mm, 0.4 mm, 0.8 mm, 1.2 mm, 1.6 mm, 2.0 mm were established, respectively. The diameter d_0 , average wall thickness t_0 and wave number n of the tube is 219 mm, 7.5 mm and 15, respectively. The software ABAQUS is used to simulate the four-pass PDR of wall thickness deviation tube. Since the tube and reducing dies are all axially symmetric structures, in order to facilitate calculation, the 1/4 finite element model was established, as shown in Figure 15.

The stress-strain curves as shown in Figure 14 were used in the corresponding reducing pass. For the boundary conditions, symmetrical constraints were set on longitudinal center-section and middle cross-section of the tube, respectively. The middle area of the tube was fixed by upper and lower clamping die, the clamping die and reducing die of each pass were set as a rigid body, while the tube was set as a deformed body. The grid type of the

tube is C3D8R, and the number of grid cells along the wall thickness direction is three. With the coulomb friction model, the rigid-flexible contact was established between the clamping die and the tube, and between the tube and each reducing die, respectively, and the dynamic friction coefficient of the contact was set as 0.15 and 0.10, respectively [24].

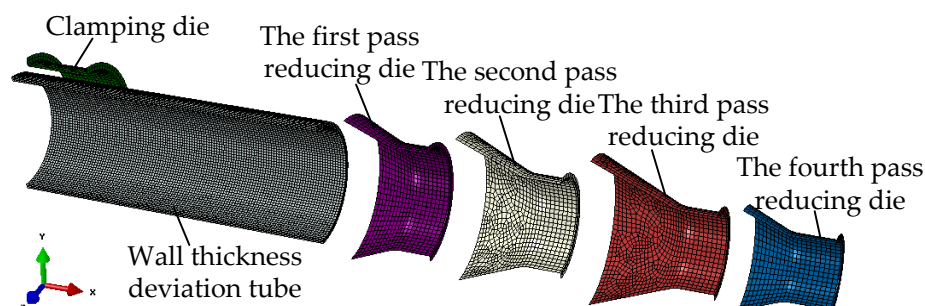


Figure 15. Finite element model.

5. Results and Discussion

5.1. End of Reduced Tubes

After each pass PDR, the maximum and minimum wall thickness of the end were measured, and the end warpage (the difference between the radius of the end and sizing area) was measured. The maximum and minimum wall thickness of the sizing area were measured by transverse cutting at the distance of 50 mm from the end. The reduced tube with $T_0 = 1.2$ and 0.4 are shown in Figure 16. It can be observed that the end of the reduced tube is warped. There is no obvious circumferential wrinkling at the end of the fourth pass reduced tube with $T_0 = 0.4$. There is no obvious circumferential wrinkling at the end of the first pass reduced tube with $T_0 = 1.2$, but obvious circumferential wrinkling on the inner wall at the end of the fourth pass, with the end unevenness of 2.47 mm and the sizing area unevenness of 0.84 mm.

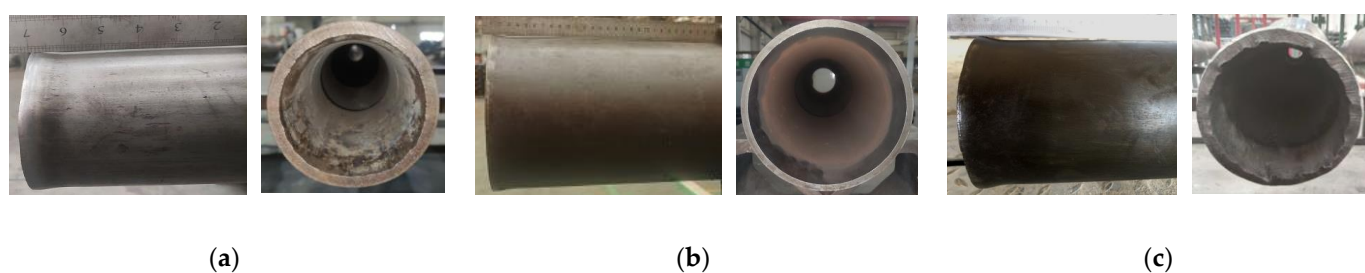


Figure 16. End warping and wrinkling of reduced tube. (a) The fourth pass reduced tube with $T_0 = 0.4$; (b) the first pass reduced tube with $T_0 = 1.2$; (c) the fourth pass reduced tube with $T_0 = 1.2$.

Half of the sum of the maximum and minimum wall thicknesses is taken as the average wall thickness. The measurement results of diameter and wall thickness are shown in Table 5. It can be found that the average wall thickness of the end is less than that of the sizing area. While the diameter of the end is greater than that of the sizing area, and the latter is less than the inner diameter of the exit area of reducing die.

Table 5. Geometric parameters of reduced tube (mm).

