Influence of the key process parameters in hydrodynamic deep drawing utilizing a combined floating and static die cavity

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Abstract
This study focuses on the effects of the key process parameters during a modified hydrodynamic deep drawing utilizing a combined floating and static die cavity (HDDC). A two-stage hydraulic loading path is recommended in the novel process, and each stage of the hydraulic loading path is a linear loading path with an inflection point. The method to evaluate the wrinkle and forming dimension precision of the formed parts is introduced at first. Then, the influence of the key parameters of the two-stage hydraulic loading path as well as the blank holder force on the dimension accuracy and surface quality of the formed parts was studied in detail. The results showed that the influence of the liquid pressure during the second stage is more significant than that in the first stage in hydrodynamic deep drawing utilizing a combined floating and static die cavity. The initial pressure of the second stage and the maximum pressure arriving moment during this stage have a significant impact on the dimensional accuracy of the formed parts, and the smaller initial pressure or the later the maximum pressure of the second stage arrives, the higher the accuracy of the formed part is. Similarly, the influence of the blank holder force in the second stage on the forming accuracy is more significant than that in the first stage.

Keywords Floating die cavity · Hydrodynamic deep drawing · Combined die cavity

1 Introduction
Sheet hydrodynamic deep drawing is a kind of advanced metal forming technology, and has gained more and more attention in the past two decades. Caused by the effect of the pressured liquids, sheet hydrodynamic deep drawing process mainly possesses three attributes: wrinkle depressing resulted due to pressure bulging effect, fracture prevention due to the friction holding effect between the punch and the blank, and resistance reduction effect of the blank flange as a result of the liquids leak flow. The combined effect of the above three attributes not only improves the formed parts quality, but also leads to larger drawing ratio. And in detail, compared with the traditional stamping technology, hydrodynamic deep drawing technology has many advantages, such as enhanced ability to form complex shaped parts, larger limited drawing ratio, higher dimensional accuracy, and better surface quality [1–5].

According to many studies on forming conical parts using sheet hydroforming, sheet hydrodynamic deep drawing (HDD) method is suitable to form conical cups [6–8]. A novel hydrodynamic deep drawing utilizing a combined floating and static die cavity was proposed to form conical sups by Wang and Shen [9]. The schematic diagram for hydrodynamic deep drawing process utilizing a combined floating and static die cavity is illustrated in Fig. 1. As presented in Fig. 1, the combined die cavity composed of a static and floating die cavity. The floating die cavity is inlaid into the static chamber and can be moved up and down freely. The process of the hydrodynamic deep drawing utilizing a combined static and floating die cavity can be divided into two stages.
As shown in Fig. 1a, the forming carries out by using the floating die cavity as the deep drawing chamber and when the floating die keeps stationary together with the static die cavity at the first stage. As presented in Fig. 1b, during the second stage, the hydrodynamic deep drawing process conducts by using the static die cavity as a liquid chamber accordingly, and when the floating die cavity keeps moving downward along with the descending punch. The feasibility and effectiveness of this modified method have been confirmed and verified in previous studies conducted by the authors, but the influence of the key process parameters such as pressure loading path and blank holder force on the forming process was not studied in detail. In this study, we will focus on the effects of the key process parameters during a modified hydrodynamic deep drawing utilizing a combined floating and static die cavity (HDDC).

2 Numerical analysis

2.1 Contact state and sealing situation at die corner

In the first stage of hydrodynamic deep drawing utilizing a combined floating and static cavity, the forming sheet metal can be divided into cone bottom area, cone wall area, floating die fillet area, floating die upper area, blank holder, and static die clamping part. For the second stage of the improved method, the deformation zoning of sheet metal in the drawing process is similar to that in the ordinary hydrodynamic deep drawing process. There is a big difference in the counter pressure distribution between the modified method and the conventional hydroforming process, owing to a floating die cavity introduced to the novel hydrodynamic deep drawing process. As illustrated in Fig. 2, the hydrodynamic deep drawing performs by using the floating die cavity, and when the floating die cavity keeps still together with the static chamber during the first stage of the novel process mentioned above. The contacts between the floating die cavity and the blank caused by deep drawing force result in the sealing effect of these two bodies. Therefore, during the first stage of the deep drawing, the blank cannot be wholly levitating from the floating die corner and a tangent contact should always be kept. At the end of the first stage, when the punch presses the blank to contact the bottom of the chamber of the floating die cavity, the floating die begins to fall with the punch. During the second stage of HDDC, since the floating cavity starts falling the pressured liquids effecting zone transforms to the domain inside the static die crater as same as that during conventional hydrodynamic deep drawing process using the static cavity as a deep drawing chamber.

