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# Hydro-forming of aluminum alloy complex-shaped components

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**Abstract:** Aimed at the high rejection ratio, poor dimensional precision and low fatigue durability for aluminum alloy complex-shaped components with a doubly curved surface, formed by conventional deep drawing and drop stamping, the hydroforming was used to investigate its formability. Based on numerical simulations and experiments, the deformation mode and the process were analyzed during hydromechanical deep drawing. The wrinkle and the fracture were discussed, and the stress state and stress value were explored in the area of defects. The results show that the reasonable chamber pressure to avoid the above defects is 10−30 MPa. According to the effects of loading paths on the thickness, a reasonable pressure of 20 MPa is determined finally.

**Key words:** aluminum alloy; sheet component; doubly-curved surface; chamber pressure

## 1 Introduction

In the sheet hydroforming process, the liquid chamber (or the lower die) is first filled with the liquid medium, and then the punch presses the sheet into the liquid chamber. Simultaneously, the established internal pressure pushes the sheet against the punch, and a lubrication film is formed that outflows between the bottom interface of sheet and the top surface of die [1]. Comparing with the conventional deep drawing, it has main advantages of high forming limit, high precision, good surface quality, less passes and lower cost [2−3]. At present, the researches on deep drawing are mostly focused on deep cylindrical cups with a large height-to-diameter ratio [4−7], and the materials include aluminum alloy, superalloy, carbon steel and stainless steel [8−11]. For aluminum alloy complex-shaped components, Amino North America Corporation did some research to reduce the mass of automobile, and the aluminum alloy autobody panels such as aluminum hood outer, aluminum fender, aluminum door inner and so on were applied to some luxury cars [12]. SPS Corporation developed 100 MN hydroforming machine, which was used to manufacture aluminum roofs of jeep. Prebulging and hydroforming were combined to improve the strain-hardening and structural stiffness [13]. For complicated components hydroforming, the above research shows that wrinkling is easy to eliminate. Based on the sheet hydroforming process, combining with the essential characteristic of deep drawing, several new methods were proposed to improve the forming limit [14−17]. By warm hydroforming, the limiting drawing ratio of 2.95 at room temperature can be increased to 3.3 at 100 °C for 1 mm thick SUS304 sheet. By hydro-forming with a circumferential pressurizing, the limiting drawing ratio of 3.3 can be reached for 1 mm thick 1050 aluminum sheet. By hydroforming with a controllable radial pressurizing, the limiting drawing ratio can be improved to 2.8 from 2.4 for 1 mm thick 5A06 aluminum alloy sheet. With a forward and backward pressurizing, the limiting deep drawing ratio of 3.5 can be reached for 0.8 mm thick DC04 carbon steel sheet.

Aluminum alloy is one of the main structure materials of launch vehicles and aircrafts. The manufacturing technology for sheet metal parts with complex curved surface in aerospace industry includes lift hammer forming (needing annealing during the processes) and manual repairing, and conventional deep drawing. For lift hammer forming, the main problems include a high rejection rate, a poor dimensional precision and an internal microstructure damage to affect the fatigue performance. Simultaneously, the tools made of lead and zinc pollutes the environment, and it is forbidden presently. For conventional deep drawing, due to a low plasticity of aluminum alloy, the main problems lie in needing multiple deep drawings and intermediate annealing, and a high rejection rate and a poor product

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quality is the main problem. With the application of high-strength aluminum alloys, the plastic forming of these materials becomes increasingly difficult.

Due to its complex curved surface and poor material performance, the aluminum alloy complex-shaped component with a doubly-curved surface is hard to fabricate. The wrinkling often occurs when the internal pressure is too small, whereas the fracturing takes place when the internal pressure is too high. Usually, the thickness distribution is affected by the internal pressure and loading path directly. So far, the research is very limited on the defects and wall thickness distribution for the hydroforming of aluminum alloy complex-shaped component. Aimed at the above problems, the hydroforming of aluminum alloy complex-shaped component with a doubly curved surface is investigated. This research will determine the practicability of hydroforming and lay a foundation for the application of hydroforming technology for aluminum alloy complex-shaped components.