Reducing Pass	End Diameter			End Wall Thickness			Sizing Area Diameter			Sizing Area Wall Thickness		
	$T_0 = 0.4$	$T_0 = 0.8$	$T_0 = 1.2$	$T_0 = 0.4$	$T_0 = 0.8$	$T_0 = 1.2$	$T_0 = 0.4$	$T_0 = 0.8$	$T_0 = 1.2$	$T_0 = 0.4$	$T_0 = 0.8$	$T_0 = 1.2$
1	191.22	191.07	190.96	7.92	7.94	7.91	188.12	188.01	187.92	8.29	8.32	8.30
2	163.39	163.86	163.75	8.56	8.59	8.55	160.21	160.72	160.65	9.19	9.22	9.24
3	140.16	140.20	140.12	9.34	9.35	9.29	136.84	136.92	136.83	10.28	10.27	10.28
4	117.67	117.70	117.73	10.33	10.29	10.22	114.17	114.24	114.21	11.60	11.61	11.58

5.2. End Warpage

The end warpage of each pass reduced tube is shown in Table 6. It can be found that the end warpage is slowly increased with the increase of reducing pass (that is, the increase of reducing deformation), but the increase value is small, while the wall thickness deviation has little effect on the end warpage. The increased value of the end warpage of the experimental four-pass reduced tubes with $T_0 = 1.2$ is 0.03 mm, 0.10 mm and 0.11 mm, respectively. While the end warpage of the experimental fourth pass reduced tube with T_0 of 0.4 mm, 0.8 mm and 1.2 mm is 1.75 mm, 1.73 mm and 1.76 mm, respectively. The maximum difference between the FEA and EXP value of the end warpage is 7.34%, which is in the third pass reduced tube with $T_0 = 0.8$.

Table 6. End warpage of reduced tube (mm).

Reducing Pass	$T_0 = 0$		$T_0 = 0.4$		$T_0 = 0.8$		$T_0 = 1.2$		$T_0 = 1.6$		$T_0 = 2.0$	
	FEA	EXP	FEA	EXP	FEA	EXP	FEA	EXP	FEA	EXP	FEA	EXP
1	1.63	-	1.64	1.55	1.65	1.53	1.63	1.52	1.64	-	1.65	-
2	1.67	-	1.68	1.59	1.69	1.57	1.67	1.55	1.69	-	1.70	-
3	1.72	-	1.74	1.66	1.77	1.64	1.74	1.65	1.75	-	1.76	-
4	1.83	-	1.85	1.75	1.86	1.73	1.84	1.76	1.86	-	1.84	-

5.3. Unevenness

The end unevenness T_d is greater than the initial unevenness T_0 , while the sizing area unevenness T_i is less than the T_0 , as shown in Figure 17. Further, it can be found that the T_d is sharply increased with the increase of wall thickness deviation and reducing pass, while the T_i is slowly increased. For example, the T_d of the experimental four-pass reduced tubes with $T_0 = 1.2$ is 1.39 mm, 1.69 mm, 1.90 mm and 2.47 mm, respectively, while the T_i is 0.69 mm, 0.73 mm, 0.80 mm and 0.84 mm, respectively. The maximum difference between the FEA and EXP value of unevenness is 11.91%, which is in the sizing area of the fourth pass reduced tube with $T_0 = 1.2$.

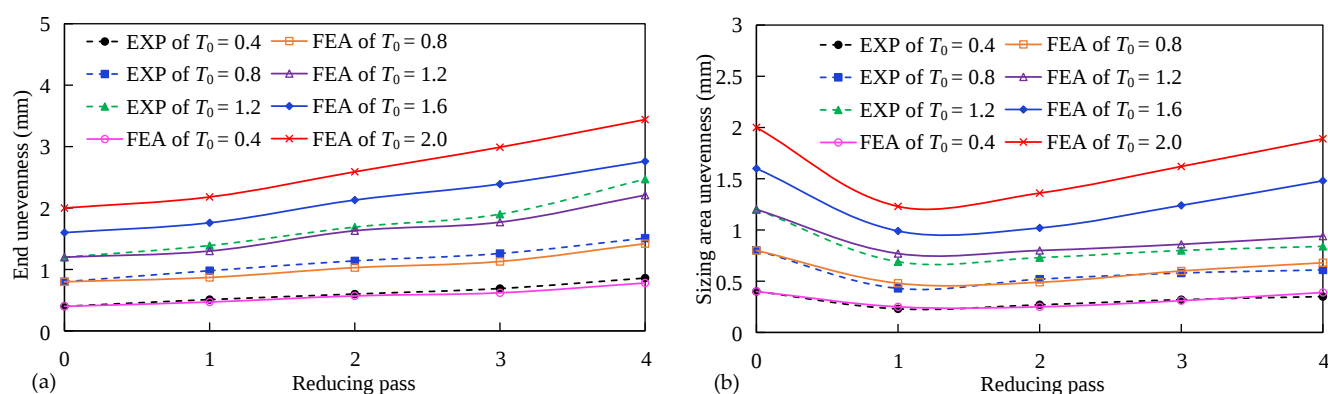


Figure 17. Unevenness of reduced tube. (a) The end unevenness; (b) the sizing area unevenness.

