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ORIGINAL ARTICLE

An approach to improve thickness uniformity within tailor-welded tube hydroforming

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Abstract Both experimental and simulation studies were run to investigate the effects of deformation sequence on stress and strain states and thickness distribution during tailor-welded tube hydroforming. The effects of geometrical boundary condition were also studied. Then, an approach to improve thickness uniformity was put forward. Both stress and strain histories indicate that the deformation states of thinner and thicker tubes were obviously different duo to the difference in thickness during tailor-welded tube hydroforming. These induce tensile strain concentrates to happen near weld seam on thinner tube, but compressive strain on thicker tube, which lead to strain mutation around weld seam on tailor-welded tube components. As result, bigger thinning takes place on thinner tube. The difference in thinning ratio between thinner and thicker tubes reaches about 6.6%. By deformation sequence optimization, thickness distribution uniformity can be improved obviously. When deformation sequence altered from thicker tube to thinner tube, the difference in thinning ratio between two segments can be decreased to 1.5%. At last, the effects of geometrical parameters of preform component were analyzed and the suitable parameters were given.

Keywords Tailor-welded tube · Deformation sequence · Thickness distribution · Hydroforming

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1 Introduction

Recently, tube hydroforming is mainly used to manufacture hollow components, which possesses great advantages in weight reduction and high utilization of material strength and stiffness, and especially applied in automobile industry [1–4]. As to tailor-welded blank (TWB), it is often used to manufacture components with dissimilar thickness or different material properties on different zones. Therefore, TWB generates enormous advantages in optimizing components performance and weight reduction [5–7]. On such background, tailor-welded tube (TWT) hydroforming is put forward, which offers a unique opportunity to meet most of these advantages both of tube hydroforming and TWB [8].

In TWT hydroforming, the initial tube blank is welded from two or more tubes with different thicknesses. The difference in thickness would induce different stress and strain states during hydroforming. Thus, deformation behavior and deformation result of TWT are different from those of conventional tube with a sole thickness. Some scholars have studied the effects of length ratio and thickness ratio on weld seam movement and thickness distribution during hydroforming by

