Investigation on Corner Filling Process in Hydroforming of Thin-Walled Aluminum Alloy Tubular Part with Polygonal Sections

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Bursting at the corner during calibration stage is a popular failure mode in hydroforming process of tubular part with polygonal sections. Bending of thin-walled tube is also a big obstacle for hydroforming process, especially for aluminum alloy tube. In this paper, a thin-walled aluminum alloy tubular part with polygonal sections was hydroformed with the step of hydro-bending, preforming and hydroforming. The influence of internal pressure during bending was discussed. Corner filling process of a symbol section was analyzed, such as filling sequence, corner shape changing and thickness distribution. The corner with less expansion ratio contacted the die first and thickness reduction is smaller. Bursting occurred in the corner with big expansion ratio. If the corner is located in the outer side of bending arc, danger of bursting is more severe. The key factor is to maintain a sound shape for the section before calibration to keep the expansion distribution evenly.

Keywords: tube hydroforming, aluminum alloy, thin-walled tube, hydro-bending, corner filling

1. Introduction

Due to the curved axes and various sections, material utilization efficiency of the hydroformed tubular part is higher contrast to that of stamping and welding part. The general forming procedure of hydroformed part is bending, preforming and hydroforming. In the ideal condition, the section of the tube after preforming is similar to the final shape of the section except the corner. Thus the calibration process is actually a corner filling process. Aluminum alloy has high strength to weight ratio and good resistance to corrosion, so it is wildly used in the aerospace and aircraft industry, and has great potential in the automobile industry. But the formability of aluminum alloy is relatively low contrast to steel; the risk of bursting is aggravate because of the uneven forming of the corner. The use of aluminum alloy is restricted.

Wrinkles in the inner side of bending arc and severe thinning in the outer side of arc are popular failure modes in thin-walled tube bending. The CNC (Computer Numerical Control) bending is a popular bending method for thin-walled tube. With the flexible mandrel balls and anti-wrinkle block used in the process, wrinkles in the inner side can be effectively avoided. The disadvantage of the CNC bending is that this method does not suit for bending tube with double or more bending radius arcs. The other shortcoming is that tube diameter is restricted by the CNC bending machine.

Hydro-bending method is a new method for bending thin-walled tube. Because the tube is supported by the internal pressure, wrinkling behavior in the inner side of arc was restrained, especially for tube with variable bending radius. And unlike the CNC bending, the tube diameter is unlimited because the die size could be big enough.

Hwang carried out hydroforming experiment of 6063 aluminum tube with rectangular sections and the total elongation is 13.9%. The working hardening exponent n is 0.258.

2. Material Property and Part Analysis

2.1 Material property

The material used in the experiment is 5A02 aluminum alloy tube. The outer diameter of the tube is 63 mm, and the thickness is 1 mm. Tube was annealed before deformation. The property of tube was gotten by the single stretch test. The yield stress $\sigma_y$ is 80 MPa, the ultimate stress $\sigma_b$ is 183 MPa and the total elongation is 13.9%. The working hardening exponent n is 0.258.

2.2 Part analysis

The thin-walled tubular part and seven symbol sections are shown in Fig. 1. The dimension of the sections is shown in Table 1.

The thin-walled tubular part and seven symbol sections are all larger than original tube diameter.
and heights of sections are smaller than the tube diameter. The expansion ratio of section D-D is 4.78% which is biggest in all sections. Meanwhile section D-D is located in the center area of the bending arc, the probability of bursting is largest. So the analysis was focused on deformation of section D-D.

The forming procedure of the part is hydro-bending, preforming and hydroforming, as shown in Fig. 2. First the tube was bent and preformed in the vertical direction, and then the tube was rotated 90° and was put in the hydroforming die to finish the curve in the horizontal direction. Then the tube was calibrated after die-closing.