During the first deep drawing stage of HDDC, the liquid pressure applies to the blank within the floating die crater. And in the second stage, the pressure-applying domain changes to the blank inner the static cavity crater since
the floating die moves downward. The contacting status between the blank and the floating die is used to diagnose the type of the hydroforming. That is to say, when the blank keeps contact with the die corner all along, we consider the deep drawing process belongs to the modified hydrodynamic deep drawing process \[9\]. During the novel method, the successful sealing can be realized if the normal contact stress \(P_{\text{normal}}\) between the blank and the corner the floating die cavity is greater than the liquid pressure \(P_s\) in the die cavity. This can be illustrated by the following equation:
\[
P_{\text{normal}} \geq P_s
\] (1)

According to Fig. 3, the contact normal stress between the blank and the floating die corner is caused by the deep drawing force at the die corner. As illustrated in Fig. 3, the blank bulged by the liquid pressure is simultaneously tangent not only to the floating die corner between the bottom surface but also to the punch wall by the upper surface of the blank. The pressure is higher, the bulging corner of the blank smaller. In addition, the least radius of the forming sheet to sustain maximum liquid pressure no leakage simultaneously tangents to both the connected tangent line between the floating die corner and the floating die upper surface. The corner value can be determined by the following equation:
\[
r_b = \left(\frac{1}{2}d_1 \ast \cot \alpha - r_{d_1} \cot \alpha - h_1 - t_b \cot \alpha \right) \left(\sqrt{\cot^2 \alpha + 1} - 1\right)
\] (2)

The functional relation between the bulging blank corner and the liquid pressure is described as the vessel theory that is illustrated as the following equation.
\[
\rho = \frac{\sigma_b t_b}{P_i}
\] (3)

Here, \(\rho\) is the radius of curvature of sheet, \(\sigma_b\) is the sheet yield strength, \(t_b\) is the sheet thickness, and \(P_i\) is the pressure of the liquid in die cavity.

### 2.2 Method to elevate formed part quality

Wrinkling is a common defect in the forming of conical cups, and can be divided into external wrinkling and internal wrinkling. The external wrinkles appear on the flange of the blank; accordingly, the internal wrinkles occur in the unsupported blank between the die cavity and the punch.

The evaluation criterion of wrinkling degree is the key issue for comparing the effects of various process parameters on the forming process quantitatively. Experiments and some related research revealed that the external wrinkle during conical cup deep drawing is always toward the outside, which means the wrinkling is one sided. The quality of a conical cup obtained by liquid filled deep drawing includes two aspects: dimension and shape accuracy as well as surface quality. The dimensional accuracy of the revolving conical cup can be evaluated by the roundness of the section circle being perpendicular to the cup’s axis at different heights. The roundness of each section refers to the degree that the outer contour of the actual section is close to the theoretical circle, which is generally expressed by the difference between the maximum radius and the minimum radius of the actual section circle. When the wrinkling degree of a conical cup is low, the source of dimensional accuracy is generally related to material anisotropy. The surface wrinkling of the conical cup affects the surface quality of the formed part in the process of deep drawing. The degree of wrinkling is identified by the amplitude of the contour of each section circle of the conical cup. As shown in Fig. 4, when analyzing the shape accuracy and wrinkling of the formed part at different heights, the cross-section circle of the conical part perpendicular to the rotation axis of the conical part at various heights is obtained firstly. Moreover, the shape accuracy, wrinkling number, and wrinkling height of the cross-section circle of the conical part are acquired at different heights along the symmetry axis. As shown in

