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# Influence of tube ends constraint on hydro-bending of thin-walled aluminum tube

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**Abstract:** The hydro-bending of thin-walled aluminum tube was researched by numerical simulation and experiments. The effects of internal pressure and tube ends constraint were analyzed. The stress state of symbol point during bending process was analyzed with tube ends constrain. The results show that wrinkling behavior is lightened when the tube is bent under higher pressure. But if the pressure exceeds the plastic deformation pressure, the tube will be pushed out of the die during the die-closing process. The bending quality is improved with tube ends constraint. The reason is that the inner tensile stress produced due to the constrained tube ends impairs the compressive stress in the inner arc of bending.

**Key words:** aluminum alloy; hydro-bending; thin-walled tube; constraint; internal pressure

## 1 Introduction

Thin-walled aluminum bent tube has been wildly used in aerospace, aviation and correlative high-tech industries [1−2]. With the increase of the diameter to thickness ratio, such defects as wrinkling and cross-section distortion are easy to occur [3]. So the difficulty of bending is increased with the accretion of the diameter to thickness ratio.

The simplest method to avoid winkling and reduce cross-section distortion is filling tube with sands, colophony or some kinds of compounds with lower melting point. The disadvantage is that the supporting effect cannot be precisely controlled. So the improvement on bending results is limited.

The computer numerical control (CNC) 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. Cross-section distortion is also under control [4−8]. Friction and axial compressive loads also have important influence. Decreasing the friction between mandrel, wiper and tube, or increasing the friction between pressure die, bending die and tube is helpful for improving the section quality [9], while the axial push assistant velocity affects tube wall thinning slightly [10]. Larger friction can improve the outside tube wall thinning, while it can also increase the inside tube wall thickening, which is possible to produce wrinkling.

With the characteristics mentioned above, CNC bending method is suitable for aluminum alloy tube. For example, the thin-walled 5A02-O aluminum tube with the diameter to thickness ratio of 50 ($d$50 mm×1 mm) was successfully bent with proper mandrel ball, process parameter and die structure [11]. The 5052 aluminum tube with the diameter to thickness ratio of 46.7 ($d$70 mm×1.5 mm) was also bent successfully. The cross-section distortion was less than 5% [12].

The fatal shortcoming of the CNC bending is that this method is not suitable for bending tube with double or more bending radius arcs. The other disadvantage 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 was supported by the internal pressure, the wrinkling in the inner side of arc was restrained, especially for tube with variable bending radius [13−15]. And unlike the CNC bending, the tube diameter is unlimited because the die size could be large enough.

In this work, the numerical simulation and experiments on bending a thin-walled aluminum alloy tube were carried out. The influence of tube ends constraint was analyzed, and the difference of stress state was analyzed.

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## 2 Experimental

### 2.1 Principle of hydro-bending

The process of hydro-bending without tube ends constraint is shown in Fig. 1(a). First, the tube is sealed and put into the lower die. Then, liquid is filled into the sealed tube and liquid pressure is set to a designed value. The tube is bent by closing the upper die. With the support of the internal pressure, the cross-section distortion is restrained and an axial tension force is produced by the action of the internal pressure on the sealing. Because only bending die and press are needed, this method is especially suitable for bending big diameter tube.

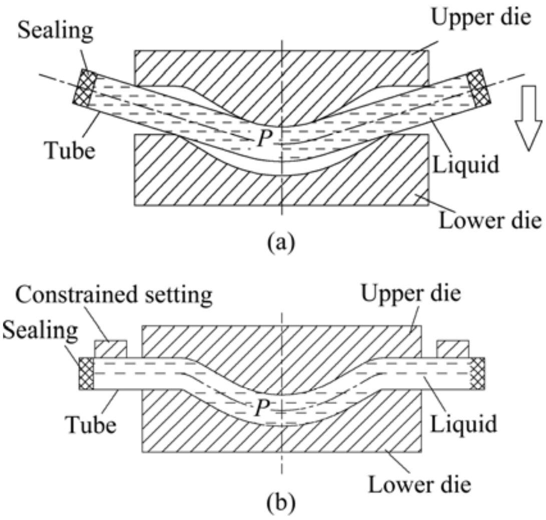


**Fig. 1** Process of hydro-bending: (a) Bending without tube ends constraint; (b) Bending with tube ends constraint

Bending process with tube ends constraint is shown in Fig. 1(b). The tube ends are constrained and kept at the initial position during the whole bending process. When the tube ends are unconstrained, it will turn up while the central area of the tube is pressed by the upper die at the beginning of the bending.

