

Effect of internal pressure distribution on thickness uniformity of hydroforming Y-shaped tube

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Abstract: The hydroforming of an integral thin-walled Y-shaped tube was investigated. With axial feeding, tube material can be pushed into the die cavity to form a higher protrusion height with relatively small thinning ratio. For the Y-shaped tube, however, owing to the high-friction forces acting at internal pressure in the guiding zone between the tube and die, less metal flows into the protrusion. A multistage punch was proposed to change the internal pressure distribution in the guiding zone and to reduce the friction force between the tube and the die. Experiments of hydroforming of aluminum alloy Y-shaped tube were carried out, in which two projects with traditional punch and multistage punch were applied to comparison. The thickness distribution and thinning ratio distribution were investigated, and the results by different punches were compared.

Key words: aluminum alloy; tube hydroforming (THF); Y-shaped tube; friction; thickness distribution

1 Introduction

Thin-walled tubular components of stainless steel and aluminum alloy are frequently used in pipe systems in some industry fields. With the high speed development of aerospace industry, the component requirements of lightmass, high-intensity, high-precision, high efficiency and low consumption were proposed. Hydroforming is an available process for manufacturing integral and high reliability tubular components without weld seams [1–2]. Moreover, higher reliability supplies possibility of reducing thickness further and is helpful for lightmass [3–4]. However, it has disadvantages due to many variables, such as loading paths, material formability and tribological conditions, which limit its applicability and influence parts failure (excessive thinning, wrinkling, buckling or bursting) [5–6].

Tribological system is an important part of hydroforming process which contains various elements, such as pressure, surface conditions, contact area and associated state of stress, materials, lubricant [7]. Friction condition in hydroforming is very critical, especially in parts where substantial axial feeding is

required. In such cases, lubricant is used to reduce the sliding friction and prevent sticking and galling to reduce tool wear, axial forces and buckling [8]. Usually, a friction coefficient is assumed in FEA to measure the friction in tube hydroforming process, and has various testing methods and apparatus. SCHMOECKEL et al [9–10] suggested a method by which friction coefficients can be tested in a guiding zone under internal pressure. DALTON [11] demonstrated the method to improve the friction conditions by using a square die to rank lubricants. A typical hydroforming process can be identified as three different frictions zones: the guided, transition and expansion zones, as shown in Fig. 1 [3]. The three zones are under different effects of axial force, feeding and geometrical aspects. Friction in the guiding zone is high. The tube and die surfaces are in contact under pressure and straight axial compression [10].

FIorentino et al [12] investigated the relation between THF and friction, showing the effect of lubricant between the tube and the die on the final characteristics of a hydroformed copper T-shaped tube by means of protrusion height and thickness distribution. In particular, it is shown that the punches compression forces (F) are gradually reduced by friction stresses (τ) as the distance

from the tube edges increases, as shown in Fig. 2 [12]. KOÇ [13] investigated the effect of T-shape tube length on the protrusion height and found that shorter protrusion height values result from longer tube length. It is concluded that longer guiding zone is influenced more obviously by friction, and thus less metal flows into the expansion zone. JIRATHEARANAT et al [14] also obtained the same result by forming a Y-shaped tube.

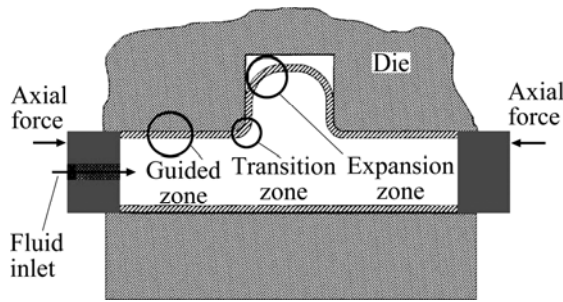


Fig. 1 Friction zone in THF [3]

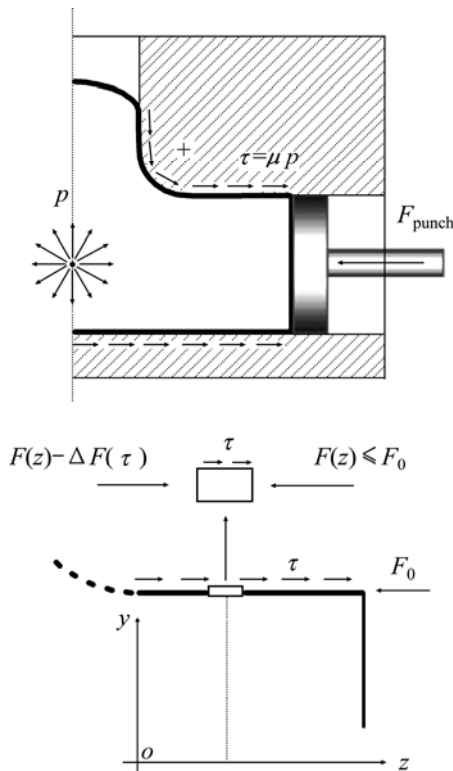


Fig. 2 Effect of friction stress on compression load [12]