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\(\text{Fig. 3}\) Contact conditions of sheet metal at the fillet of the floating during HDDC process

\(\text{Fig. 4}\) Schematic diagram of evaluation method for roundness and wrinkle height of the formed parts
Fig. 4, the shape accuracy of the cross-section circle is represented by the roundness of the cross-section circle, and the wrinkle is marked by the vertical distance from the zenith of the wave to the two neighboring troughs connected line. In addition, the maximum wrinkle height is represented by the maximum amplitude of the wrinkle ripple line of the cross-section circle. In order to estimate and compare the wrinkle during different process parameters, the wrinkle is marked by using the vertical distance from the zenith of the wave to the two neighboring troughs connected line, which as illustrated in Fig. 4.

3 Materials and experimental methodology

The annealed titanium alloy TA2-M blank with a thickness of 0.6 mm is used in both simulations and experiments. The mechanical properties of TA2-M are obtained from universal tensile tests and shown in Table 1. The anisotropy coefficient \( r \) values of the titanium alloy sheet TA2-M are 2.76, 3.56, and 3.23 along the rolling directions of 0°, 45°, and 90°, respectively.

A typical conical cup, usually found in the aerospace industry, will be used as an experimental part to validate and explore the proposed method. The shaped size information of the part is shown in Fig. 5. The blank material used in experiments is titanium alloy, and its mechanical properties are presented in Table 1. The blank thickness is 0.6 mm. A special experimental set up was designed based on the principal of the hydrodynamic deep drawing utilizing a combined die cavity proposed in this study, as is illustrated in Fig. 6, left, presents the structure members of the lower die, and the right displays the assembled lower combined die cavity. The experiments will be conducted on a hydraulic press with a capacity of 80 t. The stamping speed is set at about 5 mm/s. The geometric details are shown in Fig. 5. The die parameters are marked in Fig. 7, and those values are presented in Table 2.

The commercial FEM software Dyna-form is used to simulate the modified hydrodynamic deep drawing process utilizing a combined die cavity. The TA2-M titanium alloy sheet with a thickness of 0.6 mm is used both in simulations and experiments. The mechanical properties of the TA2-M titanium alloy sheet are shown in Table 1. The flow curve along rolling direction is directly used as the hardening curve for this material together with BARLAT yield criteria is adopted in simulations. The components of the die set are constructed as rigid bodies, and the blank is fabricated as a deformed body in simulation models. Both the floating and the static die cavity keep stationary during the first stage of the hydrodynamic deep drawing process utilizing a combined die cavity. Correspondingly, in the second stage of the novel sheet hydroforming process, the floating die cavity would move downward together with the punch. The liquid pressure is transformed into face load in the FEM model. The Coulomb friction mode was adopted in FE model. The friction coefficient of 0.01 between the blank and the floating die cavity as well as the static die cavity is used in the FEM mold considering the dynamic leakage between the two contacting interfaces exists. And the friction coefficient of 0.02 is used on the interface between the blank and the blank holder as well as the punch. The sheet was discretized into 13,190 elements of BELYTSCHKO-TSAY type. The FEM model is presented as Fig. 8.

Pressure boundary condition is one of the key parameters during hydroforming process simulation. In order to
convenience realize the pressure boundary conditions in the FE models, the pressure is simplified to be applied to the bottom of the blank inside the zones of the loops of die profile crater.

4 Analysis results

According to the above introduction, the hydrodynamic deep drawing process utilizing a combined floating and static cavity can be divided into two stages: the first stage is the hydrodynamic deep drawing subprocess using the floating die cavity, and the second stage can be regarded as the hydrodynamic deep drawing subprocess utilizing the static die cavity. The essence of the first stage is the hydrodynamic deep drawing based on the floating die, and the corresponding liquid cavity pressure is determined by the contact state between sheet metal and floating liquid die cavity. The two-step pressure loading path corresponding to the two-stage forming process is adopted in both the simulation and experiment, as shown in Fig. 9. During the first stage, the liquid pressure starts from 0 MPa and linearly rises to the maximum value, while the die stroke reaches the preset value, and then maintains this value to the end of the first stage. After the first stage is finished, the floating die starts to move down with the punch, and the corresponding seal formed by the contact between the plate material and the floating die fillet will lose effect. The liquid pressure will be reduced to the level caused by the resistance overflowing from the gap between the static die cavity and the plate, because an effective seal has not yet formed at the fillet of the static die cavity, and the corresponding maximum pressure will be determined by the contact force between the plate and the static die cavity. As illustrated in Fig. 9, the two-stage loading route which characteristic is that the pressure fluctuates in the conversion process of the first stage and the second stage will be adopted for the modified process, which is in agreement with the working condition of

