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The evolution of cross-sectional dimension for double wall brazed tube in the multi-pass roll forming

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Abstract. The manufacturing process of double wall brazed tube (DWBT) consists of the multi-pass roll forming from the flat strip to double wall structure and brazing process. And the poor roundness of cross section for DWBT in the multi-pass roll forming not only affects the forming accuracy and quality, but also restricts the subsequent brazing process of DWBT. Thus, the parameters of Hill'48 yield criterion for the steel strip were firstly determined in this paper, and the reliable 3D finite element model of the multi-pass roll forming of DWBT was established based on ABAQUS/Explicit platform. Then the cross-sectional dimension of DWBT after each roll forming was analyzed. The results show that the multi-pass roll forming of DWBT requires the cooperation of the forming roller, horizontal roller and vertical roller, and the radius of the horizontal roller profile becomes larger with the increasing roll pass. The evolution of cross section is accompanied by the accumulation of equivalent strain, following the forming sequence of two arms on both sides, inner wall, outer wall and sizing process. An expression representing roundness is proposed, and it is concluded that the roundness of the outer tube is better than that of inner tube. Moreover, the cross-sectional distribution of the outer tube is more uniform along the circumferential direction.

1. Introduction

Double wall brazed tube (DWBT) is a type of thin walled tube having a small diameter, which is manufactured by the multi-pass roll forming and the brazing. As shown in figure 1, a copper-coated steel strip is rolled 720° to form a double wall tube (DWT), then it is brazed to achieve 360° interface bonding along the circumference. Due to the merits of the uniform wall thickness, good surface quality, high burst strength and fine vibration-resistance performance, DWBT is widely utilized in pipeline systems of automobiles, household appliances and ships. In the multi-pass roll forming, the geometric pattern of rollers, roller assembly and the contact boundary are the key factors to determine the geometric shape of the cross section, and the formed shape of each pass for DWT is affected by the previous and subsequent passes. In particular, due to the geometric features of thin wall, small diameter and double wall structure, the evolution of cross section of DWBT is more complex. Meanwhile, the stability and uniformity of roll forming are affected by the multiple passes, different kinds of rollers, more parameters and poor stiffness of thin steel strip, resulting in defects such as poor adhesion between double walls and low roundness. It should be emphasized that these defects will further restrict the brazing quality. Obviously, the multi-pass roll forming is a key process in the manufacturing process of DWBT, which directly affects the evolution of cross-sectional dimension, and ultimately determines the forming quality and forming accuracy of DWBT. Therefore, it is imperative to investigate the multi-pass roll forming process of DWBT, so as to improve the forming and brazing quality.

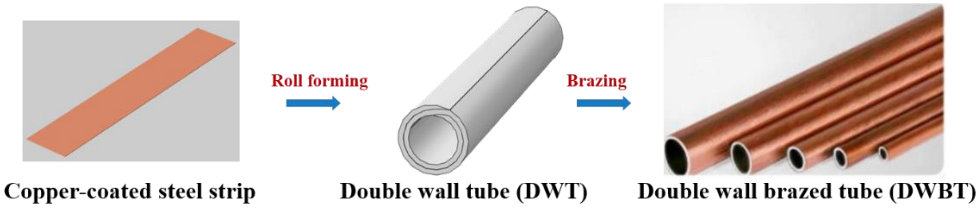

Figure 1. The manufacturing process of DWBT.

With the development of computer technology, finite element analysis has been regarded as an essential tool for die design and process calculation, which is increasingly applied in the field of roll forming. For the roll forming of tube, Ren et al [1] established the 2D finite element model of single wall tube followed by U-forming, O-forming and expansion forming (the whole UOE forming process), the U-shaped plate is subjected to bending and reverse bending deformation in the O-forming process, and the expansion forming can improve the roundness of the formed tube. Zou et al [2] proposed a numerical method for calculating the springback and predicting the O-forming gap of steel plate after CUO forming (including C-forming, U-forming, and expansion forming). The opening gap at twelve o'clock position of the O-shaped plate was affected by the radius of the lower part of U-mould, and the springback trend is different for different deformation areas. For the numerical simulation of the continuous roll forming process, some modeling techniques were proposed, and the roll forming of a closed unsymmetrical tubular rocker panel and a closed circular tube with welding and post-cut were simulated to verify the feasibility [3]. Cheng et al [4] revealed the mechanics law between strip and rolls in the roll forming of electrical resistance welding pipes by the numerical simulations, the results showed that the contact normal force plays a major role in the forming of the edge arc segment, and the straight segment restricts the deformation of strip. For X70, X80 and X90 steels, the yield stress evolution in UOE forming process was investigated by Zou et al [5], the results found that the yield stresses of pipe were unevenly distributed along both thickness and circumferential directions, and the expansion forming increases and homogenizes the tensile yield stress. The above research about the finite element modeling and deformation characteristic analysis of the tube in roll forming process can provide scientific methods and theoretical guidance for the multi-pass roll forming process of DWBT.