Owing to the asymmetrical shape of the Y-shaped tube, the length of guiding zone is longer, and less metal flows into the protrusion, which is adverse to the thickness uniformity. In this work, a multistage punch was proposed to change the pressure distribution in the guiding zone and to reduce the effect of friction in the guiding zone. A number of Y-shaped tube hydroforming experiments were conducted to investigate the effect of different punches on thickness uniformity.

2 Principle of controlling internal pressure distribution

Due to the asymmetrical shape of the Y-shaped tube, a large unilateral punch feeding is needed such that the length of guiding zone is longer. With increasing the guiding zone length, the contact surface between the tube and the die is increased, and the axial compressive forces are gradually reduced. Meanwhile, under the action of the friction forces the feeding material flowing into the forming zone is limited. Such tube feeding effect is less efficient as the distance from the tube ends increases. It is also known that the friction is in fact the driving factor that makes this effect prominent. Longer guiding zone is influenced more obviously by friction, thus less metal flows into the expansion zone. Furthermore, as the friction prevents the material from moving in, thickening in edge regions of the tube tends to become severe when the guiding zone becomes longer. Therefore, less material is moved into the protrusion while the expansion through internal pressure application can lead to the thinning of the tube wall. Therefore, the deficient punch feeding to support the expansion may cause excessive thinning or bursting at the top of protrusion.

In order to weaken the effect of friction between the tube blank and the die, thus to improve the efficiency of the axial feeding, a multistage punch was applied to changing the internal pressure distribution in the guiding zone (Fig. 3). Figure 3(a) shows the schematic diagram of the traditional punch. Figure 3(b) shows the schematic diagram of the multistage punch, which seals the tube by multistage O-rings. The seal position can penetrate deeply inside the tube from tube ends, so that the seal section in the guiding zone would not sustain the effects of the internal pressure. Then, the normal compressive stress between the tube blank and the die surface can be reduced. Furthermore, there is a small gap between the multistage punch and the tube inner face so that it will not hinder the metal flow and can restrain wrinkles on the tube. Therefore, the friction force can be reduced, and more material can move into the forming zone. The punch feeding effect is more efficient, and the thickness at the top of protrusion can be improved.

Figure 4 shows the force analysis of guiding zone where F_x is the punch feed compressive force on the tube end, F_f is the friction force between the tube and the die, F_s is the force that has the tube plastic deformed. The contact pressure between the tube blank and the die surface can be assumed to be equal to the inner pressure (p), the length of guiding zone is L and the length of seal section is L_i , the inner radius and outer radius of the tube are R_i and R , respectively.

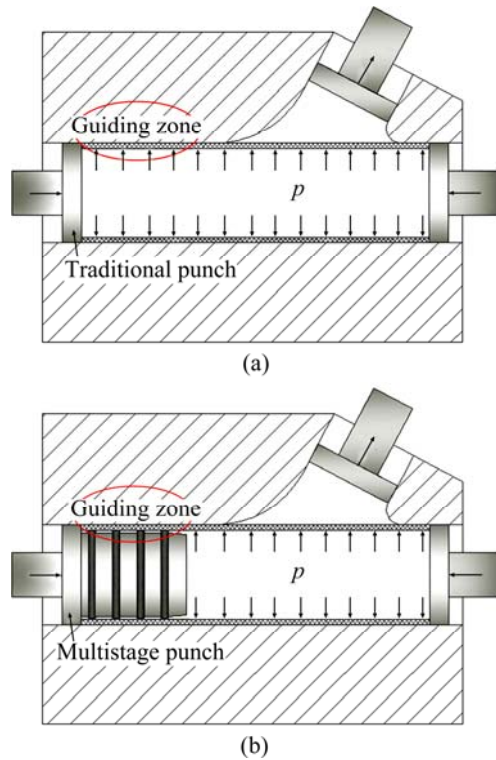


Fig. 3 Schematic diagrams of traditional punch (a) and multistage punch (b)