## 2 Component and material

The geometry of the aluminum alloy complex-shaped component is shown in Fig. 1. The surface of the component consists of a cylindrical surface at the top and a doubly curved surface at the left end, and a flange exists. The depth of the component is 118 mm, and the opening distance from the left to the right is 194 mm. The fillet radius is 32.5 mm in the left of opening, and the radius is 131 mm at the transition from the curved arc to the straight line. The radius is 105 mm at the transition from the flange to the top, and the radius of cylindrical surface at the top is 78 mm. The radius of transition corner between the curved surface and the flange is 5 mm. The size is 156 mm from the front to the back of opening. A rectangular blank with cut corners was used in the paper. The dimension is 440 mm×360 mm×160 mm.

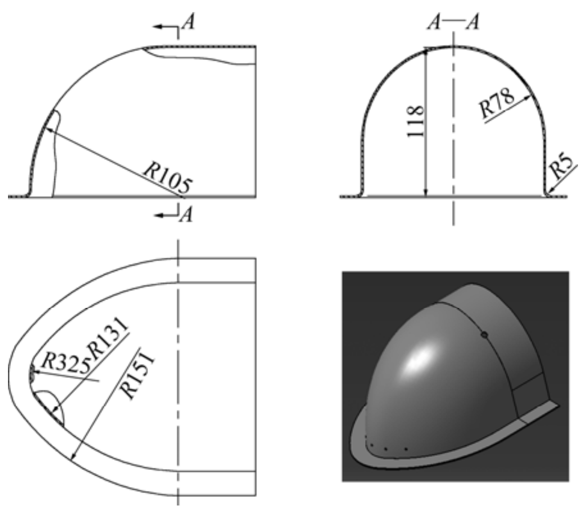


**Fig. 1** Geometry of component (unit: mm)

The material used in the experiment is 2A12 aluminum alloy with 1.5 mm thickness and the mechanical properties of the material are shown in Table 1.

**Table 1** Mechanical properties of 2A12 aluminum alloy

| Yielding stress/ MPa | Strength limit/ MPa | Elongation /% | Anisotropic parameter, $r$ | Hardening coefficient, $n$ |
|---|---|---|---|---|
| 75 | 185 | 19 | 0.80 | 0.192 |

Figure 2 shows the schematic illustration of sheet hydroforming. During the process of hydroforming, because an un-supporting area exists, the initial pressure and the subsequent chamber pressure play an important role in the forming of complex-shaped component and for the thickness distribution. With numerical simulations and experiments, under the condition of the initial pressure of 3 MPa, loading paths with different subsequent chamber pressures 3.5, 5, 10, 15, 20 and 30 MPa were analyzed, respectively, as shown in Fig. 3. The

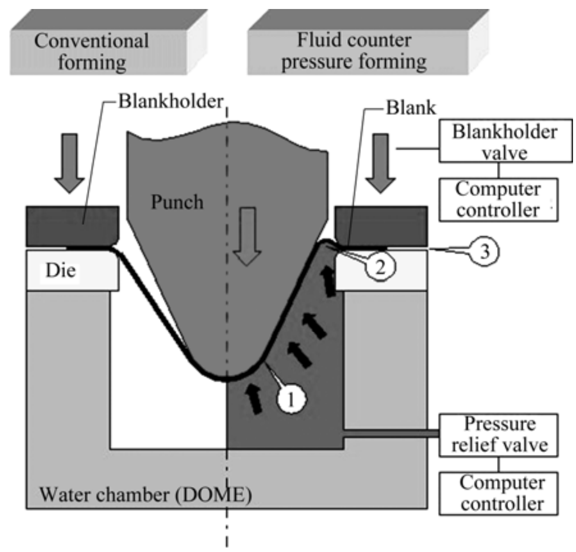


**Fig. 2** Schematic illustration of sheet hydroforming [12]

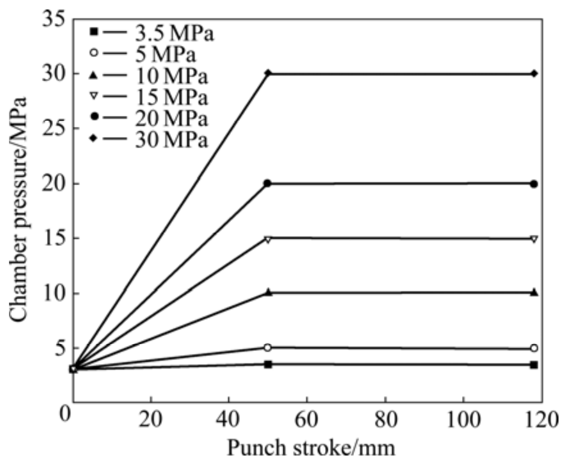


**Fig. 3** Loading paths

effects of the subsequent chamber pressure on the forming process was analyzed, and the reasonable chamber pressure was determined through comparing the minimum thickness.