| Parameter                              | Value (mm) |
|----------------------------------------|------------|
| Punch diameters, $D_p$                 | 146.06     |
| Radius of punch corner, $r_p$          | 2.5        |
| Inner diameters of the blank holder, $D_b$ | 148.06   |
| Inner radius of the blank holder, $r_h$ | 3          |
| Radius of the floating die $r_{d1}$    | 5          |
| Radius of the static die $r_{d2}$      | 3          |

Fig. 7 The marked parameters of the setup used in this research

![FEM model for HDDC](image)

Fig. 8 FEM model for HDDC

![A typical loading pressure path used in HDDC](image)

Fig. 9 A typical loading pressure path used in HDDC
hydrodynamic deep drawing based on a combined floating and static die cavity.

Finite element simulations and preliminary experiments will be carried out to evaluate the effect of the novel method of hydrodynamic deep drawing utilizing a combined floating and static die cavity. In order to make the results obtained from two methods comparable, the set up used in the common hydrodynamic deep drawing is realized by removing the floating die cavity from the equipment used in the novel method based on the combined floating and static die cavity, and the pressure loading path is completely consistent.

As illustrated in Fig. 10, the pressure loading route adopts the two stage loading route. During the first stage, the liquid pressure starts from 0 MPa and linearly rises to the maximum value of 16 MPa when the die stroke reaches 28 mm, and then maintains this value to the die stroke 50 mm. In the second stage, the pressure rises linearly from 2 MPa and up to 20 MPa when the die stroke reaches 75 mm, and then remains at this value until the end of the process.

Adopting the pressure loading curve shown in Fig. 10, the conical cups illustrated in Fig. 5 are formed by using both the common hydrodynamic deep drawing process and the modified method using a combined floating and static die cavity respectively. It is clear that the forming parts from both the simulation and experiment for the ordinary hydrodynamic deep drawing process have obvious wrinkles in the upper part of the cone wall, as shown in Fig. 11a, b. In contrast, the cone wall of the conical parts formed from both the simulation and experiment by the improved hydro mechanical drawing method utilizing a combined floating and static die cavity are smooth and wrinkle free, which is illustrated in Fig. 11c, d. One thing is very clear that the conical wall of the conical cup will inevitably appear many wrinkles when the traditional hydraulic deep drawing is used to form the conical cup, while when the hydrodynamic deep drawing process utilizing a combined floating and static die cavity is used to form the part, no wrinkles appear. According to the above analysis, it can be concluded that the modified process can effectively depress the wrinkling in the forming process of conical cups and improve the surface quality of the formed parts.

Fig. 10 The pressure loading path used in the preliminary simulation and experiment

Fig. 11 The comparison between the parts obtained by simulation and experiment of two different forming methods. (a) and (b) The forming parts from both the simulation and experiment for the ordinary hydrodynamic deep drawing process. (c) and (d) The conical parts formed from both the simulation and experiment by the improved hydro mechanical drawing method utilizing a combined floating and static die cavity.
The fracture usually occurs at the small end of the conical part during the part hydrodynamic deep drawing process, and the forming limit of the conical part is determined by both the rupture and wrinkling. The thinning ratio of wall thickness is one of the simple and effective criteria for fracture judgment. Fig. 12 is a comparative diagram of the wall thickness distribution of the parts from the simulations for both the dynamic deep drawing using a combined floating and static liquid pool and the common hydrodynamic deep drawing. Under the same technological conditions, the minimum wall thickness of the conical cup obtained by hydrodynamic deep drawing using a combined floating and static die cavity is 0.5674 mm, while that obtained from the ordinary hydrodynamic deep drawing is 0.5669 mm. That is to say, the floating die has no effect on the thinnest point of wall thickness distribution, which means that the floating die will not deteriorate the thinning thickness of the thinner point, and has no effect on the rupture limit determined by the rupture.

