Quick establishment of backpressure path in sheet hydroforming process

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Abstract. Backpressure path is a vital parameter for the control of dimensional accuracy and shape integrity of the fabricated part and the improvement of material formability in sheet hydroforming. The optimal backpressure path is closely related to the unsupported wall region between the punch and the die, which is determined by the geometric characteristic of the fabricated part. To clarify the relation between the optimal backpressure path and part feature, the workpieces are classified into three types according to the various change patterns of the unsupported area during the hydroforming deformation. To establish the correlation of unsupported region with the reasonable loading locus, three different types of workpieces including a cylindrical part with constant unsupported area, a conical part owning continuous variable noncontact region and an irregular part with composite vacant area were selected to be produced via sheet hydroforming. The forming quality of the three parts was analyzed under different backpressure loci, and the relationship between the optimal backpressure path and the unsupported region was built.

1. Introduction
The pressure cavity in hydroforming process is filled with a hydraulic fluid. The blank is deformed by the mechanical pressing action of the punch into the pressure chamber. The punch penetration into the hydraulic medium generates a pressure increase due to fluid compression that is controlled using a pressure control valve. The backpressure path is one of the most important parameters in sheet hydroforming process which has been examined by many researchers.

Lang et al. investigated the hydrodynamic deep drawing process parameters experimentally. The process windows were established in their research and the optimal gap between the blank holder and the die, the pre-bulging parameters, the liquid pressure in the cavity and the optimal variation routine of liquid pressure in the die cavity were determined. Khandeparkar and Liewald applied the hydro-mechanical deep drawing in forming metal cups with complex stepped geometries. They indicated that the successful manufacture of metal cups with complex stepped contour is found to require good control over the counter pressure curve. The optimum counter pressure curve is realized using numerical techniques. They showed that high pressure at the beginning of the drawing process is counterproductive. Hashemi et al. studied the process window diagram of the hydroforming process for the fabrication of a conical part. They found that the obtained PWD could predict an appropriate forming area and probability of rupture or wrinkling occurrence under different loading loci of cavity pressure. Khandeparkar and Liewald studied the ability of transferring complex features from the punch onto the blank surface through the hydroforming process of conical cups with complex stepped geometries. It was obtained that high pressure at the beginning of the drawing process is counterproductive.
Currently, great efforts have been provided to distinguish the optimal backpressure locus for a specific workpiece from hundreds of loading schemes. However, the trial-and-error method is ineffective and inoperative for the complicated part with narrow process window. Thus, the effective methodology for the rapid acquisition of the backpressure locus is urgently needed. In this study, three different types of workpieces including a cylindrical part with constant unsupported area, a conical part owning continuous variable noncontact region and an irregular part with composite vacant area were selected to be produced via sheet hydroforming. The forming quality of the three parts was analyzed under different backpressure loci, and the relationship between the optimal backpressure path and the unsupported region was built.

2. Experimental Procedure and Numerical Simulation

2.1. Part feature and material property
The shape and dimensions of three different types of workpieces including a cylindrical part, a conical part and an irregular part are presented in Figure 1. The annealed aluminum alloy 2A12 with thickness of 1.0 mm was employed in the hydroforming process of cylindrical part and conical part. Stainless steel 1Cr18Ni9Ti with a thickness of 1.0 mm was used in the hydroforming process of irregular part. The material properties of 2A12 and 1Cr18Ni9Ti are presented in Table 1.

![Figure 1. The shape and dimensions of three different types of workpieces.](image)

Table 1. Mechanical properties of 2A12 and 1Cr18Ni9Ti.

| Parameters                  | 2A12     | 1Cr18Ni9Ti |
|-----------------------------|----------|------------|
| Yield stress (MPa)          | 60.53    | 278        |
| Tensile stress (MPa)        | 123.23   | 598.5      |
| Young’s modulus (GPa)       | 33.81    | 206        |
| Uniform elongation (%)      | 23.02    | 40.4       |
| Elongation at fracture (%)  | 36.91    | 48.7       |
| Average anisotropy coefficient | 0.589   | 0.954      |
| Strength coefficient (MPa)  | 205.67   | 1024       |
| Work-hardening exponent     | 0.214    | 0.306      |
| Poisson’s ratio             | 0.3      | 0.3        |

2.2. Experimental details
The hydroforming experiment was conducted on special hydroforming equipment with capacity of 5500 kN. The fluid pressure in the die cavity is controlled by a proportional pressure valve, and the maximum pressure can reach 100 MPa.

2.3. Numerical simulation
In this research, the FE simulation is conducted on a Dynaform 5.8.1 with the LS-Dyna solver. The input models including die, blank, blank holder and punch were constructed in the pre-processor, and the adaptive meshing is utilized for blank. The punch, the blank holder and the die were modeled as rigid objects without elastic deformation. The blank was modeled using the four-node Belytschko-Lin-Tsay
element. The frictional effect was considered by the Coulomb law. The friction coefficient between the die tooling and blank is set to be 0.12.