5.4. Relative Unevenness of the End

The relative unevenness K_d of the end is sharply increased with the increase of wall thickness deviation and reducing pass, as shown in Figure 18. According to the judgment condition of the critical relative unevenness K_c of 1.10%, the K_d of the four-pass reduced tubes with $T_0 = 0.4$ are all less than the K_c , which indicates that there is no circumferential wrinkling. The K_d of the experimental fourth pass reduced tube with $T_0 = 0.8$ is 1.60% and the K_d of the second, third, fourth pass reduced tube with $T_0 = 1.2$ is 1.15%, 1.61% and 2.57%, respectively, which are all larger than the K_c and indicate that the circumferential

wrinkling at the end are all generated. The maximum difference between the FEA and EXP value of the K_d is 12.84%, which is in the first pass reduced tube with $T_0 = 0.8$.

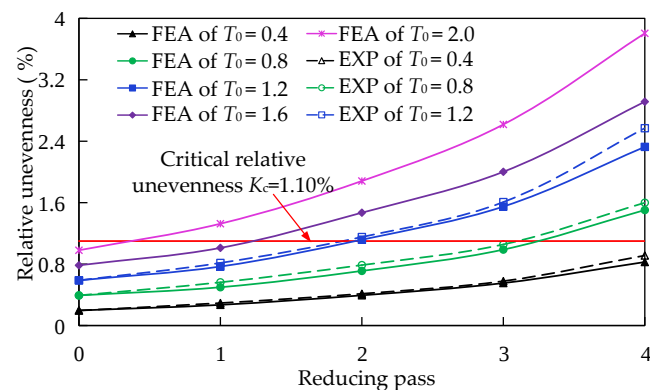


Figure 18. Relative unevenness of the end.

From the above analysis, it can be found that the trend of the FEA and EXP results is the same, but there is a deviation in the value. The deviation value is mainly due to the difference between the finite element model and experimental conditions, such as the wall thickness deviation distribution, boundary condition setting and so on, and there are also some deviations in the measurement. However, the overall trend is reliable, which verifies the reliability of the geometric model of the tube with wall thickness deviation and the FEA results.

5.5. Generation and Development of End Wrinkling by the FEA

The stress and deformation of PDR with $T_0 = 1.2$ was analyzed. The upper side of the tube is designated as the thin wall side, and the lower side is designated as the thick wall side. The measuring points A_1 , A_2 and A_3 , A_4 were respectively selected on the outer and inner surface of the thin and thick wall side at the end. The measuring points B_1 , B_2 and B_3 , B_4 were respectively selected on the outer and inner surface of the thin and thick wall side at 25 mm away from the end. For the stress values, the “+” is signed for tensile stress, while the “−” is signed for compression stress.

5.5.1. Reducing Stage

During the reducing stage, the circumferential stress σ_θ is compressive, as shown in Figure 19, the σ_θ of the point B_1 is -806.35 MPa. Moreover, the normal stress σ_n is compressive, the σ_n of the point B_1 is -85.48 MPa. After the reducing stage deformation, the diameter of the end is decreased to 185.35 mm, the end wall thickness of the thin and thick wall side is increased to 7.42 mm and 8.65 mm, respectively, the end unevenness is 1.23 mm. While the diameter of the inner side of the end is decreased to 190.09 mm, the wall thickness of the thin and thick wall side is increased to 7.68 mm and 8.63 mm, respectively, and the unevenness is decreased to 0.95 mm.



Figure 19. Reducing stage.

5.5.2. Bending Stage

After the end deformed in the bending stage, the circumferential stress of the point A_1 , A_2 , A_3 and A_4 is +464.76 MPa, +69.89 MPa, +435.95 MPa and +67.48 MPa, respectively, as shown in Figure 20. The axial stress of the outer surface point B_1 and B_3 is −564.81 MPa and −595.18 MPa, respectively. The axial stress of the thin wall side point B_2 is +471.47 MPa, which is larger than the thick wall side point B_4 of +442.55 MPa. The results are in good agreement with the theoretical analysis.



Figure 20. Bending stage.

The end wall thickness of the thin and thick wall side is decreased from 7.42 mm and 8.65 mm to 7.35 mm and 8.63 mm, respectively. The thinning of the thin wall side is 0.07 mm, which is greater than the thick wall side of 0.02 mm, and the end unevenness is increased to 1.28 mm. While the diameter of the inner side of the end is decreased to 187.56 mm, the wall thickness of the thin and thick wall side is increased to 7.92 mm and 8.69 mm, respectively, and the unevenness is decreased to 0.77 mm.