## 3 Hydroforming process of complex-shaped component

With the loading path of initial pressure of 3MPa and chamber pressure of 15 MPa, the deforming process is shown in Fig. 4. In the initial stage of deforming, as shown in Fig. 4(a), a certain bulging occurs in the role of the chamber pressure, which presses the material to form a soft bear at the unsupporting area. The main deformation mode is bulging near the left end of the doubly curved surface. The material at the flange area has almost no flowing into the die cavity. The blank becomes thinner and the minimum thickness is 1.44 mm. The main deformation mode is bending for the material to form the cylindrical surface, and the thinning is very small. With deep drawing going on, as shown in Fig. 4(b), the chamber pressure increases gradually. The curvature radius of the soft bear at the unsupporting area decreases gradually. When the depth of drawing is 50 mm, as shown in Fig. 4(c), the soft bear basically disappears. At this time, the flange near the cylindrical surface begins to flow into the die cavity at first, but the material of the left unsupporting area near the end of the doubly curved surface is used to form the doubly curved surface. The flowing delay of the flange at the end of component has some effects on the flange to form the cylindrical surface, which results in a thinning of the flange used to form the cylindrical surface near the die corner, and the minimum thickness is 1.25 mm, as shown in Fig. 4(c). When the soft bear near the left end of the doubly curved surface disappears, the flange near the left end of the doubly curved surface begins to flow into the die cavity. When the main deformation mode of the flange to form the doubly curved surface is deep drawing, the main deformation mode of the flange to form the cylindrical surface is bending. The different deformation modes result in the different thinning near the die corner, as shown in Fig. 4(d).

## 4 Typical defects and mechanism

Figure 5 shows the typical defects during the process of complex shaped component hydroforming. The width of flange is close to 45 mm, while the corner radius of the die opening is 34 mm. From the view of deep drawing, when the drawing ratio reaches 2.3, the compressive deformation is great. The deformation mode of the flange to form the doubly curved surface is mainly drawing. The tangential stress at the flange is compressive and the radial stress is tensile. As seen in Figs. 5(a) and (b), the occurrence of wrinkling can be