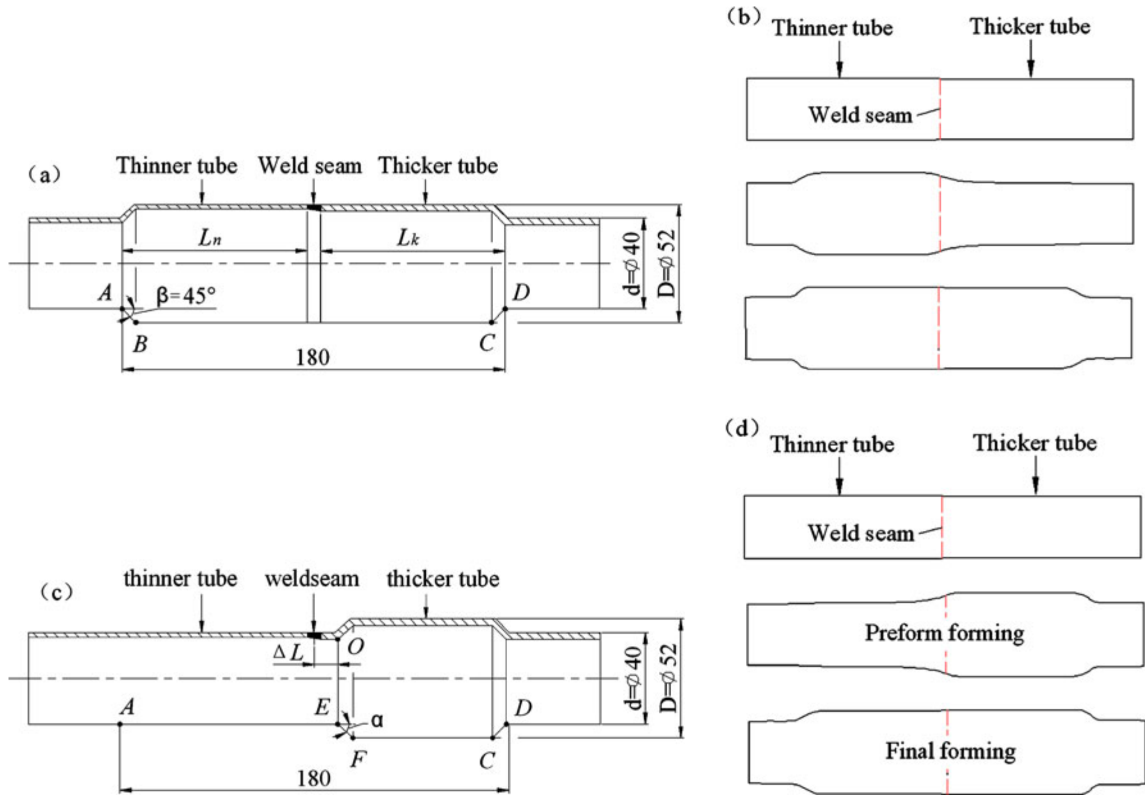


Fig. 1 Schematic of component **a** hydroforming without preforming, **b** deformation sequence from thinner tube to thicker tube, **c** hydroforming with performing, **d** deformation sequence from thicker tube to thinner tube

finite element method simulation. Liu et al. studied the effects of length ratio and thickness ratio on the expansion ratio of two segments through numerical simulation. The results showed that the maximum thickness ratio should be lower than 2.25 [9, 10]. Then, Natal Jorge further demonstrated that weld seam displacement and difference in expansion ratio can be minimized by optimizing length ratio [11, 12]. The results meant that the weld seam displacement correlated better with load path than to the thickness ratiovalues. From [13], the results show that the weld seam movement would induce non-uniformity thickness distribution. However, the method to improve thickness distribution uniformity is not studied systematically. Still, these results need to be confirmed by experimental evidence. Furthermore, plastic deformation is prior to take place on thinner tube and then extends to thicker tube during TWT hydroforming. Such deformation sequence effects on stress states and thickness distributions of TWT hydroforming were not revealed and analyzed in their studies.

In order to improve thickness uniformity during TWT hydroforming, the effects of deformation sequence on stress and strain states and thickness distribution were investigated, and the suitable geometrical parameters for preform component were also analyzed.

2 Study schemes

2.1 Study schemes design

To facilitate strain and thickness comparison between thinner and thicker tubes, reducer pipe component was selected as shown in Fig. 1a to study the effects of deformation sequence on thickness distribution, whose diameter and length of bulging zone are Φ52 and 180 mm, respectively. The expansion ratios both of two segments are the same and its value is 30%, which can help to remove the effects of

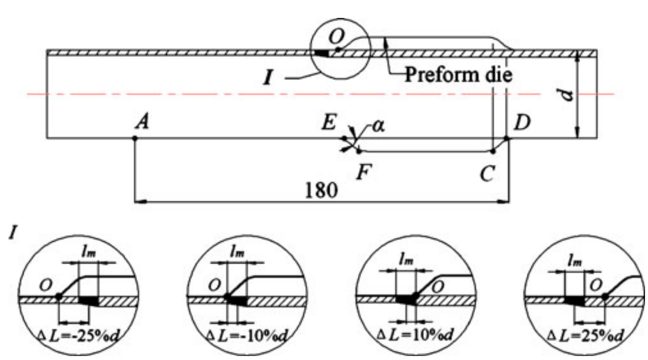
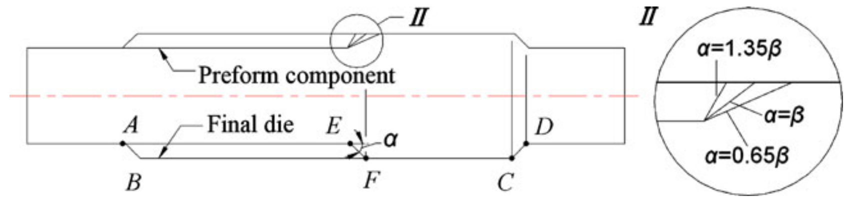


Fig. 2 Schematic of offset value

Fig. 3 Schematic of transition angle



expansion ratio on strain and thickness distribution. The initial thicknesses of the two segments are 2.8 and 2.3 mm, respectively.