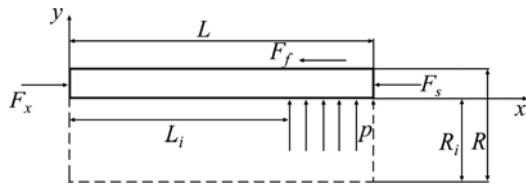


Fig. 4 Force analysis of guiding zone

The punch feeding compressive force on the tube end F_x is

$$F_x = F_f + F_s \quad (1)$$

$$F_f = 2\pi\mu p_i R_i (L - L_i) \quad (2)$$

$$F_s = (\pi R^2 - \pi R_i^2) \sigma_s \quad (3)$$

At the initial forming stage, for a given initial internal pressure, by using the traditional punch, all areas of the tube are under the effect of internal pressure, and the length of areas affected by the internal pressure is L . By using multistage punch, the length of areas affected by the internal pressure is $(L - L_i)$.

And then, the axial stress on the tube ends is

$$\sigma_z = \frac{2\mu p_i R_i (L - L_i)}{R^2 - R_i^2} + \sigma_s \quad (4)$$

The reduction of the friction force is defined as ΔF

by using multistage punch, and ΔF is

$$\Delta F = 2\pi\mu p_i R_i L_i \quad (5)$$

The reduction of the axial stress is defined as $\Delta\sigma_z$.

$$\Delta\sigma_z = \frac{\Delta F}{\pi R^2 - \pi R_i^2} = \frac{2\mu p_i R_i L_i}{R^2 - R_i^2} \quad (6)$$

It can be seen that the axial stress at the end of the tube is related to the friction coefficient, internal pressure, and the length of area affected by the internal pressure, initial tube length and yield strength of the tube material.

In this work, the tube with $R_i=47.5$ mm, $R=50$ mm and $\sigma_s=80$ MPa was adopted. The initial internal pressure is $p_i=7$ MPa, and the length of seal section is $L_i=90$ mm. Substituting these parameters into Eq. (6), the relation between the axial stress reduction on tube ends ($\Delta\sigma_z$) and the relative length of seal section (L_i/L) was obtained, as shown in Fig. 5. The axial force at the tube end decreases with increasing the length of seal section (L_i). These results are due to the smaller contact area of the friction. The friction coefficient is also an important factor for the axial force at the tube end. With the increase of friction coefficient, the effect of internal pressure distribution on the reduction of axial force ($\Delta\sigma_z$) at the tube end is more obvious.

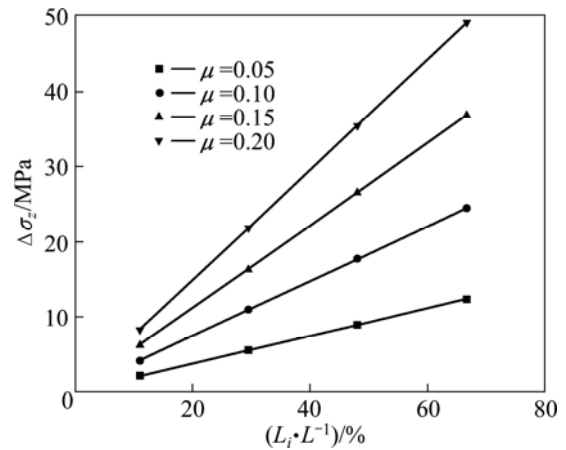


Fig. 5 Relation between $\Delta\sigma_z$ and L_i/L

3 Experimental tools and projects

The hydroforming experiments were conducted using the tools represented in Fig. 6. The tube was positioned in the die and sealed at the ends by the axial punch. The counter punch was used to control the protrusion height and avoid over-thinning or bursting at the top of the protrusion. The three punches are controlled in position and the left punch is hollow to enable the tube filling with high-pressured water.

Owing to the poor formability of the material, it is impossible to form the aluminum Y-shaped tube through one step THF. A two-step THF was carried out. In the

preforming stage, a counter punch with a slope top was applied to changing the stress state at the top of protrusion, and this method was used to produce the thin-walled Y-shaped tubes [15]. Two experimental projects were proposed to compare the results as the same loading path was used. Project (a) used traditional punch as the left punch to seal, and project (b) used multistage punch as the left punch to seal. Figure 6 shows the experimental tools, in which the multistage punch was applied as the left punch with 4 O-rings sealing. And the length of seal section can be adjusted by changing the number of O-rings.