For the manufacturing process of DWBT, some scholars have carried out relevant research. Mahendra and Hardik [6] introduced the major forming steps of DWBT, the nominal diameter, strip thickness, bevel outer angle and bevel inner angle are the key parameters to determine the geometric dimensions of the tube. The beveling forming of DWBT was simulated using explicit code LS-DYNA and the stress-strain relationships were analyzed by Wang and Xiao [7], it is obtained that the maximum deformation of the steel strip occurs in the position where contact with roller in the beveling forming. Yan et al [8] explored the reasons underlying the frequent appearance of "marking problem" in the production of DWBT, and found that the high roughness of the trimmed edge will directly result in low precision of beveled edge, finally causing the "marking problem". Compared with the roll forming of other profiles, the manufacturing of DWBT is that the initially flat strip is incrementally curled for two circles to form a double wall structure, which makes the numerical simulation more complex. However, it is easily found that there is still a lack of research on the important 720° curling forming process of DWBT.

Therefore, based on ABAQUS platform, the 3D finite element model of the multi-pass roll forming for DWBT was established and validated. The formed cross section in each pass and its evolution were analyzed, and the roundness of cross section for the finally formed double wall structure was calculated and evaluated, which will be used to predict defects in the forming process, and also provide a powerful guidance for the improvement of the forming accuracy for DWBT.

2. The finite element model of the multi-pass roll forming for DWBT

2.1. The determination of parameters for Hill'48 yield criterion

The steel strip for manufacturing DWBT is specially designed and provided by Baoshan Iron & Steel Co., Ltd, which is called BHG2 steel. In order to obtain the anisotropy of mechanical properties, the uniaxial tensile samples were taken along rolling direction (RD), transverse direction (TD) and diagonal direction (DD), and the gauge dimensions are 25×6×0.35 mm, as shown in figure 2. Then the tensile test was carried out on WDW-100 electronic universal testing machine equipped with digital image correlation (DIC) speckle strain measurement system. The mechanical parameters for three directions were summarized in table 1. Due to the very thin BHG2 steel strip and the forming characteristic, it can be regarded as in plane stress state. Hence, Hill'48 yield criterion under plane stress state is given in equation (1), which can describe the yield behavior of anisotropy materials.

$$f(\sigma_{ij}) = (G+H)\sigma_{xx}^{2} + (H+F)\sigma_{yy}^{2} - 2H\sigma_{xx}\sigma_{yy} + 2N\sigma_{xy}^{2} - \bar{\sigma}^{2} = 0 \tag{1}$$

where σ_{xx} and σ_{yy} are the normal stress in RD and TD, respectively. σ_{xy} is the shear stress, $\bar{\sigma}$ is the equivalent stress. *F*, *G*, *H*, *N* can be expressed by r_0, r_{45} and r_{90}, as shown in equation (2).

$$\begin{cases} F = \dfrac{r_0}{r_{90}\left(r_0+1\right)} \\ G = \dfrac{1}{r_0+1} \\ H = \dfrac{r_0}{r_0+1} \\ N = \dfrac{\left(r_0+r_{90}\right)\left(1+2r_{45}\right)}{2r_{90}\left(r_0+1\right)} \end{cases} \tag{2}$$

where r_0, r_{45} and r_{90} are the *r*-value of RD, DD and TD in uniaxial tensile test, respectively. Finally, the calculated parameters *F*, *G*, *H*, *N* were 0.329, 0.334, 0.666, 1.295, respectively.