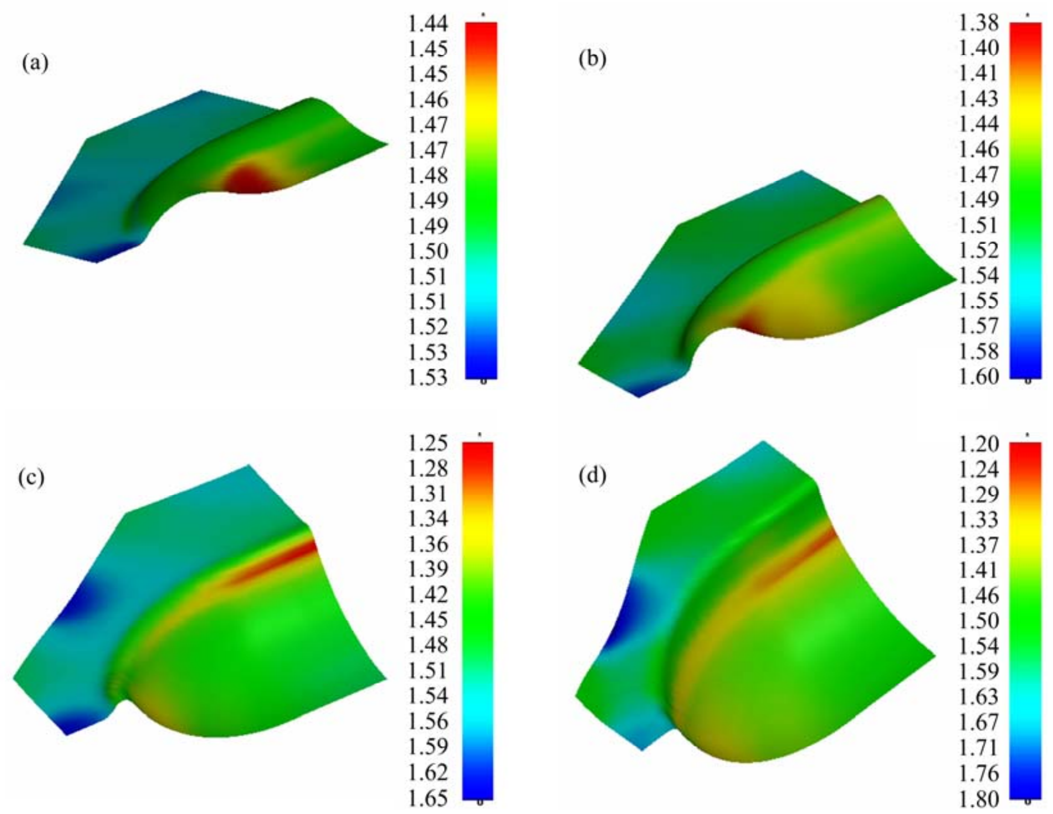


**Fig. 4** Hydroforming process (unit: mm): (a) Initial bulging; (b) Stroke of 15 mm; (c) Stroke of 50 mm; (d) Stroke of 118 mm

observed both in the experiments and simulations. It is mainly because the compressive deformation is too large that the reverse bulging pressure cannot effectively reduce the compressive stress during hydroforming. Figure 6(a) shows the result of the tangential compressive stress under different chamber pressures. The compressive stresses are −121, −106, −92, −78, −60 and −48 MPa under the chamber pressures of 3.5, 5, 10, 15, 20 and 30 MPa, respectively. When the pressure is lower than 10 MPa, the compressive stress reaches the critical wrinkling stress and the wrinkling occurs. The radial tensile stress increases with increasing chamber pressure (Fig. 6(b)). The frictional resistance between the upper surface of the flange and blank holder increases when the pressure reaches 30 MPa and the radial tensile stress reaches 350 MPa. At the same time, due to the excessive bulging, serious thinning occurs after the soft bear experiences bending and reverse bending. Its thickness is only 1.19 mm and it will fracture during the subsequent hydroforming, as shown in Fig. 7.