5.5.3. Warping Stage

In warping stage, the end diameter is expanded to 190.36 mm. The circumferential stress σ_θ of the thin wall side point A_1 is +643.36 MPa, which is greater than the thick wall side point A_4 of +639.79 MPa. The σ_θ of the thin wall side point A_2 is +625.74 MPa, which is greater than the thick wall side point A_3 of +605.49 MPa. The FEA results are in good agreement with the theoretical analysis. There is the shear stress $\tau_{\rho n}$ in the end warping area, as shown in Figure 21; the maximum shear stress of the thin and thick wall side is 81.02 MPa and 75.13 MPa, respectively.

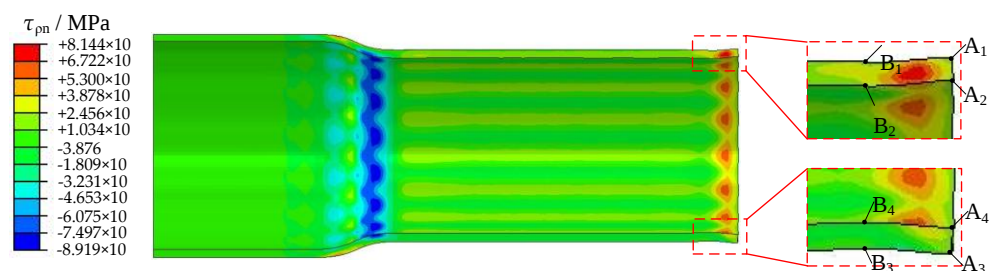


Figure 21. Warping stage.

The end wall thickness of the thin and thick wall side is decreased from 7.35 mm and 8.63 mm to 7.28 mm and 8.58 mm, respectively. The thinning of the thin wall side is 0.07 mm, which is greater than the thick wall side of 0.05 mm. Moreover, the end unevenness is further increased to 1.30 mm. While the inner side of the end is no longer warped, and the unevenness is no longer changed as well.

5.5.4. Multi-Pass Diameter-Reducing

The FEA results of the reduced tubes were mirrored for convenient observation, as shown in Figure 22. It can be observed that the end unevenness T_d is gradually increased with the increase of reducing pass, which is consistent with the trend of the EXP results. For

each pass reduced tube, the T_d is 1.30 mm, 1.63 mm, 1.77 mm and 2.21 mm, respectively, the sizing area unevenness is 0.77 mm, 0.80 mm, 0.86 mm and 0.94 mm, respectively, and the relative unevenness of the end is 0.76%, 1.13%, 1.56%, 2.34%, respectively. In addition, circumferential wrinkles are generated on the inner wall at the end warping area in the second, third and fourth pass.

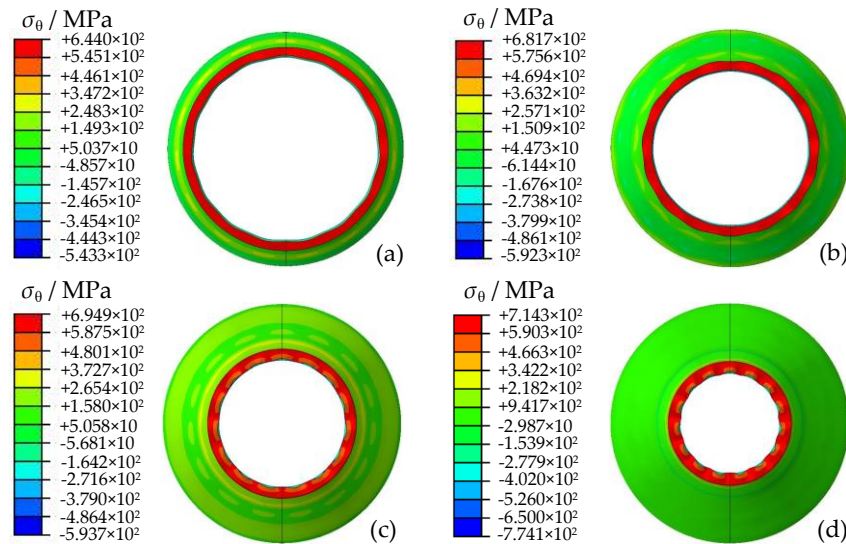


Figure 22. Four-pass reduced tubes of $T_0 = 1.2$. (a) The first pass; (b) the second pass; (c) the third pass; (d) the fourth pass.

5.6. Evolution Law of Unevenness

The end unevenness T_d is greater than the initial unevenness T_0 , while the sizing area unevenness T_i is less than the T_0 , as show in Figure 23. It can be found that the T_d is gradually increased from the reducing stage to warping stage. While the T_i is gradually decreased from the reducing stage to bending stage, and no longer changed in the warping stage.