During tube hydroforming, two segments are under equal pressure acting. Thus, thinner tube is prior to begin plastic deformation due to the difference in thickness as shown in Fig. 1b. As a result, the deformation sequence of tailor-welded tube is from thinner tube to thicker tube during free hydrobulging process.

In order to alter deformation sequence, a preform component was designed as shown in Fig. 1c. In such forming process, deformation is divided into two steps, i.e., preforming and final forming as shown in Fig. 1d. The forming processing is as follows. During preforming process, only thicker tube takes place expansion deformation, while thinner tube is constraint by die and formed a preform component as Fig. 1c. During the second step, preform component is placed into final die and hydrobulged to form the shape as shown in Fig. 1a. By this method, deformation sequence is changed to from thicker tube to thinner tube. For preform component, there are two key geometrical parameters, such as ΔL and α (so-called offset value and transition angle, respectively) as shown in Fig. 1c. ΔL is the distance from weld seam to key point *O*. Negative value means point *O* locates at the left of weld seam.

The position of point *O* has two schemes, i.e., at left or right of weld seam, which decides the deformation moment of weld seam. When point *O* locates at left of weld seam, weld seam would take place synchronizing deformation with that of the thicker tube. On the contrary, deformation synchronization would take place with that of the thinner tube.

Angle α reflects the length relation of hydrobulging zone between preform and final components, which affects strain state evolution during hydroforming. When $\alpha<\beta$, the length of hydrobulging zone for preform component is less than that of final component, i.e., $\overline{AEFCD} < \overline{ABCD}$. On the contrary, it is bigger than that of final component. Figures 2 and 3 show the schematic of offset value and transition angle.

According to previously mentioned, the preform component with different ΔL and α, as shown in Tables 1 and 2, were hydrobulged to show the effects of geometrical parameters on thickness distribution during TWT hydroforming.

The parent tubes are stainless steel corresponding to 0Cr18Ni9. In order to avoid the effect of anisotropic properties on the experiments, both tubes were solution heat treated. Argon-arc welding was used to prepare the TWT blanks.

2.2 Finite element model

In view of the axisymmetrical shape of the TWT blank, applying the advantage of symmetry, only one-half model was built as shown in Fig. 4. The weld seam on TWT is circumferential one so that the weld seam will experience severe deformation during hydrobulging. Therefore, the differences in the mechanical properties of the tubes and the weld seam will have great effect on the deformation behavior. In the finite element model, the weld seam was built as the third body with special mechanical properties, except for thicker and thinner tubes. The weld seam was 6 mm wide according to the measurements made with the real TWT samples prepared by argon-arc welding. The commercial code, eta/DYNAFORM, was selected for simulation.

The tubes had been solution heat-treated, and so, they were modeled as isotropic material obeying Mises yielding criterion and was meshed by Belytschko–Tsay shell

Table 1 Study schemes of offset value

Offset value(ΔL)		Transition angle(α)	
Dimension	Position of point *O*	Value	Length relation
ΔL=−25%*d* ΔL=−10%*d*	Left from weld seam	$\alpha=\beta$	$\overline{AEFCD} = \overline{ABCD}$
ΔL=10%*d* ΔL=25%*d*	Right from weld seam		

Table 2 Study schemes of transition angle

Relation between α and β	Relation of hydrobulging zone	Offset value (ΔL)
α=0.65β=30°	$\overline{AEFCD} < \overline{ABCD}$	25%*d*
α=β=45°	$\overline{AEFCD} = \overline{ABCD}$	
α=1.35β=60°	$\overline{AEFCD} > \overline{ABCD}$	