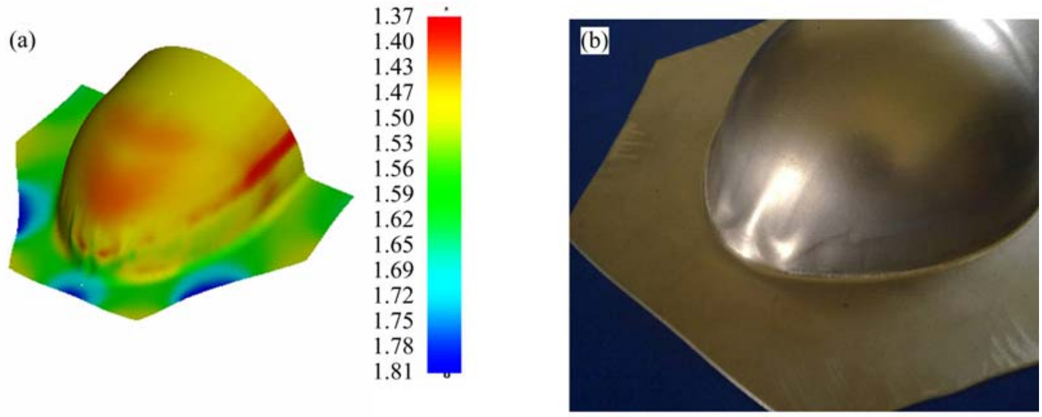


**Fig. 5** Defects of wrinkling: (a) Numerical result ($p$=3.5 MPa); (b) Experimental result ($p$=3.5 MPa)

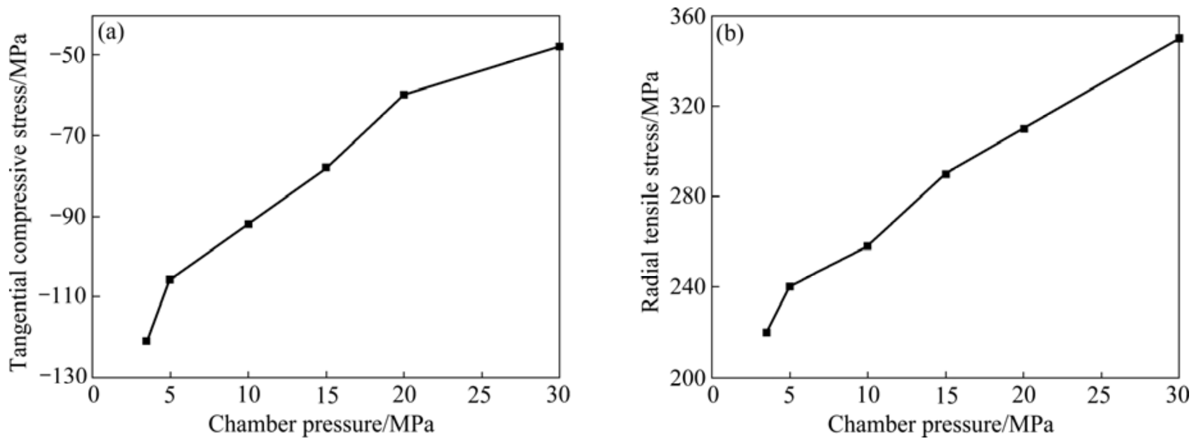


**Fig. 6** Relation between stress and chamber pressure: (a) Tangential stress; (b) Radial stress

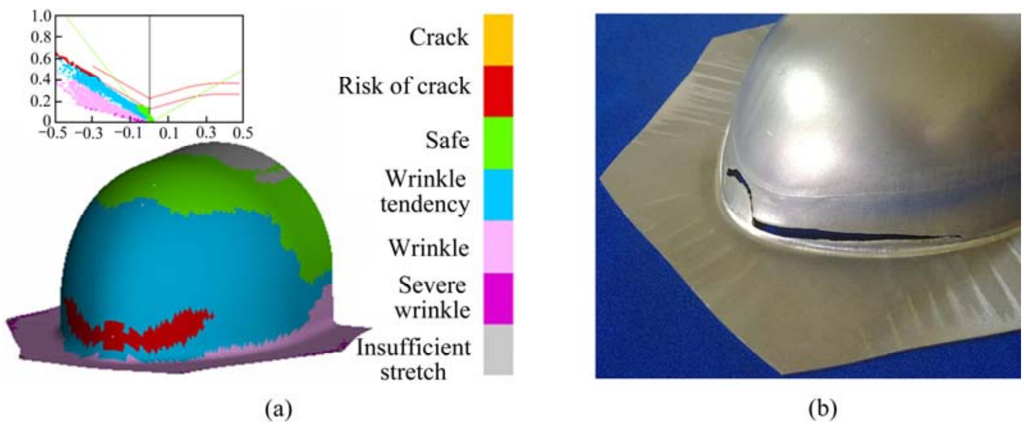


**Fig. 7** Defects of fracturing: (a) Numerical result ($p$=30 MPa); (b) Experimental result ($p$=30 MPa)

## 5 Effects of pressure on thickness distribution

Based on the process parameters obtained by the numerical simulation, the hydroforming experiments were conducted with the pre-bulging pressure of 3 MPa and different chamber pressures including 10, 15 and 20 MPa, respectively. The complex-shaped component can be formed successfully, as shown in Fig. 8. The thickness was measured along the transverse and longitudinal sections, as shown in Fig. 9.

**Fig. 8** Hydroformed component

Figure 9(a) shows the thickness distribution of transverse section. The minimum thickness is about 1.30 mm under the chamber pressure of 10 MPa, which is located at the measured point 8. It can be seen that the thinning is larger because of the lower chamber pressure when point 8 contacts with the punch, which is about 7 MPa. Although the chamber pressure can increase the beneficial friction between the punch and blank effectively, which can decrease the thinning, the bulging is the main deformation mode that is easy to result in thinning. The deformed blank gradually contacts with the punch, and the thinning no longer occurs at point 8. Figure 9(b) shows the thickness distribution of longitudinal section. The minimum thickness is about 1.36 mm, which is located at the measured point 6. The flowing delay of the flange at the left end of component has some effects on the flange to form the cylindrical surface, which results in a thinning of the flange to form the cylindrical surface near the die corner after bending and re-bending. From the above results, due to the different deformation modes, the thinning is different at the transverse section and longitudinal section.