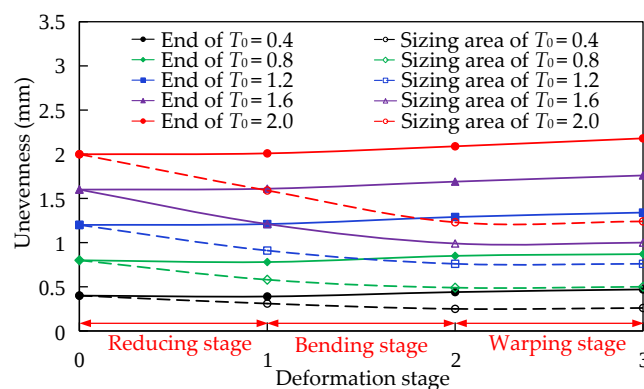


Figure 23. Evolution process of unevenness.

5.7. Circumferential Residual Stress of the End

In the thin wall side, the average value of the sum of circumferential residual tensile stress of each depth layer at the end is taken as the circumferential residual tensile stress σ_θ . The σ_θ of each pass reduced tube is shown in Figure 24. It can be observed that the σ_θ is increased with the increase of reducing pass, while the wall thickness deviation has little effect on the σ_θ . When the σ_θ is greater than the ultimate tensile strength, the end may be cracked axially.

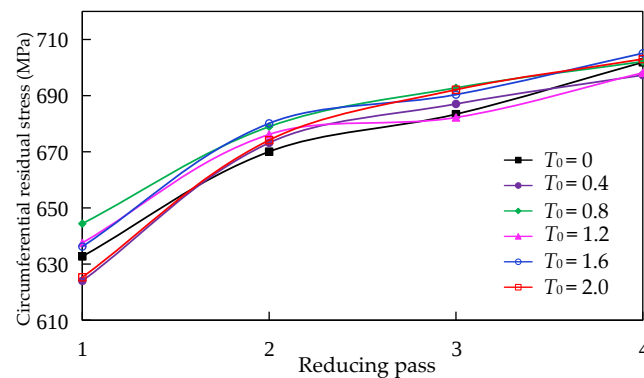


Figure 24. Circumferential residual stress of the end.

6. Control Method

6.1. PPDR Process

From the above analysis, it can be known that the end warping and wrinkling are mainly caused by the bending deformation in the rounded corner area of reducing die, which results in the diameter of sizing area being less than that of the end and the reducing die exit area and leads to the circumferential residual tensile stress at the end. In order to control the end circumferential wrinkling and axial cracking, it is necessary to decrease the bending deformation, so as to decrease the deformation difference between the inner and outer side metals, and then decrease the end warping.

The PPDR process is proposed based on the above control ideas. The mandrel is pushed into the tube inside before reducing. During the reducing die moves inward from the tube end with the speed V_0 under the pushing force F_r , the mandrel moves from the tube inside to outside with the speed V_m under the pulling force F_m . Moreover, the pulling speed V_m is greater than the tube elongation speed V_1 , as shown in Figure 25.

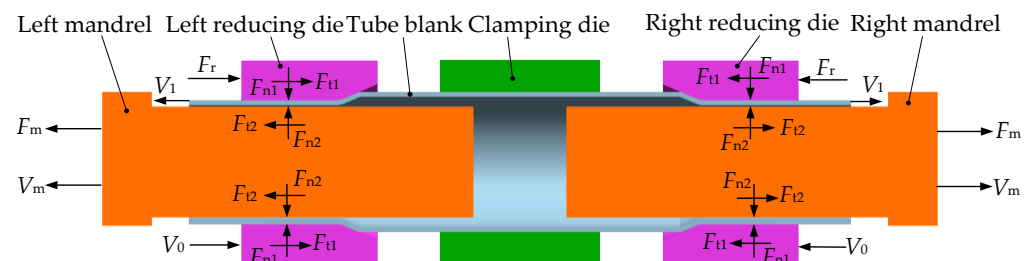


Figure 25. Process of PPDR.

After the tube deformed in the reducing stage, the inner surface of the tube is in contact with the outer surface of the mandrel, and the tube is subjected to the normal pressure F_{n2} and the tangential friction force F_{t2} . The direction of the F_{t2} is opposite to the speed V_0 of the reducing die, which is equivalent to the drawing force exerted on the tube inner wall. Compared with the fixed mandrel, the possibility of axial instability in the tube middle force transfer area is effectively decreased by the pulling mandrel. Under the combined action of the reducing die and mandrel, the bending deformation is decreased, the deformation difference between the inner and outer side metals is decreased and then the end warpage and unevenness are decreased.