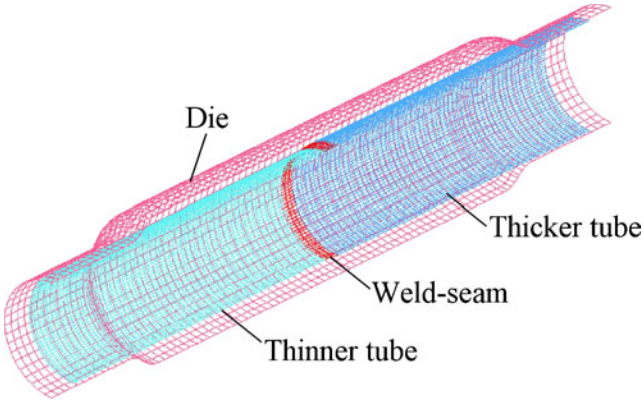


Fig. 4 Finite element model

elements. The tube material obeys the power-hardening law represented by $\sigma=k\varepsilon^n$, and the parameters obtained through uniaxial tensile test are listed in Table 3.

Axial movement constraints were applied to either end of the TWT to simulate the end fixture acted by the sealing punches. Symmetrical constraints were applied to the nodes on the symmetric surfaces. Coulomb friction model was used for simulation and the friction coefficient assigned is 0.12.

3 Strain states and strain distribution

3.1 Strain states

For the hydrobulging of a thin-wall tube, there is a free surface on the outer side of the tube so that the stress state of the tube is usually dealt with as a plane stress by assuming the stress through thickness direction (σ_t) as zero. Assuming that σ_z is a stress along axial direction, and σ_θ is a stress along hoop direction, and then according to von Misses yield criterion, the yielding condition of the tube under plane-stress state could be described as an ellipse shown in Fig. 5. According to simulation results, the stress paths and strain states of TWT before and after deformation sequence altered can be recorded as shown in Fig. 5.

It can be seen that the stress paths of thinner and thicker tubes locate at either side of line $d\varepsilon_z=0$, respectively, before deformation sequence altered. The stress path of thinner tube locates at zone A, where, $d\varepsilon_z>0$ and $d\varepsilon_\theta>0$. That of thicker tube locates at zone B, where, $d\varepsilon_z<0$ and $d\varepsilon_\theta>0$.

Table 3 Material parameters

Material	Hardening exponent(n)	Strength coefficient(K)
Parent tubes	0.45	1,250
Weld seam	0.31	1,550

These mean axial strain states of thinner and thicker tubes are tensile and compressive strain states respectively all the way through hydroforming process. As a result, tensile deformation happens on thinner tube along axial direction, but compressive deformation happens on thicker tube along axial direction.

After altering deformation sequence, the stress paths and strain states of thinner and thicker tubes vary greatly as shown in Fig. 5b. It can be seen stress paths located at zone A (where, $d\varepsilon_z>0$ and $d\varepsilon_\theta>0$) only during early stage of forming process both of thinner and thicker tubes, but transfer to zone B (where, $d\varepsilon_z<0$ and $d\varepsilon_\theta>0$) during middle and late stages. These two mean deformation segment does not belong to a unique strain state all the way through hydroforming process. As a result, there is no accumulated axial deformation on thinner and thicker tubes.

3.2 Strain distribution

Figure 6 shows the hoop and axial strain distributions before altering deformation sequence, measured by Automated Strain Analysis and Measurement Environment. It can be seen hoop strain distributions are similar for both of thinner and thicker tubes. But there is great difference in axial strain distribution between two segments. Thinner tube is in the state of tensile and its average value is about 0.02. Thicker tube is in the state of compression and its average value is about −0.02. There is obviously sharp improvement of axial strain in the zone adjacent to weld seam of thinner tube and the maximum value is about 0.067. In contrast, sharp decrease of axial strain occurs in the zone of the thicker tube near the weld seam, and the minimum value is about −0.037. Thus, thinner and thicker tubes are just in different axial strain states and the maximum strain difference reaches 0.104, although all have the same expansion ratio and axial constrains are carried out. Besides, the average thinning ratio of thinner tube is bigger than that of the thicker tube.