With the chamber pressure of 15 and 20 MPa, the thickness of transverse section are 1.32 and 1.41 mm at the measured point 8, the thickness of longitudinal section is 1.38 and 1.40 mm, respectively, at the measured point 6. It can be seen that the increase of chamber pressure can improve the uniformity of the thickness distribution of the transverse section and longitudinal section. When the chamber pressure exceeds 30 MPa, the beneficial friction caused by chamber pressure makes the thickness unchanged at the measured point 8, and the thinning point gradually transforms to the die opening. Severe thinning results in bursting, as shown in Fig. 7(b).

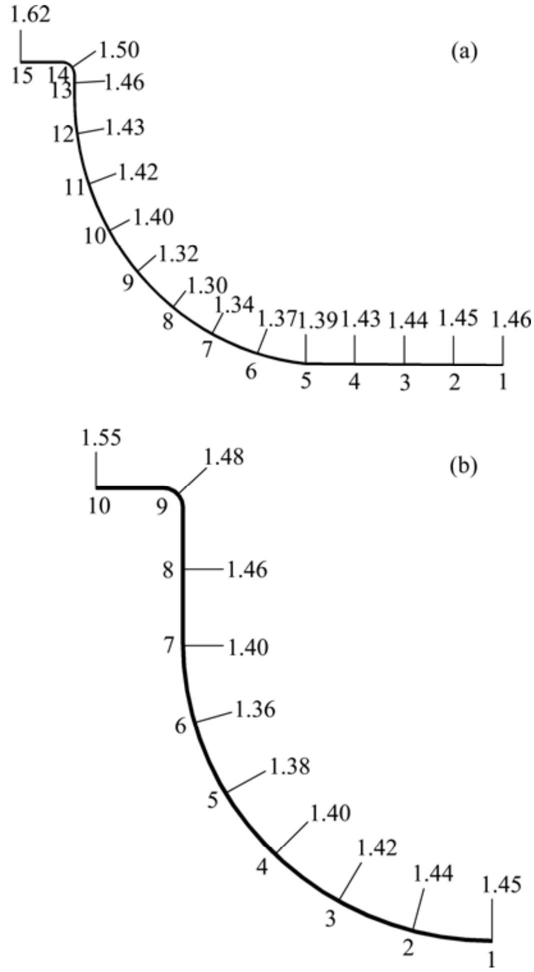


**Fig. 9** Thickness distribution ($p$=10 MPa) (Unit: mm): (a) Transverse section; (b) Longitudinal section

## 6 Conclusions

1) Aluminum alloy complex-shaped component with a doubly curved surface can be hydroformed in one step. It can avoid the microstructure damage by lift hammer forming and multiple annealing, and can improve the dimensional precision.

2) Different deformation modes result in different thinning at the transverse section and longitudinal section for the complex-shaped component. The thinning is affected by the chamber pressure. The minimum thickness is 1.41 and 1.40 mm at the transverse section and longitudinal section, respectively, when the pressure is 20 MPa. The optimal chamber pressure is 20 MPa.

3) The wrinkling and fracturing of the complex-shaped component are directly affected by the chamber pressure. The radius of curvature at the left end of the component is small, which is easy to result in a wrinkling because of larger compressive deformation at the unsupporting area when the pressure is lower than 10 MPa. Moreover, if the pressure is higher than 30 MPa, the radial tensile stress is too large and causes a fracturing. The reasonable pressure to avoid the above defects is 10−30 MPa.

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# 铝合金异型曲面件液压成形过程


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**摘 要**：针对低塑性铝合金的双曲率异型曲面件“落压”导致废品率高、尺寸一致性差、材料内部组织损伤影响疲劳性能等问题，采用液压成形技术对其进行研究。采用数值模拟和实验方法，对液压作用下的拉深过程及变形方式进行分析；探讨成形过程中起皱、破裂等失效形式及其机理，分析液压对缺陷发生区域典型点的应力状态和应力大小的影响。结果表明，避免缺陷的液室压力区间为 10~30 MPa；根据不同液压加载路径对异型曲面件横纵截面壁厚影响，确定合理的液室压为 20 MPa。



**关键词**：铝合金；板材；双曲率；液室压力


**(Edited by HE Xue-feng)**