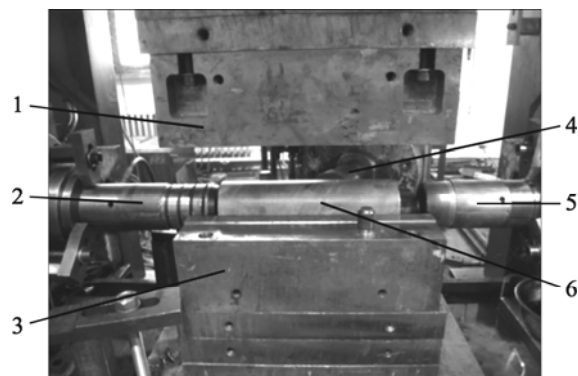


Fig. 6 Experimental tools: 1—Upper die; 2—Left punch; 3—Lower die; 4—Counter punch; 5—Right punch; 6—Tube blank

The material used as the thin-walled tube was aluminum alloy with an outer diameter of 100 mm, a length of 350 mm and a thickness of 2.5 mm. Table 1 lists the initial material and tube parameters used for the experiment. These parameters were determined through the tensile tests.

Table 1 Mechanical properties of tube blank (5A03)

σ_s /MPa	σ_b /MPa	δ_s /%	K /MPa	n
80	252	22	375	0.23

4 Results and discussion

4.1 Thickness distributions after preforming

Figure 7 shows the preforming part produced through the counter punch with a slope top. After preforming, the thickness distributions of preforming parts were measured. Figure 8 shows a comparison of thickness distributions of the two projects. Thinning ratio distributions are shown in Fig. 9.

It can be seen that the thickness distributions are basically the same, thickening occurs in the guiding zone and the transition zone, thinning occurs at the top of protrusion, and the thinnest point is located at the top of protrusion. Furthermore, thickening in edge regions of the tube tends to become severe when the tube becomes longer as friction prevents material moving in.



Fig. 7 Photo of preforming part

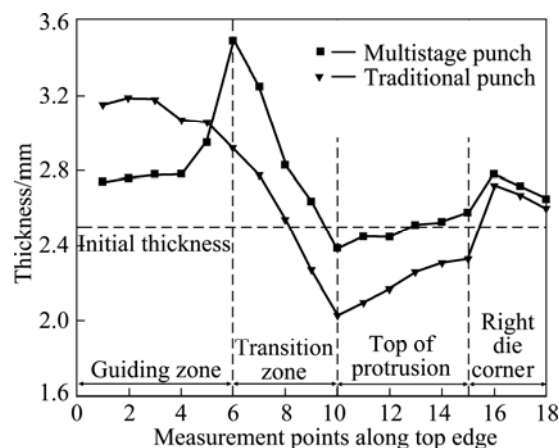


Fig. 8 Thickness distributions after preforming

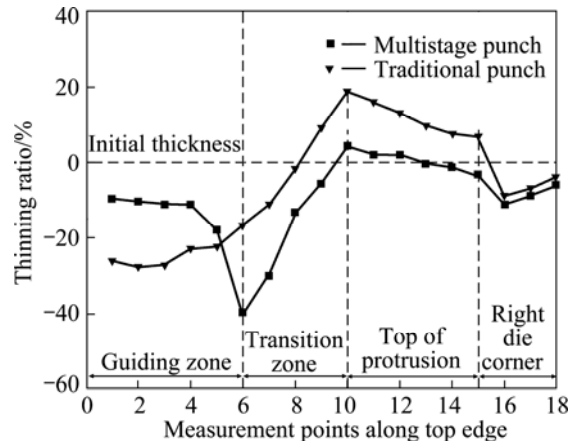


Fig. 9 Thinning ratio distributions after preforming

In the guiding zone, by using the multistage punch, the thickness distribution is relatively uniform. The thickness is about 2.78 mm, and thinning ratio is about -11%. By using the conventional punch, the maximum thickness is 3.2 mm, and the thinning ratio is about -24%. Comparing these two results, thickening is severe in the guiding zone by using conventional punch. Multistage punch can inhibit thickening in the guiding zone and is helpful to homogenize the thickness. In the transition zone, there is a sudden increase in wall thickness, and the maximum thickness is 3.5 mm because the tube feeding effect is more efficient by using multistage punch. In the same punch stroke, the material

feeding is increased. Unfortunately, thickening in the transition zone is severe as friction prevents material moving into protrusion. At the top of protrusion, by using multistage punch, the thickness is improved a lot. The minimum thickness is 2.39 mm, and the maximum thinning ratio is 4.4%. But by using traditional punch, the minimum thickness is only 2.03 mm, and the maximum thinning ratio is 18.8%. It can be seen that by using multistage punch, the tube feeding effect is more efficient, and it is available to improve the thickness distribution at the top of protrusion. On the right side of the part, the wall thickness is not very different because the same right punch was applied in the two projects.