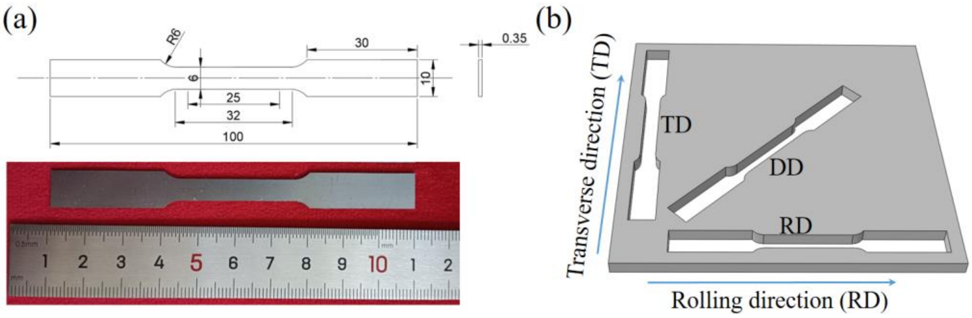

Figure 2. Dog-bone sample of BHG2 steel: (a) shape and size (b) sampling direction.

Table 1. Main mechanical properties of BHG2 steel.

Directions	RD	DD	TD
Yield stress σ_s/MPa	241	244	248
Elongation ratio δ/%	35.2	36.9	36
Hardening exponent n	0.27	0.25	0.24
Strength coefficient *K* /MPa	675.37	649.51	660.31
Lankford's coefficient *r*	1.99	1.45	2.02

2.2. Establishment and validation of finite element model

In this paper, the outer diameter and wall thickness of DWBT to be studied and simulated are 4.76 and 0.70 mm, respectively. In the continuous forming process, since the deformation of BHG2 steel strip is constrained by the front and rear forming passes, the length of steel strip is selected to 750 mm, and the width is 27.65 mm according to the diameter of DWBT. The multi-pass roll forming of DWBT consists of the beveling forming, 720° curling and sizing forming. In the beveling forming, only local zone deforms and has little influence on the cross-sectional dimension. Hence, it is not considered in the finite element modeling. If so, the steel strip can be regarded as the plane strain state, and shell element can be applied, which will not affect the forming results, but also improve the calculation efficiency to a great extent.

The material properties of BHG2 steel were input according to the tensile tests in Section 2.1. Along the width direction, each zone of the steel strip is deformed, so the small mesh size is used for the deformed part, that is 0.4×0.4 mm. As a result, there are 70 nodes in the width direction, and is numbered from right to left as 1 - 70, represented by i_1 - i_{70}. Meanwhile, due to the transfer of stress and strain history among passes, the continuous analysis step is used to inherit the stress and strain of the previous step in the numerical simulation. Moreover, the roll forming is conducted under the combined action of vertical roller, forming roller, horizontal roller and sizing roller, so the roller system assembly and surface to surface interaction become the critical problems. Roller profile, relative position and the clearance between roller and steel strip in each pass determine the strain path of the deformed part and have a decisive influence on the forming quality of DWBT. Hence, the assembly sequence is as follows, firstly the horizontal position of all down vertical rollers is unified, and the up vertical rollers are identified according to the gap between the roller and the strip, then the front and rear position of rollers for first roll pass are adjusted on the basis of the roller profile. Finally, the rest rollers for subsequent passes were gradually determined on the condition of the first pass. Since the dies consist of 58 rollers and mandrel in the roll forming process, all rollers adopt analytical rigid bodies in order to save the time of numerical simulation.

The surface-to-surface interaction between rollers and steel strip is of great significance to the quality of formed surface. The friction coefficient of roller material Cr12 and BHG2 steel strip was measured by the friction test under different pressures. It is worth emphasizing that the contact interaction between inner and outer wall of DWBT must be considered due to the gapless double wall structure.

Based on the solution of the above key modeling technologies, the finite element model of the multi-pass roll forming process of DWBT was established, as shown in figure 3. The steel strip is gradually formed into double wall tube along the rolling direction.