6.2. FEA of PPDR

6.2.1. Finite Element Model

For the initial tube with $T_0 = 1.2$, the software ABAQUS is used to simulate the four-pass PPDR. Based on the axial stability of the tube force transfer area and the end without cracking [25], the diameter of each pass mandrel is respectively determined as

173.8 mm, 144.8 mm, 118.6 mm and 93.7 mm. The finite element model of PPDR is shown in Figure 26. The setting of tube, clamping die and reducing die is the same as that of the PDR finite element model, and the mandrel is set as rigid body, the friction coefficient between mandrel and tube is set as 0.15, the pushing speed of reducing die is 10 mm/s and the pulling speed of mandrel is 12 mm/s.

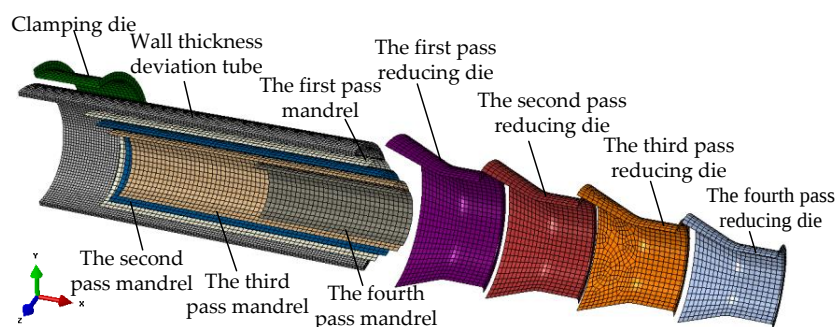


Figure 26. Finite element model.

6.2.2. FEA Results and Discussions

(1) End warpage

A comparison of the end warpage and sizing area diameters between PDR and PPDR is shown in Table 7. It can be found that the end warpage is greatly decreased by the PPDR, while the sizing area diameter is increased, which indicates that the deformation difference in the bending stage is decreased. In addition, the end warpage of each pass PPDR is decreased by 85.89%, 86.83%, 82.76% and 82.07%, respectively, and the forming quality of reduced tube is better.

Table 7. Comparison of warpage and diameter (mm).

Reducing Pass	Sizing Area Diameter		End Warpage	
	PPDR	PDR	PPDR	PDR
1	189.85	187.74	0.23	1.63
2	162.88	160.28	0.22	1.67
3	137.91	136.27	0.30	1.74
4	114.92	113.76	0.33	1.84

(2) Circumferential residual tensile stress of the end

Comparison of the circumferential residual tensile stress at end in the first pass between PDR and PPDR is shown in Figure 27. The comparison results were as follows:

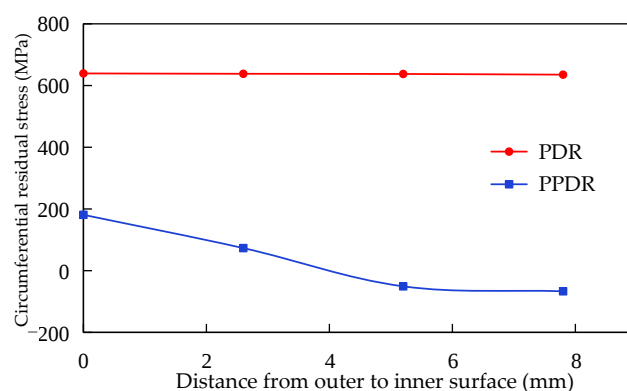


Figure 27. Circumferential residual stress of end.

- (1) The circumferential residual tensile stress of the end can be effectively controlled by the PPDR. The circumferential residual stress of the outer and inner surface at the end is tensile and compressive, respectively.
- (2) The circumferential residual tensile stress can be greatly decreased by the PPDR. In the first pass, the circumferential residual tensile stress at the outer surface of end is decreased by 71.67%, which effectively eliminates the risk of axial cracking at end.
- (3) End unevenness

Comparison of end unevenness and relative unevenness between PDR and PPDR is shown in Table 8. It can be found that the end unevenness and relative unevenness can be greatly decreased by the PPDR. The end unevenness of each pass PPDR is decreased by 65.37%, 79.14%, 81.92%, 84.16%, respectively. The end's relative unevenness is less than the initial and critical relative unevenness, which effectively controls the circumferential wrinkling at end.

Table 8. Comparison of unevenness.

Reducing Pass	Unevenness (mm)		Relative Unevenness	
	PPDR	PDR	PPDR	PDR
1	0.45	1.30	0.26%	0.76%
2	0.34	1.63	0.23%	1.13%
3	0.32	1.77	0.27%	1.56%
4	0.35	2.21	0.37%	2.34%

6.3. Experimental Verification

The initial tube with $T_0 = 1.2$ was selected to carry out the four-pass PPDR on the THP63-200/300/100 $\times$ 2 hydraulic press. The reducing die of each pass is the same as the PDR, and the mandrel diameter of each pass is the same as the FEA.

