Plastic deformation regularity of tailor-welded tube hydroforming

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To reveal the deformation characteristics and influence of dissimilar thickness on hydro-bulging of tailor-welded tube (TWT), FEA, experiments and mechanics analysis are conducted. The effects of length ratio, weld-seam movement and work-hardening on deformation compatibility are analyzed. It indicates that the plastic deformation occurs first at the middle zone of the thinner tube, and then extends to the thicker tube crossing the weld-seam. The expansion occurring on the two parts with dissimilar thickness is non-uniform, higher the length ratio and higher the deformation compatibility. Stress-strain analysis reveals that though the whole TWT suffers biaxial tensile stresses and the biaxial elongation occurs in the thinner tube, axial compressive strain occurs in the thicker tube. It is concluded that the mechanism for improving the deformation compatibility is to induce the deformation in the thicker tube by enhancing the bulging pressure needed for the thinner tube through changing the stress state of the thinner tube and flowing stress. Weld-seam movement happens during tailor-welded tube hydroforming, which induces uneven distribution of axial strain and thinning ratio in the TWT.

Keywords: Tailor-welded tube, Dissimilar thickness, Weld-seam movement, Thinning ratio

Tube hydroforming is becoming more and more important process for manufacturing hollow components in aviation, astronavigation and automobile due to its advantages such as weight reduction and high utilization of the strength and stiffness1-4. By controlling a loading path determined by the relation between internal pressure and axial feeding, material can be pushed into die cavity from two ends of a tube blank so that a part with larger expansion ratio and relatively smaller thinning ratio can be produced5. However, even though an optimal loading path is applied, obviously uneven thickness appears along axial direction of the components. Usually, the end of the tube blank becomes thicker than the initial thickness, but the expanded zone becomes thinner. The thickness non-uniformity is imputed to friction effect and difference in expansion ratio6. To improve the thickness uniformity, hydroforming of tailor-welded tube (TWT) with dissimilar thickness has been put forward7. The TWT in the process has a thicker segment corresponding to the largely expanded zone of the component, but a thinner segment to the slightly expanded zone. During hydroforming of TWT, the thickness difference induces various stress states so that the evolution of plastic deformation is affected.

Some researchers studied the effects of length ratio and thickness ratio on weld-seam displacement and expansion ratio of the two segments by using numerical simulation. The results showed it would be better if the thickness ratio less than 2.25. The weld-seam displacement and difference on expansion ratio can be minimized by optimizing the length ratio7,8. However, the mechanics factors affecting deformation characteristics, deformation compatibility of the hydro-bulged TWT with dissimilar thickness and weld-seam movement were not revealed and analyzed.

Finite Element Model and Process Parameters

On a TWT with a circumferential weld-seam, the weld-seam will experience severe deformation during hydro-bulging. Therefore, the difference on mechanics properties of the tubes and the weld-seam must affect the deformation behaviour considerably. In the finite element model, the weld-seam was built as the third body with measured mechanics properties, as shown in Fig. 1. The width of the weld-seam was set as 6 mm according to the measured results through hardness-testing for TWT samples prepared by

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Argon-arc welding. The shape of the weld-seam is shown in Fig. 2. A commercial FEM code, eta/DYNAFORM, was used to carry out the simulation.

Before welding, the tubes had been solution heat-treated, therefore the tubes were modeled as isotropic material obeying Mises yielding criterion and were meshed by Belytschko-Tsay shell elements. The tube materials obey the power-hardening law represented by 

\[ \sigma = k \varepsilon^n \]

and the parameters are given in Table 1, corresponding to stainless steel (0Cr18Ni9) and its weld-seam.

Axial movement constrains were applied to both ends of the TWT to simulate the end fixture acted by the sealing punches. Coulomb friction model was used in the simulation and the friction coefficient was assigned to be 0.12.

The initial thicknesses of the two tube blanks are 2.8 mm and 2.3 mm respectively. Both of the tubes have the outer diameter of 40 mm. The length of the thinner tube and thicker tube are represented by \( L_n \) and \( L_k \), and the length of the expansion zone is represented by \( L \).

In TWT hydro-bulging with dissimilar thickness, the place of weld-seam directly determines the ratio of the thicker tube length to the whole TWT length (so called length ratio), which would affect stress and strain state in the TWT. Represented by \( \eta \), the length ratio can be calculated by the equation \( \eta = L_k / L \). The TWTs with different length ratios were hydro-bulged to show the effects of the length ratio on expansion limit, weld movement and deformation characteristics of the TWT.

### Analysis of Deformation Characteristics of TWT Hydro-bulging

Simulation on hydrobulging without die cavity, as shown in Fig. 2, illustrates the deformation characteristics of the TWT with dissimilar thickness.

In this model, there is no die cavity limit for the expansion zone of the part so tube blank can be expanded to the bursting limit freely.