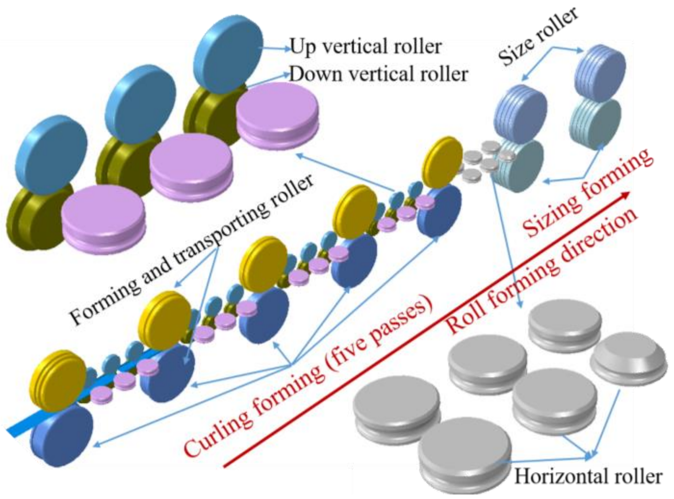

Figure 3. The finite element model of multi-pass roll forming for DWBT.

In general, the stability of the model is evaluated by examining the variation in the ratio of total kinetic energy (ALLKE) to total internal energy (ALLIE) and the ratio of total artificial strain energy (ALLAE) to total internal energy with the roll forming process. When the above values are less than

10%, it indicates that the finite element model has no significant dynamic effect, that is, the model is stable [9]. Hence, the above ratios with the multi-pass roll forming were displayed in figure 4. It can be seen that in the early stage of deformation, both curves have peaks owing to the sudden loading, but two curves stabilize quickly and remain at a low level (less than 5%), so it can be judged that the three-dimensional finite element model of multi-pass roll forming for DWBT established in this paper is stable.

After the multi-pass roll forming, the final cross section of DWT in the experiment and numerical simulation was shown in figure 5. Specifically, figure 5(a) gives the metallographic structure of cross section for DWBT, the brazing seam between the inner and outer tubes is distinguished by red lines. Judging from the shape of double wall tube, the conformability between double walls is fine and there is no gap. Based on the finite element simulation results, the node coordinates of the formed double wall tube are given in figure 5(b), and the node order corresponds to the position of steel strip described above. It is noted that the node coordinates represent the middle position of strip along thickness. Meantime, in order to estimate the similarity, the comparison results of the experiment and numerical simulation were shown in figure 5(c), it can be concluded that the contour profile of both can coincide well, the curvature of the rest arc is consistent except the beveling position, which further exhibits that the established finite element model is accurate.

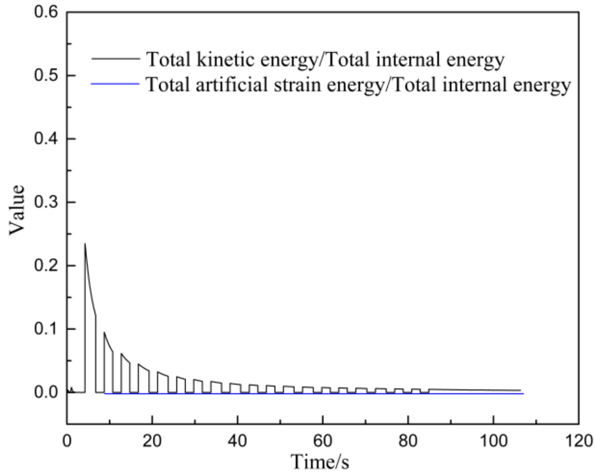

Figure 4. Verification of the stability for the finite element model.

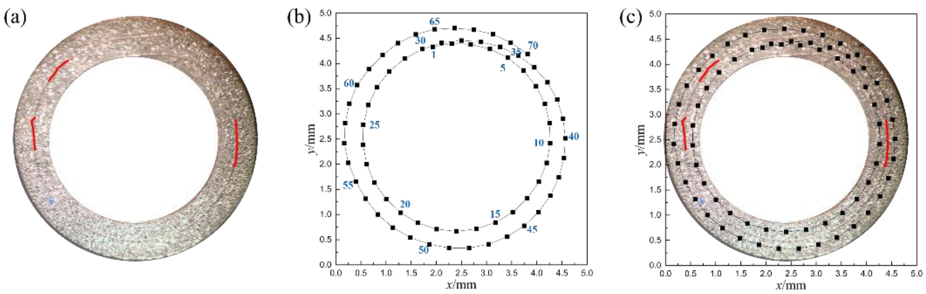

Figure 5. The final cross section of DWT in multi-pass roll forming: (a) the experiment result (b) the numerical simulation result (c) the comparison results between experiment and numerical simulation.