The cross-section distortion is represented by the non-circularity and the non-circularity is calculated by

$$U = \frac{d_{\max} - d_{\min}}{d} \times 100\% \tag{1}$$

where $U$ is the non-circularity; $d_{\max}$ is the maximum diameter of the section after bending; $d_{\min}$ is the minimum diameter of the same section; and $d$ is the diameter of original tube.

### 2.2 Research plan

The annealed 5A02 aluminum tube was used in the experiment. The out diameter of the tube was 63 mm and the thickness was 1 mm. The mechanical properties were obtained by the single stretch test, which is shown in Table 1.

**Table 1** Properties of aluminum alloy tube

| Yield stress, $\sigma_s$/MPa | $K$/MPa | $n$ |
|---|---|---|
| 76.57 | 350 | 0.258 |

The tube was unsymmetrical and consisted of three arcs in the part totally, as shown in Fig. 2. The outer diameter of the tube was 63 mm and the thickness was 1 mm. The radius of central arc was 2.86$d$ and the bending angle was 39°. The radii of the left and right arc were 1.14$d$.

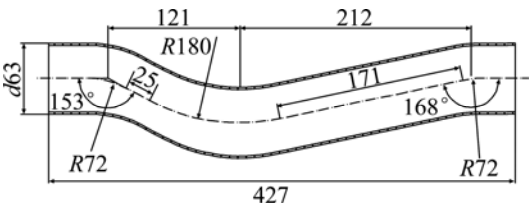


**Fig. 2** Part with three arcs

The bending angle was 27° for the left arc and 12° for the right arc. The distance between the central arc and the left arc was 25 mm while the distance was 171 mm for the right arc.

The research plan of numerical simulation and experiment is shown in Table 2. The tube was bent under different internal pressure while the tube ends were constrained or unconstrained. The internal pressure was kept constant during the bending process.

**Table 2** Research plan of numerical simulation and experiment

| No. | Tube ends condition | Internal pressure/ MPa | Pressure interval/MPa |
|---|---|---|---|
| 1 | Unconstrained | 1.8−3.4 | 0.2 |
| 2 | Constrained | 1.8−3.4 | 0.2 |

The commercial code LS-DYNA was used in the simulation. The tube blank was modeled as isotropic material obeying Mises criterion and meshed by Belytschko-Tsay shell elements. Coulomb friction model was used in this simulation and the friction factor was assigned to be 0.125. The die was meshed by rigid element. The simulation model is shown in Fig. 3.

The experiment was carried out on a four-column press with the maximum closing force of 5 MN. The internal pressure was supplied by a manual controlled pump. The experiment device with tube ends constraint is shown in Fig. 4.

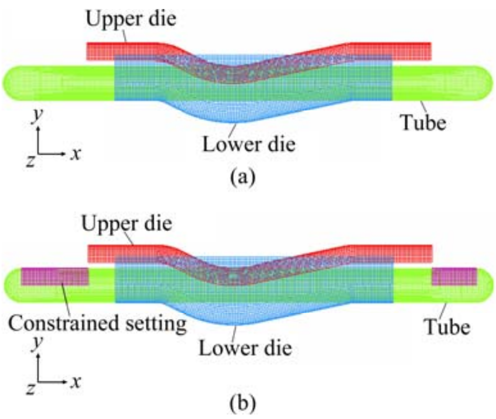


**Fig. 3** Simulation model: (a) Tube ends unconstrained; (b) Tube ends constrained

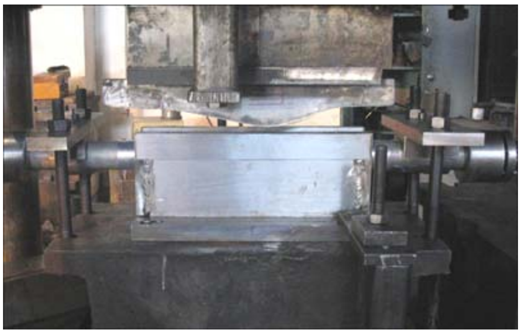

**Fig. 4** Experiment device with tube ends constraint

## 3 Results and discussion

### 3.1 Influence of internal pressure

The experimental result of plan 1 is shown in Fig. 5. When the internal pressure is 2.2 MPa, two wrinkles appear on the inner side of the arc. When the pressure is elevated to 3.0 MPa, wrinkles on the left side disappear. When the internal pressure is 3.4 MPa, the wrinkles on the right side disappear. But the tube was pushed out of the die cavity when closing the die, as shown in Fig. 6. The thin-walled tube cannot be bent successfully with tube ends constraint.

The symbol points *A* and *B* of central arc are shown in Fig. 7. The stress states of the two points at different pressures when the downward distance of the upper die is 20 mm are shown in Figs. 8 and 9. With increasing the internal pressure, the axial compressive stress on the inner side decreases and the axial tensile stress in the outside also increases.