### Characters of plastic deformation extending

The effective stress distributions on the TWT during hydro-bulging are shown in Fig. 3 according to the simulated results of the TWT with \( \eta = 0.5 \). It can be seen that plastic deformation occurs firstly at the middle zone of the thinner tube. With the increase in pressure, the plastic region extends towards both ends simultaneously. However, as for the thicker tube, the
plastic region occurs firstly at the end adjacent to the weld-seam, and then extends to another end gradually with the pressure increasing. Because of the deformation of the thicker tube lags behind the thinner tube in a great degree, the expansion ratios of the two parts on the TWT have a big difference, which induces the poor deformation compatibility.

**Effects of length ratio on geometry of TWT**

To illustrate the effect of length ratio on the deformation, finite element simulations and experiments were carried out for various length ratios ranging 0.35-0.80. The shapes when the TWT with different length ratios were bursted are shown in Fig. 4.

In order to quantify the deformation compatibility, a coefficient $c$ is defined as the ratio of the maximum diameter on the thinner tube after bulging to that of the thicker tube, which is named as compatibility coefficient. If the compatibility coefficient is equal to 1.0 ($c = 1.0$), the expansion ratio of the two parts of a TWT are identical and means the best deformation compatibility is obtained. The compatibility coefficients for TWTs with different length ratios are drawn in Fig. 5 according to the simulated results and experiments. It can be seen that higher the length ratio, better the deformation compatibility. When the length ratio is equal to 0.8, the compatibility coefficient is about 0.9. This means there is only slight difference between the maximum expansion ratio of the thinner tube and the thicker tube. The results reveal that increasing length ratio of TWT might be an effective method to improve the deformation compatibility of TWT hydro-bulging.

**Analysis of strain state**

For hydro-bulging 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 ($\sigma_t$) as zero. Assuming that $\sigma_z$ is a stress along the longitudinal direction, and $\sigma_\theta$ is a stress along the hoop direction of the tube, and then according to Mises yielding criterion, the yielding condition of the tube under plane-stress state could be described as an ellipse shown in Fig. 6. Based on the simulated results, the stress paths of the two typical points, point $N$ and $K$ on the thinner tube and the thicker tube as shown in Fig. 2, can be recorded in Fig. 6 for different length ratios respectively.

It can be seen that there are biaxial tensile stresses acting on both of the tubes, but the stress paths locate at different zones of strain state. The stress paths of
the thinner tube locate at zone A (where, \( \sigma_z > \sigma_\theta / 2 \)),
with strain states of \( d\varepsilon_\theta > 0 \) and \( d\varepsilon_z > 0 \).
Therefore, the deformation pattern of the thinner tube is biaxial
elongation along the longitudinal and the hoop direction.
Moreover, bigger the length ratio, more the stress paths offset
the dividing line of \( d\varepsilon_z = 0 \), consequently higher the tensile stain along
longitudinal direction.

Nevertheless, the stress paths of the thicker tube
locate at zone B (where, \( \sigma_z < \sigma_\theta / 2 \)),
with strain states of \( d\varepsilon_\theta > 0 \) and \( d\varepsilon_z < 0 \).
Therefore, the deformation pattern
of the thicker tube is single-axial elongation along the
hoop direction.

**Factors of Deformation Compatibility**

Hydroforming of TWT has the characteristics of
axisymmetric deformation of thin shell. According to
the Laplace equation shown in Eq. (1), the instant
pressure is derived as shown in Eq. (2).

\[
\frac{\sigma_H - \sigma_z}{t} - \frac{\sigma_z}{R_z} - \frac{\sigma_\theta}{R_\theta} = 0 \quad \text{... (1)}
\]

where,

\[
\sigma_H - \text{stress in thickness direction;}
\sigma_z - \text{longitudinal stress; \( \sigma_\theta \) - hoop stress;}
t - thickness; \( R_z \) - longitudinal curvature radius;
R_\theta - hoop curvature radius
\]

So,

\[
p = \sigma_H = \left( \frac{\sigma_z}{R_z} + \frac{\sigma_\theta}{R_\theta} \right) t \quad \text{... (2)}
\]

For tube hydro-bulging, when there is no axial
feeding and the same expansion ratio takes place,
with the ratio of length to diameter decreasing,
the longitudinal curvature radius decreases,
but stress ratio of \( \sigma_z \) to \( \sigma_\theta \) increases,
the thickness \( t \) varies slightly. Therefore,
according to Eq. (2), the pressure needed for bulging increases
with decrease in the ratio of length to diameter.

In terms of the TWT hydro-bulging with dissimilar
thickness, the bigger the length ratio, the less
the length of the thinner tube. Therefore,
the pressure needed for bulging of the thinner tube increases
with the length ratio. Consequently, the expansion ratio of
the thicker tube is increased.