3. Cross-sectional dimension for multi-pass roll forming

3.1. The evolution of cross section

During the multi-pass roll forming process, BHG2 steel strip is gradually curled 720° from the plane strip to a double wall structure. The roller profile and the corresponding position in each roll pass determine the cross-sectional dimension and its evolution process. Some typical cross sections and the equivalent stress and strain distribution of the formed product are exhibited in figure 6. Overall, it is clearly that the evolution of cross section follows the sequence of curling forming on both sides, the formation of inner wall, the formation of outer wall and sizing forming of double walls. In details, under the action of the forming rollers (figure 7(a)), both sides of the thin steel strip are concurrently curled into arcs, and the formed section is an asymmetric U-shape (figure 6(a)-(b)), the left arm is slightly higher than the right. The equivalent stress and strain at the arcs are the largest, but the corresponding strain on the left side is slightly larger. This is because the higher left arm is convenient for positioning in the rear forming process. From the middle to both sides of steel strip, the equivalent stress and strain increase first and then decrease, which is because that the flow of material near the roller is different from other areas, and the occurrence of work hardening causes high stress and strain. Then, the left 90° arm is supported by the up and down vertical rollers (figure 7(b)), the right area is gradually formed into an inner tube (figure 6(c)-(e)) under the action of the horizontal roller (figure 7(b)), and with the increase of forming passes, the distance between the horizontal roller and the vertical rollers is getting closer and closer, and the radius of roller is also increasing, the formed degree is rising and the shape of cross section changes gradually with the increasing arc length. In general, the equivalent stress of the formed inner tube is greater than that in other areas as a whole, and the equivalent strain of the undeformed zone is not affected by the rollers and is almost equal to 0. In addition, the stress and strain distribution along the circumference is uneven, minor changes occur in the left arm. In the next, the right area is fixed by the horizontal roller (figure 7(c)) with a suitable radius, the left 90° arm moves to the right to form an outer tube (figure 6(f)-(g)). At this time, the radius of the horizontal roller is the largest compared with the previous. Till now, each area of the steel strip has been deformed under the action of the rollers. Finally, the sizing rollers have the task to implement the calibration to achieve the required diameter and roundness. In order to guarantee the dimensional accuracy, the olive shaped mandrel (figure 7(d)) is necessary inside the double wall tubes. When the olive is correctly positioned under the sizing roller, it can make sure the optimal strain hardening of the steel strip, the proper clamping force between inner and outer walls results in a positive brazing quality.