Figure 7 shows the hoop and axial strain distributions after altering deformation sequence. A great improvement can be seen and axial strain distribution achieved. Axial strain both of thinner and thicker tubes are quite homogeneous. Most zone of the thinner and thicker tubes are in a slight tensile strain state beside the weld seam which is in a compressive strain state.

4 Thickness distribution

Considering the different initial thickness of two segments, it is indistinct if using the ultimate thickness dimension to contrast the thickness variation of two segments. However, thinning ratio can help to overcome this difficulty and is effective to compare the thickness variation. Represented by

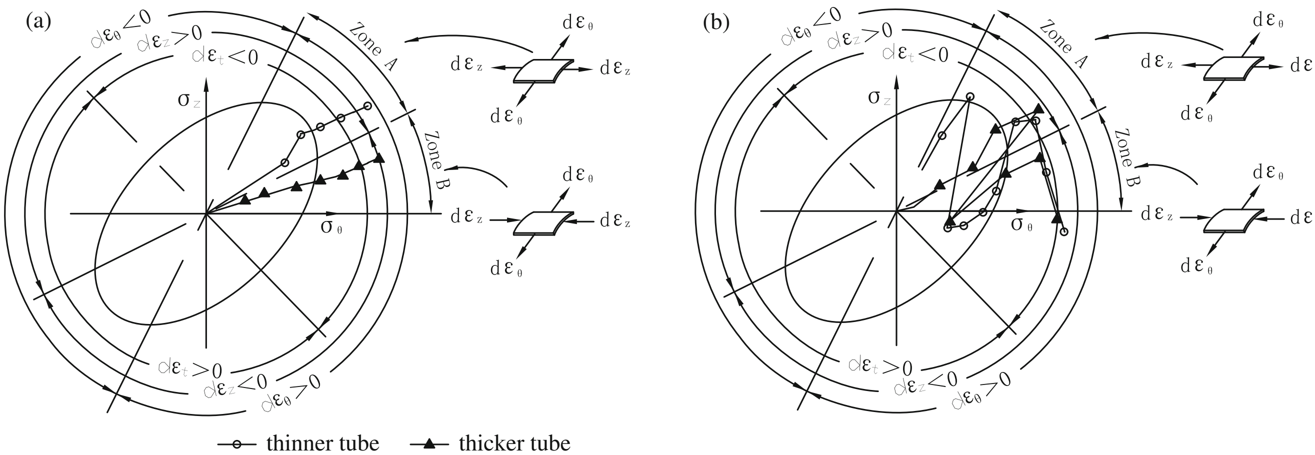


Fig. 5 Stress paths and strain states **a** before deformation sequence altered **b** after deformation sequence altered

δ, thinning ratio can be calculated using equation $\delta=\Delta t/t_0$. Where, Δt is the variation in thickness and t_0 is the initial thickness of tube.

Experimental thickness distributions of the two types of deformation sequence are shown in Fig. 8. It can be seen that thinning ratio distribution is uneven before deformation sequence is altered, although all have the same expansion ratio and axial constrains were carried out. The average thinning ratio of thinner tube is bigger than that of thicker tube. Maximum thinning ratio takes place on thinner tube near the weld seam and its value is about 30.5%. In contrast, minimum thinning ratio takes place on thicker tube near weld seam and it value is about 23.1%. Consequently, sudden and large fluctuation of thickness appears in the zone near the weld seam and the difference in thinning ratio between two segments is about 6.6%. The main reason to induce thickness fluctuation is the difference in strain states between two tubes. Mechanical analysis is given in detail in [13].

After deformation sequence is altered from thicker to thinner tube, the uniformity of thickness distribution is improved greatly. The maximum thinning ratio is about 27%, which locates at the thinner tube near the weld seam. The minimum thinning ratio is 25.5%, which locates at the middle zone of the thinner tube. The difference between the maximum and minimum thinning ratios is decreased to only 1.5%.