**Fig. 5** Bent tube under different pressures (plan 1)


**Fig. 6** Bent tube at internal pressure of 3.4 MPa

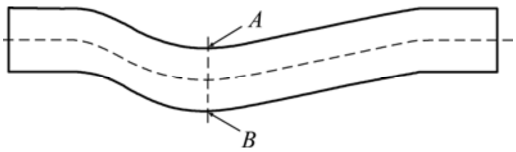


**Fig. 7** Location of measuring points

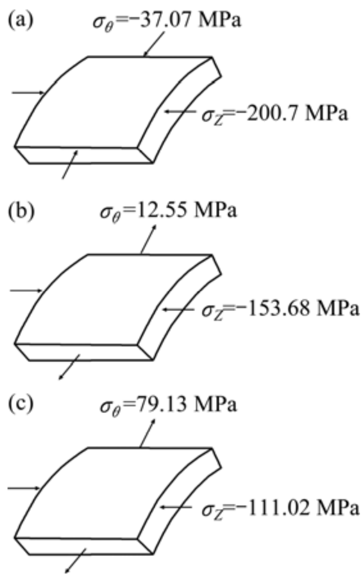


**Fig. 8** Stress state of point *A* at different pressures: (a) 2.2 MPa; (b) 2.6 MPa; (c) 3.2 MPa

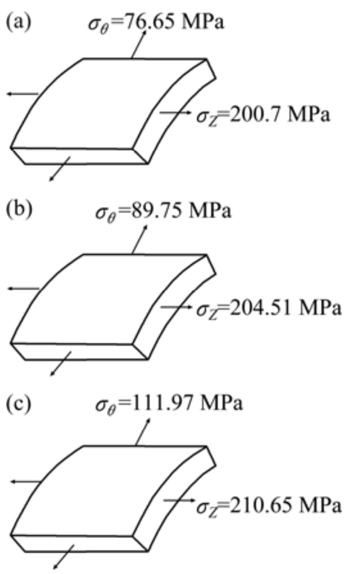


**Fig. 9** Stress state of point *B* at different pressures: (a) 2.2 MPa; (b) 2.6 MPa; (c) 3.2 MPa

### 3.2 Influence of tube ends constraint

3.2.1 Experiment results

The bent tubes with tube ends constraint (plan 2) are shown in Fig. 10. With the increase of the internal pressure, the wrinkling behavior is improved. When the internal pressure is 2.8 MPa, the wrinkles are eliminated.


**Fig. 10** Bent tube under different pressures (plan 2)

The thickness distribution and cross-section distortion of tube bent at 2.8 MPa are shown in Figs. 11 and 12, respectively. The maximum thickness reduction is 11% in the central arc. And the maximum non-circularity is 2.7% in the left arc.

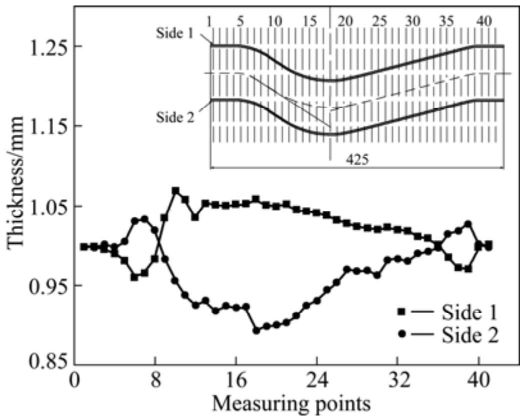


**Fig. 11** Thickness distribution of bent tube at 2.8 MPa

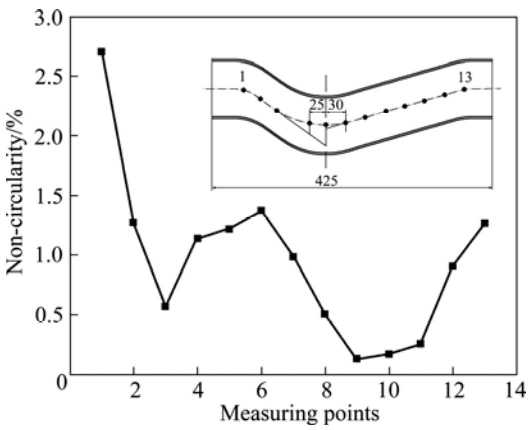


**Fig. 12** Distribution of non-circularity

3.2.2 Analysis of bending process with tube ends constraint

When there is no constraint, the two ends of the tube are supported by the down die with two fulcrums, as shown in Fig. 1(a). When the upper die moves downward, the tube between the two fulcrums will move downward while the tube in the outside of the two fulcrums will move upward.