The dies of PPDR are shown in Figure 28. The left and right reducing die are respectively fixed on the left and right support cylinder, which are respectively connected with the left and right slider of hydraulic press. The left and right mandrel are respectively connected with the left and right central cylinder of hydraulic press. The upper clamping die is fixed on the upper die base, which is connected with the upper slider of hydraulic press. The lower clamping die is fixed on the lower die base, which is fixed on the working platform of hydraulic press.

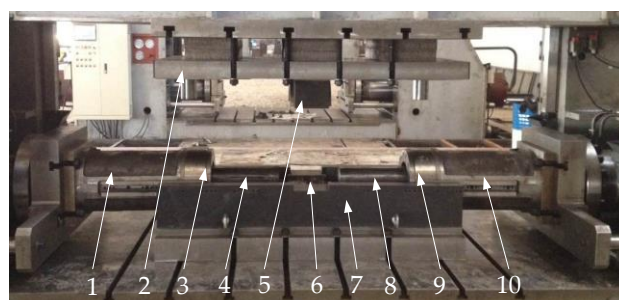


Figure 28. PPDR dies. 1. Left support cylinder; 2. Upper die base; 3. Left reducing die; 4. Left mandrel; 5. Upper clamping die; 6. Lower clamping die; 7. Lower die base; 8. Right mandrel; 9. Right reducing die; 10. Right support cylinder.

Before diameter-reducing, the upper slider of hydraulic press drives the upper die base and upper clamping die to move downward to clamp the middle area of the tube, and the left and right mandrel are respectively pushed into the tube inside by the left and right central cylinder. During diameter-reducing, the left and right reducing die are respectively pushed inward from the tube end with the speed 10 mm/s by the left and right slider, while

the left and right mandrel are respectively pulled from the tube inside to outside with the speed 12 mm/s by the left and right central cylinder. For the convenience of measurement and observation, the reduced tube is cut along the 1/4 longitudinal section, as shown in Figure 29. It can be observed that there is no obvious warping and circumferential wrinkling at the end.

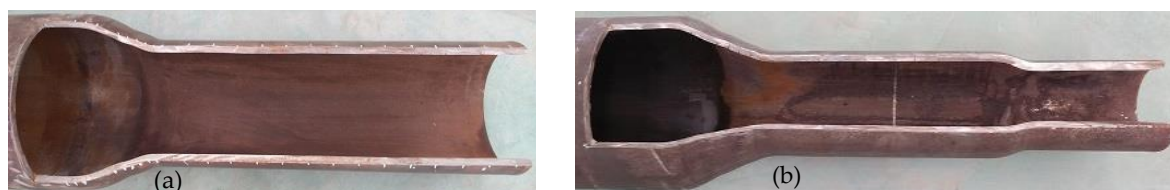


Figure 29. Reduced tube of PPDR. (a) The first pass; (b) the fourth pass.

Comparison of the EXP and FEA value of end warpage and unevenness between PDR and PPDR is shown in Table 9. The comparison results showed as follows:

Table 9. Comparison results (mm).

Reducing Pass.	End Warpage			End Unevenness		
	EXP of PPDR	EXP of PDR	FEA of PPDR	EXP of PPDR	EXP of PDR	FEA of PPDR
1	0.43	1.52	0.23	0.65	1.39	0.45
2	0.36	1.55	0.22	0.54	1.69	0.34
3	0.35	1.65	0.30	0.50	1.90	0.32
4	0.41	1.76	0.33	0.49	2.47	0.35

- (1) The end warpage can be greatly decreased by the PPDR. Compared with the EXP results of PDR, the end warpage of each pass PPDR tube is decreased by 71.71%, 76.77%, 78.66% and 76.70%, respectively. The FEA results of the PPDR are in good agreement with the EXP results.
- (2) The end unevenness can be effectively decreased by the PPDR. Compared with the EXP results of the PDR, the end unevenness of each pass PPDR tube is decreased by 53.24%, 68.05%, 73.68% and 80.16%, respectively. Furthermore, the FEA results of the PPDR are consistent with the EXP results.

The above research results indicate that the end warping and circumferential wrinkling can be greatly controlled by the PPDR, the risk of axial cracking at end can be effectively eliminated and the forming quality of reduced tube can be improved.

7. Conclusions

In this paper, the mechanical model of PDR and the geometric model of the tube with the wall thickness deviation were established to reveal the axial cracking and circumferential wrinkling mechanism of PDR. The experiments and simulations were developed to validate the theoretical analysis and reveal the influence of process parameters on the wrinkling and cracking. In order to solve the above problems, the method of PPDR was proposed. The main conclusions could be summarized as follows:

- (1) The Equation of circumferential residual stress at end was deduced from the warping deformation and shear stress, it reveals that the circumferential residual stress in the end warping area from the inner to outer surface is tensile. The circumferential residual tensile stress of the thin wall side is greater than that of the thick wall side.
- (2) The generation mechanism of circumferential wrinkling on the inner wall at the end was revealed. The geometric model of tube with wall thickness deviation was proposed, in which the outer surface shape is a circle and the inner surface shape is a periodic sinusoidal variation. On the base of it, the generation and development

of circumferential wrinkling at the end was demonstrated and the evolution law of unevenness was revealed.