5 Effects of geometrical parameters on thickness distribution

To illustrate the effects of geometrical parameters on thickness distribution, experiments were also run with ΔL=−25%d, ΔL=−10%d, ΔL=10%d, ΔL=25%d, and α=0.65β, $\alpha=\beta$, α=1.35β.

Figure 9 shows the effect of offset value on thickness distribution. It can be seen that offset value has great influence on thickness distribution. Only when ΔL=

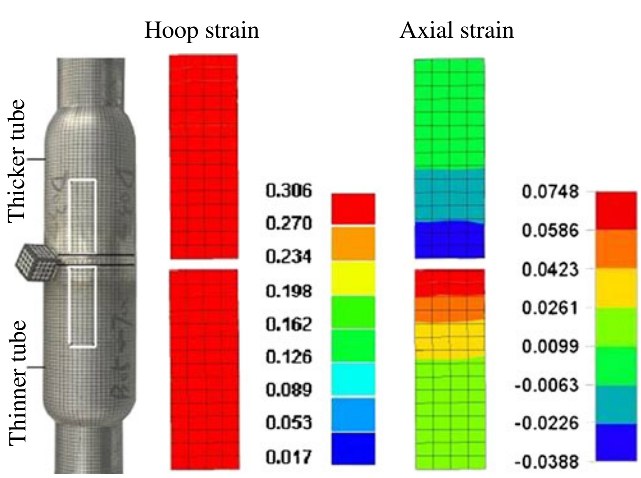


Fig. 6 Strain distribution before deformation sequence altered

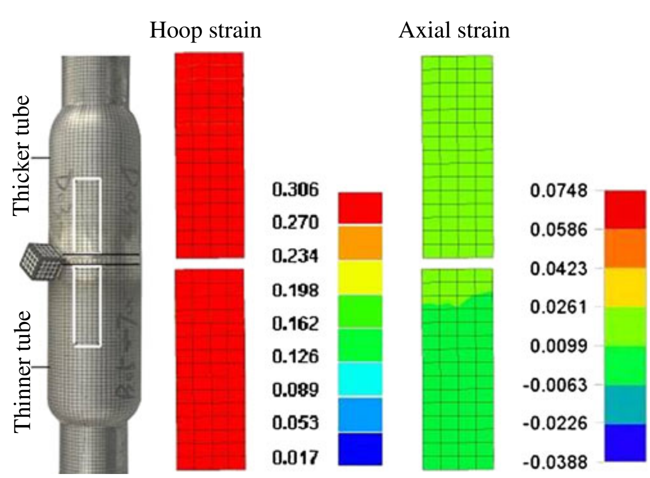


Fig. 7 Strain distribution after deformation sequence altered

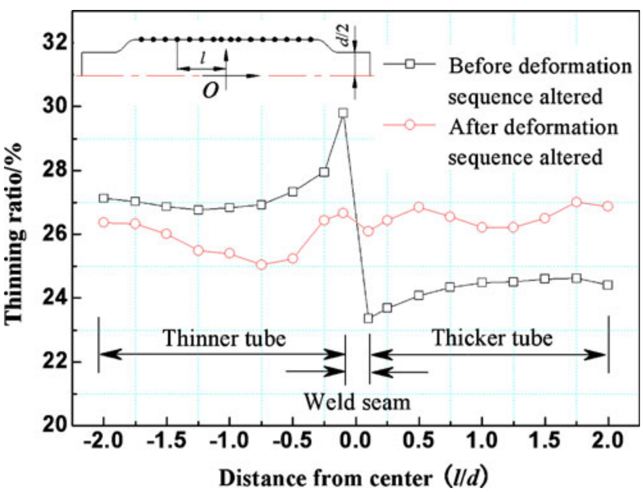


Fig. 8 Thickness distribution before and after deformation sequence altered

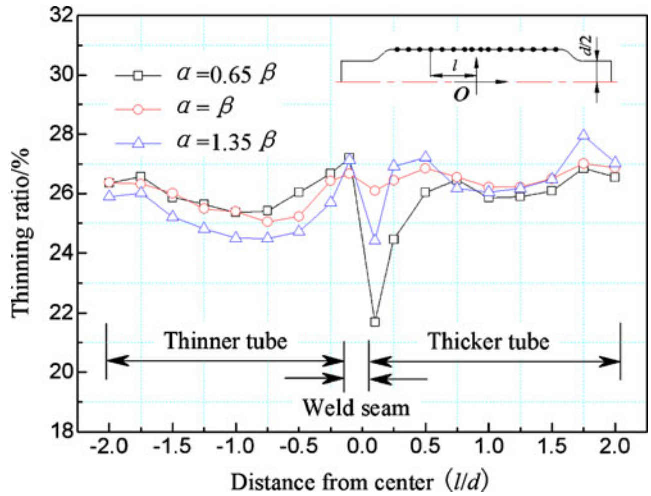


Fig. 10 Effects of transition angle on thickness distribution

10%*d*, thickness distribution is sound. When $\Delta L \leq -10\%d$, though the uniformity of thickness distribution improves for thicker tube, it deteriorates sharply for thinner tube, especially on the zone near weld seam and its maximum thinning ratio increases to 35.1%. When $\Delta L > 25\%d$, thickness distribution is even for thinner tube, but aggravates for thicker tube. Sharp thickness fluctuation happens on the zone near weld seam, which induces nonuniformity thickness distribution.

Figure 10 shows the effects of transition angle on thickness distribution. It can be seen that thickness distribution is suitable only when $\alpha=\beta$. When $\alpha<\beta$, though the uniformity of thickness distribution improves for thinner tube, it deteriorates sharply for thicker tube especially