From the above analysis, it can be seen that the floating die can ameliorate the wrinkling of the conical part in the process of hydraulic deep drawing, and improve the quality of the part. Moreover, besides improving the wrinkling, it has no effect on the forming limit determined by the small end fracture.

4.1 The effect of pressure loading path of the first stage of the hydroforming process

4.1.1 Influence of the maximum pressure in the first stage

The pressure-loading path has important effects on the forming process, which is one of the most important process parameters during the HDDC. The corresponding pressure loading path is adopted by two sage stepwise loading since the process of hydrodynamic deep drawing utilizing a combined static and floating die cavity obviously shows two stages. As shown in Fig. 13, the loading pressure path during the first stage of HDDC is similar to that in conventional hydromechanical deep drawing, in which a linear loading pressure path of one inflection point is implemented; the cavity pressure starts from a pre-set value and rises linearly to the maximum value during the second stage. Keeping the pressure loading path of the second stage unchanged, the influence of the maximum pressure in the first stage on dimension and surface quality of the forming part is studied by using the four pressure loading paths in the first stage as shown in Fig. 13.

It can be seen from the figure that the change of the maximum pressure in the first stage affects the forming dimensional accuracy and surface quality of the conical wall. In the first stage, when the maximum liquid pressure changes within 12~18 MPa, the roundness of the cross section of the conical part is lied in the mouth of the conical part, and the maximum value is 0.11 mm. The wrinkling height of different height sections of conical parts is shown in Fig. 14. It can be seen from Fig. 14 that the wrinkling height of the parts is less than 0.09 mm under the above process conditions; the dimension precision and surface quality of the upper half part of the conical cups are lower than that of the bottom half part. It can be seen from Fig. 15 that the dimensional accuracy and surface quality of the parts obtained under the maximum pressure of 16 MPa are higher. The maximum value of the first stage and 16 MPa is the best choice for the maximum pressure during the first stage.
In order to study the influence of the moment while the maximum liquid pressure arriving on the forming accuracy in the first stage of the liquid pressure loading path, four loading paths are designed as shown in Fig. 16. The maximum pressure in the first stage among the four pressure loading paths is 16 MPa. The difference is that the maximum pressure is reached when the punch stroke is 20 mm, 24 mm, 28 mm, and 32 mm, respectively. The pressure in the second stage starts to load linearly from 2 MPa, and reaches the maximum liquid pressure of 20 MPa when the punch stroke is 75 mm, and the maximum liquid pressure is maintained until the punch stroke is 80 mm.

It can be seen from Figs. 17 and 18 that the maximum liquid pressure reaching moment in the first stage affects the dimensional accuracy and surface quality of the part. When the maximum liquid pool pressure in the first stage is 20 MPa, the maximum value is reached when the die stroke is 28 mm, and the dimensional accuracy and surface quality of the parts are relatively high. In the first stage, under the premise of the floating punch playing a role, the influence of the liquid pool pressure on the forming accuracy and the maximum wrinkle height is small.
4.2 The effect of the loading path of Stage 2

4.2.1 Influence of the maximum pressure in the second stage of HDDC process

The liquid pressure is one of the most important parameters during the sheet HDDC process. As mentioned above, the pressure loading path during the HDDC process is divided into two stages. In order to investigate the effect of the maximum pressure of the second stage on the forming process, a series of liquid loading paths illustrated in Fig. 19 are adopted in the following investigations.

It can be seen from Fig. 20 that the change of the maximum pressure in the second stage has little influence on the dimensional accuracy of the part. However, the change in the maximum pressure in Stage 2 has a great influence on the surface quality of the conical wall obtained in the second stage of liquid filling drawing. It can be seen from Fig. 21 that when the pressure in the second stage is 20 MPa, the wrinkle at the mouth of the conical part is the weakest, and the surface quality is relatively average.