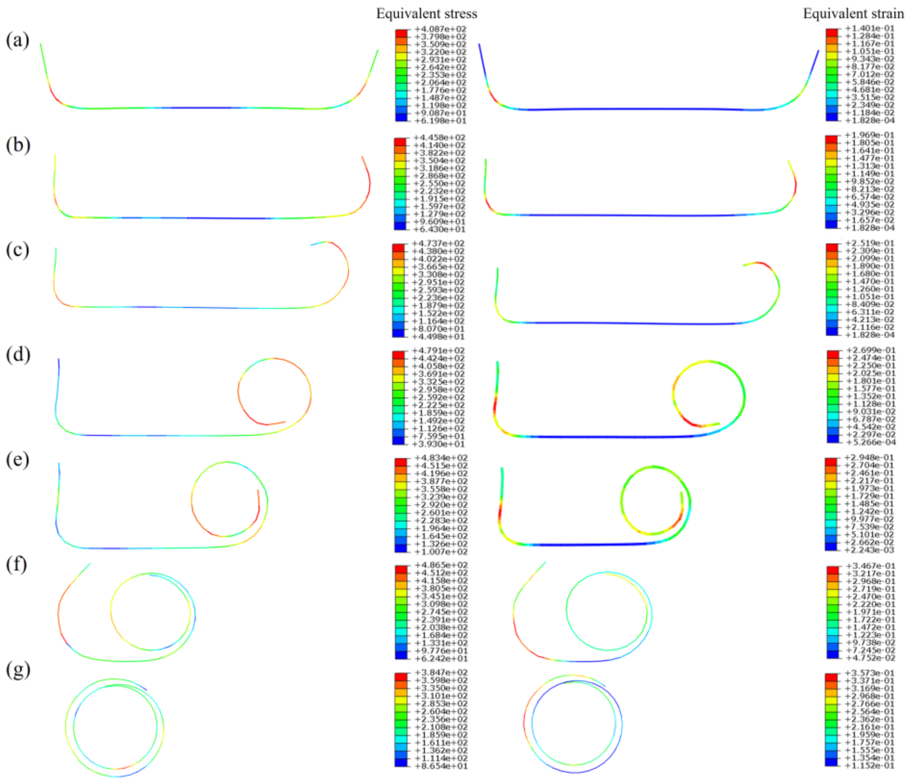

Figure 6. The evolution of cross section for DWBT in multi-pass roll forming process.

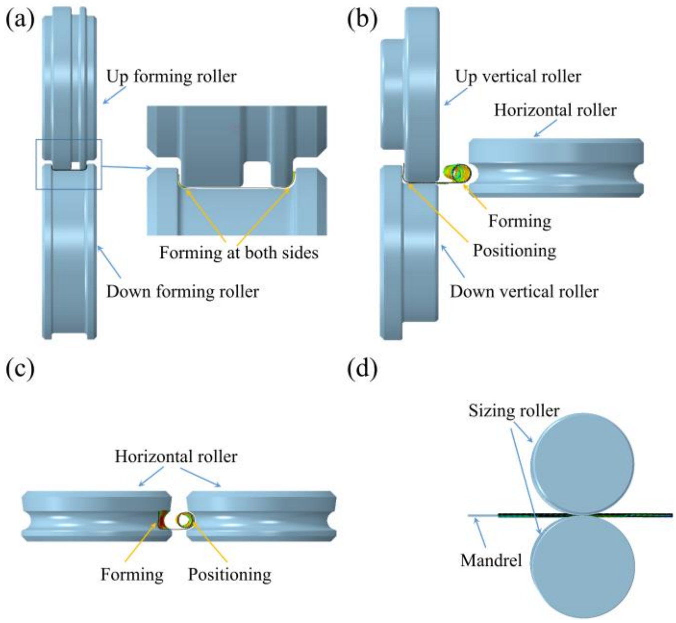

Figure 7. The assembly of the typical roller system.

In conclusion, the maximum equivalent strain is rising with the increasing passes, and the evolution of cross section follows the accumulation of strain. The formation of DWBT from the plane strip to double wall structure is complex, including the diversity of forming dies, the number of forming passes and the structural characteristics of thin wall, small radius and 720° double walls. Hence, in order to consider both cross-sectional accuracy and forming efficiency, the following principles must be observed in the multi-pass roll forming: (a) the stability of the strip; (b) the homogeneity in each pass; (c) inner and outer interference forming; (d) the larger deformation as much as possible in each forming pass. Otherwise, the BHG2 steel strip is prone to wrinkling, poor roundness and fracture in the roll forming process.

3.2. The dimensional accuracy of DWBT

Since the shell element is used in the finite element modeling process, the obtained geometric coordinates refer to the data of the neutral layer (R_1 and R_2) for the inner and outer tubes, as shown in figure 8. According to the theoretical values of the outer diameter and wall thickness, R_1 and R_2 are equal to 1.855 and 2.205 mm, respectively. According to the assembly relation of the mandrel and size roller, the x and y coordinates of the circle center are 2.36 and 2.53. If the distance between a node on a circle and circle center of inner or outer tubes is greater or less than the theoretical radius, it will affect the roundness of cross section. The farther the distance, the worse the roundness. Thus, except the beveling position, the maximum deviation distance between the actual and theoretical radius (R_1 and R_2) and the average deviation distance are used to measure the roundness, as shown in equations (3)-(5).

$$D_{out}=|R_i\text{-}R_2|/R_2\times 100\% \text{ (for outer tube)} \tag{3}$$

$$D_{in}=|R_i\text{-}R_1|/R_1\times 100\% \text{ (for inner tube)} \tag{4}$$

$$R_i=\sqrt{(X_i\text{-}2.36)^2+(Y_i\text{-}2.53)^2} \tag{5}$$

Where X_i and Y_i is the coordinates of the node i in Section 2.2.