3. Process window diagram

The process window diagram (PWD) approach which includes upper and lower limit critical pressure was employed to investigate the proper cavity pressure loading locus for the hydroforming process of the part with deep cavity. Cavity pressure loading locus is one of the key parameters in the hydroforming process, and there is a suitable range of cavity pressure for fabricating a particular workpiece. The principle for determining the upper limit of cavity pressure loading locus is to ensure the maximum tensile stress of dangerous area should not exceed the tensile strength. The hydraulic pressure should be enough to lift the blank separate from the die corner to decrease the friction is the principle for determining the lower limit of cavity pressure loading locus. The forming quality index $\psi$ in the hydroforming process can be expressed as:

$$\psi = F\left(p(h), f_b(p(h))\right)$$

(1)

where $p(h)$ is the path of fluid pressure versus drawing stroke; $f_b(p(h))$ is the counter force on the binder induced by $p(h)$.

Therefore, the PWDs of cavity pressure of cylindrical part and conical part can be acquired by calculating the lower and upper bound using the parameters of materials and the tool sets. PWD can predict the proper forming area and the occurrence of rupture. Moreover, the sound part area is related to the drawing coefficient. Narrow area between the two critical pressure loci indicates a small drawing coefficient.

If there are cross-fields between the two critical wrinkling paths for components with both convex and concave features, the wrinkling phenomenon cannot be prevented by optimizing the loading path of fluid pressure, namely, Eq. (1) cannot be solved with an optimum solution. To prevent inner wrinkling in the hydroforming process for an irregular part, the method of using drawbeads is put forward, and in this condition, Eq. (1) can be expressed as:

$$\psi = F\left(d, p(h), f_b(p(h))\right)$$

(2)

where $d$ indicates the parameters of drawbeads.

4. Result and discussion

4.1. Cylindrical part

The formed cylindrical part is shown in Figure 2. To explore the effect of cavity pressure on the wall thickness distribution of the fabricated cylindrical part, six loading loci were designed as shown in Figure 3.

![Figure 2. Fabricated cylindrical part.](image-url)
\[ \varphi = \frac{t_{\text{max}} - t_{\text{min}}}{t_0} \times 100\% \]  

where \( t_{\text{max}} \) and \( t_{\text{min}} \) are the maximum and minimum wall thickness. Figure 3 represents the wall thickness homogeneity of the cylindrical part under A-F loading loci of cavity pressure illustrated in Figure 4. It is seen that the suitable loading path for the minimum thickness homogeneity has three characteristic points, i.e., the inverse bulging pressure \( p_0 \), the piecewise punch stroke \( h_p \) and the full pressure \( p_{\text{max}} \).

**Figure 3.** Different backpressure loci for the hydroforming process of cylindrical part.

It is also observed that excessive or insufficient cavity pressure induces the severe thinning around the punch radius region. For the loading loci A and B, the flow resistance is increased because the cavity pressure is too low to entirely separate the blank from the die orifice when the punch stroke is less than 10 mm. On the other hand, for the locus C, obvious deformation and thickness reduction have been occurred before the blank fully coated with the punch due to the excessive pressure, which is not conducive to the subsequent forming. With respect to locus E, the pressure fails to reach the maximum value as the punch completely penetrates into the die, and the beneficial friction between the punch and the blank is not established. For locus F, the excessive pressure in the later period exacerbates the friction between the blank and the binder, resulting in the increase of tensile stress around the punch nose. Moreover, the reasonable loading profile of backpressure initiates from a small value, then keeps growing until the full pressure when the drawing stroke attains \((r_{d1} + r_{p1} + t_0)\).

**Figure 4.** Wall thickness uniformity of the cylindrical part under diverse loading loci.

4.2. Conical part

The formed conical part is shown in Figure 5. To investigate the effect of the locus profile on the forming quality of the conical part in the hydroforming process, several backpressure loading loci were proposed, as shown in Figure 6. To evaluate the different locus profiles of cavity pressure, the forming limit curve (FLC) is used, and the major and minor true strains in the selected areas of parts of different profiles of loading loci are mapped in Figure 7.
It is obtained that some measuring points of loci A and B are very close to the FLC. Although there is no obvious fracture defect in the numerical simulation result, serious necking was observed in the unsupported area between the punch and the die. This indicates that excessive or insufficient initial pressures increase the risks of rupture in the unsupported region and punch corner. Locus C is a typical loading locus of cavity pressure for the hydroforming process of the axisymmetric cup-shape part. However, it is observed that measuring points of locus C are slightly closer to the necking line compared with those using locus D.

4.3. Irregular part
The formed irregular part is shown in Figure 8. Experiments were performed with reasonable parameters of drawbeads and backpressure determined by FE simulations except the drawbead height $h$, which
could be regulated experimentally. The experimental parts were compared with the predictions obtained from FE simulations. The process windows of drawbead penetration were acquired from experiments by regulating the height of drawbeads, as shown in Figure 9.

![Fabricated irregular part.](image)

**Figure 8.** Fabricated irregular part.

![Experimental process windows of drawbead height.](image)

**Figure 9.** Experimental process windows of drawbead height.

5. Conclusion

In this study, quick establish of backpressure path for forming the cylindrical, conical and irregular part in hydrodynamic deep drawing process has been studied. For selecting the desired pressure path, several pressure paths were examined and their effects on the occurrence of defects and thickness distribution of different formed parts were studied. In order to obtain more uniform thickness distribution, maximum thickness in the critical region of the part has been investigated. Results indicated that utilization of the proper loading path yields lower thickness reduction of the part in the critical region. The results obtained in this research can be beneficial for engineers in the industry and for researchers working on the subject of hydroforming.

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