Experiment and simulation verified the analysis.
For TWTs with different length ratios, when the
expansion ratio of the thinner tubes reaches 40%,
the pressures needed for bulging are as shown in Fig. 7,
which increase with length ratio.

On the other hand, work-hardening plays a role on
improving deformation compatibility. The initial
yielding pressure for the tube within bulging can be calculated by Eq. (3).

\[ p = \frac{2t}{d} \sigma_s \]  \quad \ldots (3)

where \( p \) is pressure, \( t \) is thickness, \( \sigma_s \) is yielding stress and \( d \) is diameter.

As for the TWT with same material, the initial yielding pressures for the two segments of TWT depend on their initial thickness. Therefore, the thinner tube undergoes deformation firstly. Due to work-hardening after some degree of deformation, the pressure needed for continuous deformation increases to a higher level. When the pressure reaches to the initial yield pressure of the thicker tube, the thicker tube starts to deform. The higher the work-hardening exponent of the thinner tube, easier the thicker tube deformation starts.

In general, during hydro-bulging of TWT with dissimilar thickness, with increasing work-hardening exponent and length ratio, the difference of the expansion ratio between the thinner tube and the thicker tube can be reduced and the deformation compatibility can be improved.

**Weld-seam Movement of TWT Hydroforming with Dissimilar Thickness**

To facilitate the strain and thickness comparison between the thinner tube and the thicker tube, a double-diameter part was designed as shown in Fig. 8, which has two diameters of \( \Phi \) 40 mm and \( \Phi \) 52 mm respectively. To form the part from a TWT, a same expansion ratio of 30\% will occur at the two segments of the TWT under the contra of the die cavity with the shape of the formed profile.

**Effect of length ratio on weld-seam movement**

Figure 9 shows the effect of length ratio on weld-seam movement. It can be seen that weld-seam
movement happens with similar values at any length ratio. The effect of length ratio is slight. The value of the weld-seam movement decreases from 1.44 mm to 1.3 mm as the length ratio increases from 0.35 to 0.80.

As mentioned earlier, in TWT hydroforming, obvious non-uniform deformation appears due to the unequal thickness between thinner tube and thicker tube. In order to describe the process of the weld-seam movement clearly and quantificationally, a coefficient $\delta$ is defined. Assuming the length of the part attached to the die surface is $L$, the ratio of the length $L$ to the initial length of the thinner tube $L_n$ can be defined as a forming ratio represented by $\frac{\delta}{\gamma}$. When $\delta = 1$, it means the thinner tube has been formed completely.

The relations between weld-seam movement and the forming ratio are shown in Fig. 10. It can be seen that the weld-seam movement mainly occurs during the ending of the thinner tube deformation, especially when $\eta < 0.5$. About 80% of the weld-seam movement happens during the forming ratio increases from 0.8 to 1.

Effects of weld-seam movement on thinning

During hydroforming of TWT, if the tube material attaches to the die surface, it is difficult to be deformed and moved continuously due to the friction force under the high internal pressure. Therefore, the weld-seam movement mainly affects the deformation in the zone which has still not attached to the die during the ending stage of the hydroforming.

Figure 11 shows the axial strain distribution near the welding seam. It can be found non-homogeneous axial strain happened in the TWT. The average axial strain of thinner tube is bigger than that of thicker tube. There is obviously sharp increasing of axial strain in the zone of thinner tube near the weld-seam. On the contrary, sharp decreasing of axial strain, in the zone of thicker tube near the weld-seam, occurred.

For comparing the thickness variation in the two segments of the TWT, thinning ratio is analyzed. Thinning ratio means the ratio of thickness variation $\Delta t$ to the initial thickness $t_0$ of the tube blanks. The thinning ratio distribution of the part (shown in Fig. 8) along axial direction is shown in Fig. 12.

It can be seen that the thinning ratio is also uneven, although everywhere have the same expansion ratio and axial constrains were carried out. The average thinning ratio of the thinner tube is bigger than that of the thicker tube. The maximum thinning ratio took place on the thinner tube near the weld-seam. On the contrary, the minimum thinning ratio took place on the thicker tube near the weld-seam. Consequently, sudden and large fluctuation of thinning ratio appeared nearby the weld-seam.

Conclusions

The following conclusions can be drawn from this study:

(i) Plastic deformation first occurs in the middle zone of the thinner tube and then extends towards two ends simultaneously with increasing pressure. As for the thicker tube, the plastic region occurs firstly at the end adjacent to the weld-seam and then extends to another end.

(ii) There are differences in strain state between the thinner tube and the thicker tube. Tensile strain in longitudinal direction occurs on the thinner tube but contrarily compressive strain occurs on the thicker tube along the longitudinal direction.

(iii) Work-hardening and increasing of length ratio can reduce the difference in expansion ratio between the thinner tube and the thicker tube and improve the deformation compatibility.

(iv) Weld-seam movement happens during hydroforming of the tailor-welded tube which affects the strain and thinning ratio distribution.

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