4.2 Thickness distributions after final forming

Figure 10 shows the final forming part. After the final forming, the thickness distributions of final forming parts were measured. Figure 11 shows the comparison of thickness distributions of the two projects. The thinning ratio distributions are shown in Fig. 12.



Fig. 10 Photo of final forming part

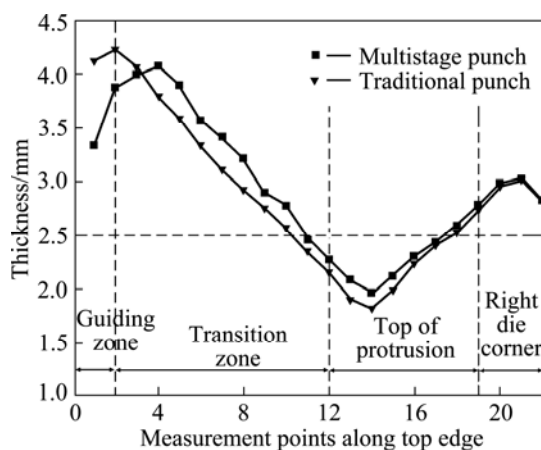


Fig. 11 Thickness distributions after final forming

It can be seen that the regulation of the thickness distribution is almost the same. At the top of protrusion, by using multistage punch, the minimum thickness is 1.96 mm, and the maximum thinning ratio is 21.6%. While by using traditional punch, the minimum thickness is only 1.81 mm, and the maximum thinning ratio is

27.6%. During the final forming process, the protrusion height is higher, so that the contact surface between the tube and the die increases. Meanwhile, higher internal pressure leads to larger friction forces that limit the material to flow into the forming zone. The effect of multistage punch is weakened as the process proceeds. Another reason is that the reduced length of guiding zone results in the reduced effect of multistage punch.

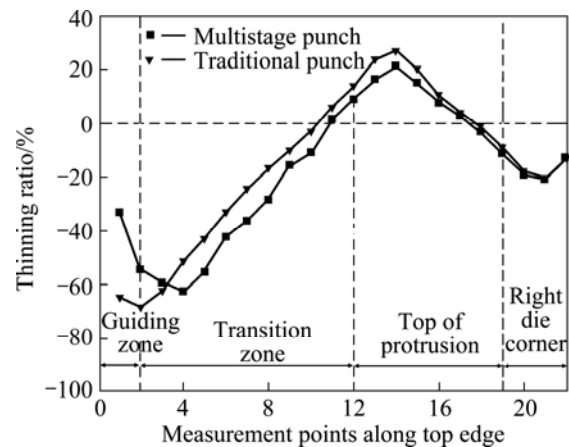


Fig. 12 Thinning ratio distributions after final forming

5 Conclusions

1) Through stress analysis, the axial stress on the end of the tube is a function of friction coefficient, internal pressure and length of the area acted by the internal pressure. The shorter the length, the lower the axial stress acted on the end of the tube.

2) The principle of controlling internal pressure distribution is proposed, in which a multistage punch is applied to controlling the internal pressure distribution in the guiding zone. The length of sealing section can be adjusted by changing the number of O-rings on the multistage.

3) Experiments verify the analysis and prove the effectiveness of the multiple stage punch. By using the multistage punch, the distribution of the internal pressure is shortened and then the friction force in guiding zone is reduced. The thickening ratio in the guiding zone is reduced by 20% and the thinning ratio is reduced by 6%. The axial feeding becomes easier and more efficient, so that the thinning ratio at the top of the protrusion becomes smaller and the thickness uniformity is enhanced.

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内压分布对内高压成形 Y 型三通管壁厚均匀性的影响

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摘 要: 对薄壁 Y 型三通管的内管压成形进行研究。通过轴向补料, 管材可以被推入模腔从而获得更高并且相对减薄率小的支管。但是 Y 型三通管的导向区较长, 在内压作用下管材和模具之间会产生较大的摩擦力, 使得材料难以流入支管。提出了采用多段式冲头用来改变导向区的内压分布并且减小导向区的摩擦力的方法。对铝合金 Y 型三通管进行内高压成形实验, 采取两种方案, 分别使用传统冲头和多段式冲头进行对比。对壁厚分布和减薄率分布进行研究, 并对使用不同冲头的结果进行对比。

关键词: 铝合金; 内高压成形; Y 型三通管; 摩擦; 壁厚分布

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