- (3) The end unevenness is greater than the initial unevenness, while the sizing area unevenness is less than it. The end unevenness and relative unevenness are sharply increased with the increase of wall thickness deviation and reducing pass, while the sizing area unevenness is increased slowly. The end warpage and circumferential residual tensile stress at end are increased slowly with the increase of reducing pass, while the wall thickness deviation has little effect on them.
- (4) The pushing-pulling diameter-reducing process was proposed to control the wrinkling and cracking. The simulation and experimental verification results showed that the sizing area diameter is increased, the deformation difference in bending stage is decreased, then the end warpage, unevenness and circumferential residual tensile stress of the end are all greatly decreased, the risk of axial cracking and circumferential wrinkling is eliminated and the forming quality of the reduced tube is improved.

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Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

PDR	Pushing diameter-reducing
PPDR	Pushing-pulling diameter-reducing
L_0	Length of the initial tube (mm)
d_0	Outer diameter of the initial tube (mm)
t_{m0}	The maximum wall thickness of the initial tube (mm)
t_{n0}	The minimum wall thickness of the initial tube (mm)
t_0	Average wall thickness of the initial tube (mm)
T_m	The positive deviation (mm)
T_n	The negative deviation (mm)
T_0	The initial wall thickness deviation (mm)
θ_n	Period angle ($^\circ$)
n	Wave number
t_m	The maximum wall thickness (mm)
t_n	The minimum wall thickness (mm)
T	Unevenness (mm)
K	Relative unevenness (%)
d_i	Average inner diameter of tube (mm)
K_c	Critical relative unevenness (%)
T_x	The maximum allowable wall thickness deviation (mm)
d_{i0}	Inner diameter of initial tube (mm)
α	Half-cone angle of reducing die ($^\circ$)
d_m	Inner diameter of the exit area (mm)
R	Rounded corner radius of reducing die (mm)
R_{m0}	Intermediate layer radius of the thick wall side (mm)
R_{n0}	Intermediate layer radius of the thin wall side (mm)
R_{m1}	Intermediate layer radius of the thick wall side in reducing stage (mm)
R_{n1}	Intermediate layer radius of the thin wall side in reducing stage (mm)
t_{m1}	Wall thickness of the thick wall side in reducing stage (mm)
t_{n1}	Wall thickness of the thin wall side in reducing stage (mm)
R_{m2}	Intermediate layer radius of the thick wall side in bending stage (mm)

R_{n2}	Intermediate layer radius of the thin wall side in bending stage (mm)
t_{m2}	Wall thickness of the thick wall side in bending stage (mm)
t_{n2}	Wall thickness of the thin wall side in bending stage (mm)
d_{02}	Outer diameter of the tube end in bending stage (mm)
dl	Axial length of the bending element body (mm)
dy	Circumferential length of the bending element body (mm)
t_e	Wall thickness of the bending element body (mm)
σ_{pe1}	Axial equivalent compressive stress on the outside of intermediate layer (MPa)
σ_{pe2}	Axial equivalent tensile stress on the inside of intermediate layer (MPa)
dM	Torque on the right surface of the bending element body (N·m)
τ_{pn}	Shear stress (MPa)
R_{m3}	Intermediate layer radius of the thick wall side in warping stage (mm)
R_{n3}	Intermediate layer radius of the thin wall side in warping stage (mm)
t_{m3}	Wall thickness of the thick wall side in warping stage (mm)
t_{n3}	Wall thickness of the thin wall side in warping stage (mm)
r_ρ	Axial curvature radius of the upper side of warping element body (mm)
β	Included angle of the upper side of warping element body (°)
σ_{po}	Axial tensile stress on the outer layer of warping element body (MPa)
σ_{pi}	Axial compressive stress on the inner layer of warping element body (MPa)
$\sigma_{\theta m}$	Circumferential residual stress of the thick wall side (MPa)
$\sigma_{\theta n}$	Circumferential residual stress of the thin wall side (MPa)
σ_θ	Circumferential residual stress (MPa)
l_0	Gauge length (mm)
l_t	Length of tensile specimen (mm)
T_d	End unevenness (mm)
T_i	Sizing area unevenness (mm)
K_d	Relative unevenness of the end (%)
σ_n	Normal stress (MPa)
V_0	Speed of reducing die (mm/s)
F_r	Pushing force of reducing die (KN)
V_m	Speed of mandrel (mm/s)
F_m	Pulling force of mandrel (KN)
V_1	Speed of tube elongation (mm/s)
F_{n2}	Normal pressure (KN)
F_{t2}	Tangential friction force (KN)

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