for the zone near the weld seam and its minimum thinning ratio even decreases to 21.5%. When $\alpha>\beta$, thickness distribution both of thinner and thicker tubes deteriorate greatly. The uniformity of thickness distribution is worth than it is when $\alpha=\beta$.

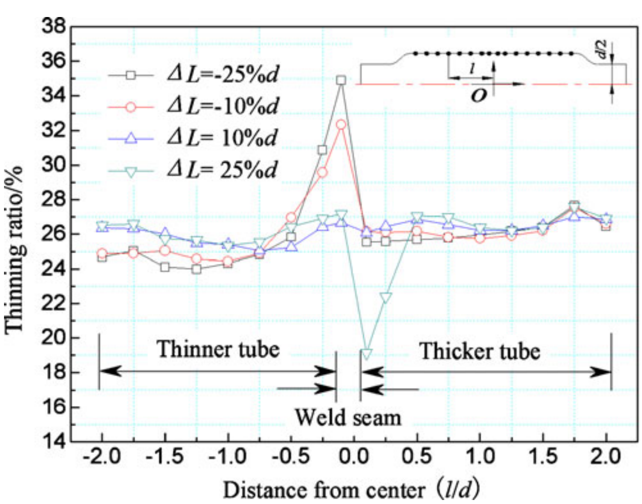


Fig. 9 Effects of offset value on thickness distribution

6 Conclusions

1. Obvious improvement or decreasing of axial strain occurs on the zone near the weld seam during TWT hydroforming. As a result, uneven thickness distribution appears. Excessive thinning and thickening take place on thinner and thicker tubes, respectively. The difference in thinning ratio between thinner and thicker tubes reaches 6.6%. Sudden and large fluctuation of thickness appears nearby weld seam.
2. Deformation sequence has great effects on thickness distribution during TWT hydroforing. An approach to improve thickness uniformity was put forward. The nonuniformity of thickness distribution can be overcome by altering deformation sequence. Thickness distribution improves greatly when deformation sequence altered from thicker tube to thinner tube and the difference in thinning ratio between thinner and thicker tubes decreases to 1.5%.
3. The geometrical parameters, such as offset value and transition angle play an important role during the process. Reasonable geometrical parameters are that $\Delta L=10\%d$ and $\alpha=\beta$, i.e., bulging zone both of preform and final components is equal in length and the deformation moment of weld seam must be synchronized with that of thinner tube.

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