3. Experiment of Hydro-Bending

3.1 Bending part design

The bending part was designed according to the final part. The bending part is unsymmetrical and consists of three arcs as shown in Fig. 3. The outer diameter of the bending part is 63 mm. The radius of the central arc is 2.86 times of the original tube diameter and the bending angle is 39°. The radius of the left arc and right arc are both 1.14 times of tube diameter. The bending angle is 27° for the left arc and is 12° for the right arc respectively. The distance between the central arc and the left arc is 25 mm while the distance is 171 mm for the right arc. The sketch of hydro-bending with tube ends constraint was shown in Fig. 4. The tube ends were constrained and kept at the initial position during the whole bending process. The experiment was carried out on a four-column press. The internal pressure was kept constant during the bending process.

3.2 Experimental results

The bent tubes under different pressure are shown in Fig. 5. When there was not internal pressure, the tube was crashed. When the internal pressure was 2.2 MPa, one wrinkle appeared in the inner side of the arc. When the pressure was elevated to 2.4 MPa, the wrinkle obviously diminished. When the internal pressure was 2.8 MPa, the wrinkle disappeared. The depth and width of wrinkles were measured as shown in Fig. 6 and the results are shown in Table 2. With the increase of the internal pressure, the dimension of the wrinkle reduced and the wrinkles disappeared when the pressure was bigger than 2.8 MPa.

The axial thickness distribution along the inner and outer sides is shown in Fig. 7; thinning occurred along the outer side of the arc. When the internal pressure was 2.8 MPa, the maximum thickness reduction occurred at point B which is located the outer side of the central arc and the thinning strain rate was −10.7%.

### Table 1 Dimension and expansion ratio of sections

<table>
<thead>
<tr>
<th>Section</th>
<th>A-A</th>
<th>B-B</th>
<th>C-C</th>
<th>D-D</th>
<th>E-E</th>
<th>F-F</th>
<th>G-G</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width b/mm</td>
<td>69.24</td>
<td>71.17</td>
<td>72.00</td>
<td>73.74</td>
<td>72.66</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Height h/mm</td>
<td>58.09</td>
<td>50.53</td>
<td>48.00</td>
<td>49.46</td>
<td>54.22</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Radius of the corner r/mm</td>
<td>27.00</td>
<td>21.30</td>
<td>19.00</td>
<td>22.00</td>
<td>28.60</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Diameter d/mm</td>
<td>65.50</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>65.50</td>
</tr>
<tr>
<td>Expansion ratio η/%</td>
<td>3.97</td>
<td>3.96</td>
<td>4.28</td>
<td>4.78</td>
<td>3.91</td>
<td>4.12</td>
<td>3.97</td>
</tr>
</tbody>
</table>

![Fig. 1 Thin-walled tubular part.](image)

![Fig. 2 Forming procedure of thin-walled tubular part.](image)

![Fig. 3 Designed bending part.](image)

![Fig. 4 Sketch of Hydro-bending with tube ends constraint.](image)
4. Hydroforming Experiment

4.1 Experimental plan and device

The experimental device is shown in Fig. 8. It consists of upper die, lower die and sealing of the tube ends. The experiment was finished at different pressure from 6 to 10 MPa. The interval was 1 MPa. The PE film was used as lubricant.

4.2 Corner filling sequence at symbol section

The corner definition of section D-D and the relation between internal pressure and the corner radius are shown in Fig. 9. The corner \( r_1 \) and \( r_2 \) are in the inner arc of die-close bending (horizontal direction) while \( r_1 \) and \( r_4 \) are in the outer arc of hydro-bending (vertical direction) as shown in Fig. 2. The size of the four corners is different before calibration. The radius of corner \( r_4 \) is the largest, 27 mm. The radius of corner \( r_2 \) is smallest, 22 mm. The corner \( r_2 \) touched the die first while the corner \( r_4 \) touched the die in the end.