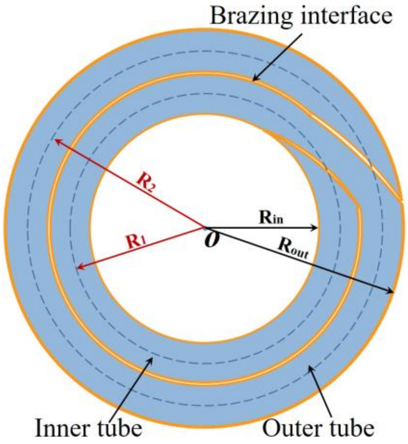

Figure 8. Geometric dimensions of DWT.

Table 2. The calculation of roundness of DWBT.

i	X_i/mm	Y_i/mm	D_{in}/%	i	X_i/mm	Y_i/mm	D_{out}/%
7	3.99	3.55	3.46	40	4.57	2.51	0.12
8	4.16	3.20	3.63	41	4.54	2.12	0.63
9	4.26	2.81	3.40	42	4.44	1.74	0.88
10	4.27	2.42	2.91	43	4.27	1.38	1.15
11	4.20	2.03	2.73	44	4.04	1.05	1.40
12	4.04	1.65	2.22	45	3.75	0.78	1.44
13	3.81	1.32	1.75	46	3.41	0.56	1.29
14	3.52	1.05	1.54	47	3.04	0.41	0.97
15	3.18	0.84	1.09	48	2.65	0.34	0.41
16	2.80	0.71	0.72	49	2.25	0.34	0.38
17	2.40	0.67	0.43	50	1.86	0.41	1.18
18	2.01	0.71	0.05	51	1.48	0.54	1.58
19	1.63	0.83	0.45	52	1.14	0.74	1.67
20	1.29	1.04	1.02	53	0.83	1.00	2.09
21	1.01	1.31	1.58	54	0.59	1.31	2.77
22	0.77	1.63	1.56	55	0.40	1.66	2.69
23	0.61	2.00	1.70	56	0.25	2.03	1.55
24	0.54	2.39	1.64	57	0.17	2.42	0.51
25	0.55	2.79	1.35	58	0.19	2.82	0.54
26	0.64	3.17	1.20	59	0.27	3.20	0.45
27	0.82	3.53	0.91	60	0.43	3.57	0.36

The final cross-sectional dimensions of double wall tube not only affect the shape accuracy, but also restrict the brazing quality. It is necessary to analyze the specific dimensions in details. Thus, the roundness of DWBT is proposed to quantitatively describe the forming accuracy in this paper. For the inner and outer tubes, the adopted nodes are 7 - 27 and 40 – 60 (figure 5(b)), respectively. As shown in table 2, the coordinates and the distance deviation of the nodes for inner and outer tubes are given. For the inner tube, the maximum and average errors are 3.63% and 1.68%. Obviously, the error is relatively small, which shows that the roundness of DWT in the multi-pass roll forming meets the actual requirements. Meanwhile, it should be pointed out that there are differences in errors for the different regions, which shows that the forming accuracy of local parts can be better by changing the shape and position of roller, the mandrel and the assembly clearance. The maximum and average errors of the outer tube are 2.77% and 1.15%, respectively. Compared with the inner tube, the error of the outer tube is smaller. It shows that the roundness of the outer tube is better than that of the inner tube.

In summary, in the multi-pass roll forming, the formation of the inner tube is more critical than that of the outer tube, and its forming quality determines the final forming precision of DWT.

4. Conclusions

- The parameters of the Hill'48 yield criterion of BHG2 steel are determined. Based on ABAQUS/Explicit platform, 3D finite element model of the multi-pass roll forming for double wall brazed tube has been built, and the model was verified to be accurate.
- The evolution of cross section for double wall brazed tube follows the sequence of curl forming on both sides, the formation of inner wall, the formation of outer wall and sizing forming, and the equivalent strain gradually accumulates in the multi-pass roll forming. The radius of the horizontal roller is rising with the increasing forming pass.
- The expression of the roundness for double wall brazed tube is given. Although the forming accuracy of the inner and outer tubes meets the requirements, the roundness of the outer tube is better than that of the inner tube. Meantime, the cross-sectional distribution of the outer tube is more uniform.

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