When there is constraint, the tube ends are restricted and cannot move upward. As the tube has a tendency to move into the die cavity, the constrained setting will give a frictional force to the tube. The tensile force will decrease the axial compressive stress on the inner side of the arc, thus the wrinkles are eliminated.

The simulation result also shows that the axial stress is smaller when the tube ends are constrained. For example, when the internal pressure is 2.6 MPa, wrinkles appear with the tube ends free (Fig. 5) while the wrinkles are lightened with the tube ends constraint.

A symbol point $C$ was chosen to investigate the stress state of bending with and without tube ends constraint. The location of point $C$ is shown in Fig. 13. The vertical distance from the die touched point $C$ to die-closing is 34 mm.

The relationship between the die downward distance and the stress state of tube bending with and without tube ends constraint is shown in Fig. 14.

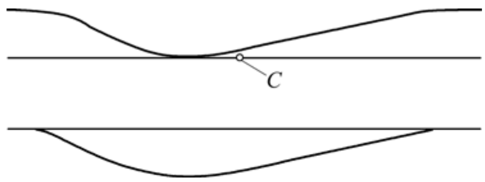


**Fig. 13** Location of symbol point $C$

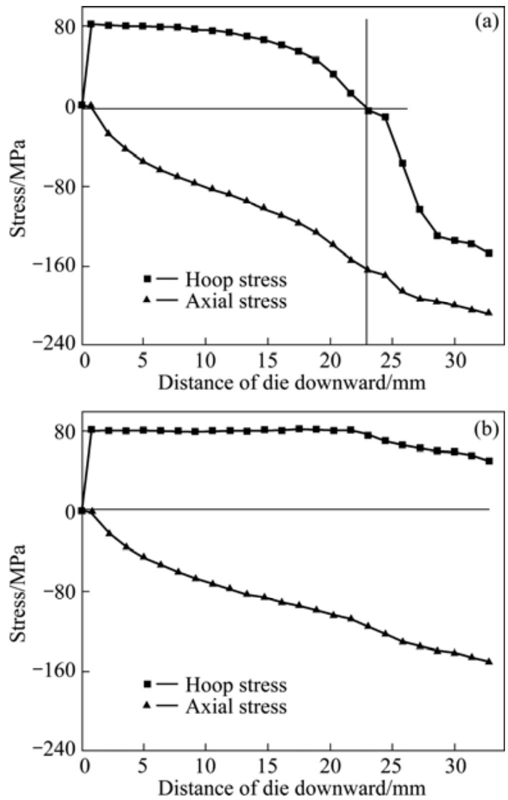


**Fig. 14** Relationship between die downward distance and stress state of symbol point: (a) Tube ends unconstrained; (b) Tube ends constrained

When the tube ends are free, the axial stress is compressive and increases with the growth of the downward distance as shown in Fig. 14(a). When the downward distance exceeds 23 mm, wrinkles occur. The hoop stress changes from tensile to compressive and the tube is in a two-dimension compressive stress state.

The relationship between the die downward distance and the stress state when tube ends constrained is shown in Fig. 14(b). The hoop stress for the point is tensile stress and the axial stress is compressive during the whole bending process. No wrinkles occur, and the value of the compressive stress is smaller than that when the tube ends is unconstrained.

## 4 Conclusions

1) With the increase of the internal pressure, the wrinkling behavior on the inner side of the arc is lightened. But if the pressure is too high, the tube will be expanded and pushed out of the die cavity in the die-closing process.

2) The minimum internal pressure to bend the tube successfully decreases with tube ends constrained. The axial tension stress is added by the tube ends constraint. The wrinkles behavior is lightened.

3) The thin-walled aluminum tube is successfully bent with tube ends constraint when the internal pressure is 2.8 MPa. The maximum thickness reduction is 11% and the non-circularity is 2.7%.

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# 管端约束对薄壁铝合金管材充液弯曲的影响

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**摘 要**：对薄壁铝合金管材的充液弯曲进行数值模拟与实验研究；讨论内压与管端约束对成形结果的影响；分析在管端约束的情况下充液弯曲过程中管材典型点的应力状态。结果表明：在充液内压较高的情况下，管材内侧的起皱现象得到减轻；但是，当内压超过管材发生塑性变形的内压时，管材会在弯曲合模过程中被挤出型腔。由于管端约束而产生的拉应力抵消了弯曲过程中内侧的压应力，管端约束情况下弯曲质量更好。

**关键词**：铝合金；充液弯曲；薄壁管；约束；内压

**(Edited by CHEN Wei-ping)**