4.3 Thickness distribution at symbol section

The thickness distribution of section D-D is shown in Fig. 10. For corner \( r_1 \), \( r_2 \) and \( r_3 \), the maximum thickness reduction occurred at the transition point between the corner

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Table 2  Dimensions of wrinkles under different internal pressure.

<table>
<thead>
<tr>
<th>Internal pressure ( p/\text{MPa} )</th>
<th>Dimension of the wrinkle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Depth ( h/\text{mm} )</td>
</tr>
<tr>
<td>2.2</td>
<td>2.58</td>
</tr>
<tr>
<td>2.4</td>
<td>1.46</td>
</tr>
<tr>
<td>2.6</td>
<td>0.72</td>
</tr>
<tr>
<td>2.8</td>
<td>0</td>
</tr>
<tr>
<td>3.0</td>
<td>0</td>
</tr>
</tbody>
</table>

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Fig. 5 Bent tube under different internal pressure.

Fig. 6 Sketch of dimension of wrinkles.

Fig. 7 Axial thickness distribution (2.8 MPa).

Fig. 8 Hydroforming device.

Fig. 9 Relation between corner radius and pressure (D-D).

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and the straight line. The thickness reduction at corner $r_4$ was the largest, the minimum thickness is 0.802 mm and the thinning strain was $-19.8\%$.

If the press distance of preforming is not enough, then the distance between corner $r_4$ region and the die cavity will be larger and the thickness reduction will be severe, and accordingly bursting will occur in this area, as shown in Fig. 11.

5. Numerical Simulation

5.1 Model of simulation

The commercial code LS-DYNA was used to carry out the multi-stage simulation. The tube blank was modeled as isotropic material obeying Von Mises criterion and meshed by Belytschko-Tsay shell elements. Coulomb friction model was used and the friction factor was assigned to be 0.05.

5.2 Hydro-bending

The stress state at symbol point A and B was obtained when the downward distance of the upper die was 20 mm. The positions of point A and B are shown in Fig. 7. The stress states at the two points under different pressure are shown in Figs. 12 and 13. With the increase of the internal pressure, the axial compressive stress at the inner side is decreasing and the hoop tensile stress at the outside is increasing.

5.3 Forming process at symbol section

The shape change in section D-D is shown in Fig. 14. After preforming, the section is anomalous, as shown in Fig. 14(a). The upper half is raised and the lower half is nearly straight. The section D-D changed to the trapezoid after the tube rotated and hydroforming die closed, as shown in Fig. 14(b). Corner $r_1$, $r_2$ and $r_3$ nearly touched the die. Radius of the corner $r_4$ was largest.

5.4 Process of contacting die and mechanism of bursting

The equivalent strain and shape of section D-D under different internal pressure are shown in Fig. 15. Seven points were chosen for measurement of the displacement and the equivalent strain. For corners $r_2$ and $r_3$, the material nearly touches the die after die-closing. The corner $r_4$ touched the die last. When the internal pressure reached 4 MPa, point 1 is nearly touching the die, and the equivalent strain of point 1 increased from 0.132 to 0.142. The reason is that the material from corner $r_4$ could feed to corner $r_1$ because the tube material close to point 7 is free.

When the internal pressure reached 8 MPa, the expansion concentrated at corner $r_4$ and the equivalent strain of point 7 increased very fast from 0.125 to 0.200. Because the expansion was totally limited at corner $r_4$, the equivalent strain increased to 0.287 when the internal pressure is 10 MPa. And the thickness strain was $-20\%$, thus bursting easily occurred there.
6. Conclusion

(1) Internal pressure decreased the axial compressive stress and wrinkling tendency was weakened. But the hoop tensile stress in the outer side of bent arc became larger with the increase of the internal pressure.

(2) The analysis of equivalent strain showed that the change in the maximum equivalent strain occurred in the region of last filling corner. Thus bursting easily occurred there. The key factor is to make the material distribution even before calibration.

Acknowledgments

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