4.2.2 Influence of the moment of maximum pressure arriving in the second stage

In order to study the influence of the moment of the maximum liquid pressure arriving in the second stage on the dimensional accuracy of the forming part, four loading paths of different four maximum pressure arriving moments in the second stage are designed respectively as shown in Fig. 22. As shown in Fig. 22, with the punch stroke increasing, the
liquid pressure rises linearly from 0 MPa to the maximum of 16 MPa when the punch stroke arrives at 28 mm, and then maintains this value until the punch stroke of 50 mm while the first stage of hydraulic deep drawing is completed. In the second stage, all the four loading paths increase linearly from 2 MPa to the maximum pressure of 20 MPa, but there are differences in the time when the maximum pressure reaches and the maximum pressure arrives at 60 mm, 65 mm, 70 mm, and 75 mm, respectively.

Fig. 23 shows the influence of the moment of the maximum force arriving on the roundness and wrinkling height of the formed part in the second stage of pressure loading. As shown in Fig. 23, the moment when the maximum liquid pressure reaches in the second stage has a significant effect on the precision of the formed part. It can be concluded from Fig. 24 that the moment when the maximum liquid pressure arrives in the second stage has a significant effect on the roundness and wrinkle height of the upper part of the conical wall of the forming part. The later the maximum pressure arrives in the second stage, the higher the forming accuracy of the forming part. Among the four designed loading paths, the one while the pressure in the second stage reaches the maximum at the stroke of 75 mm, the dimension accuracy and surface quality of the forming parts are relatively highest.

### 4.2.3 Influence of initial pressure in the second stage

During the hydrodynamic deep drawing utilizing a combined floating and static die cavity, the beginning of the second stage of the process is very important because the contact state of the suspended sheet between the static die and the punch will change caused by the floating die moving along with the punch. In order to study the influence of the initial pressure of the second stage on the accuracy of the forming parts, four loading paths are designed as shown in Fig. 25. As shown in Fig. 25, in the first stage, the liquid pressure rises linearly from 0 MPa and reaches to the maximum value of 16 MPa at the punch stroke of 28 mm, and then maintains the value until the punch stroke of 50 mm, which means the first stage of liquid filling drawing is completed. Accordingly, in the second stage, the pressure linearly rises from different values to the maximum of 20 MPa when the punch stroke is 70 mm, and maintains this value until the process is completely finished. The four loading paths are mainly different from the initial pressure, which are set as 0, 4, 6, and 10 MPa respectively.

Figure 26 shows the maximum wrinkle height at different heights of the conical parts obtained from the simulations.
It can be seen from the figure that the initial pressure has a significant effect on the precision of the formed part in the second stage of pressure loading. Moreover, the smaller the initial pressure is, the better the precision of the formed part is. It can be concluded that the path of linear loading from zero after the loading pressure of the first stage is completed is most beneficial for the dimensional accuracy and surface quality of the formed parts.

4.3 The influence of the blank holder forces on the formed parts’ accuracy

As illustrated in Fig. 9, a two-stage pressure loading strategy for the blank holder force (BHF) is used in the hydrodynamic deep drawing process utilizing a combined static and floating die cavity. Three kinds of BHF of the first stage, 30 t, 40 t, and 50 t, are designed to study the influence of the BHF of the first stage on the forming accuracy of the part under the condition that the blank holder force of the second stage is kept constant value of 40 t. The simulation results are shown in Figs. 27 and 28. It can be seen from the figures that under the condition of ensuring the minimum blank holder force without wrinkling, increasing the blank holder force in the first stage of the deep drawing cannot significantly improve the forming accuracy of the part, and the change of the blank holder force in the first stage has little effect on the roundness and wrinkling height of the part. Therefore, for the modified hydrodynamic deep drawing method, on the premise of ensuring that the flange does not wrinkle, the smaller the
blank holder force in the first stage, the better the forming ability of the drawing part. In the case of the blank holder force for the first stage keeping 40 t, the influence of the blank holder force of the second stage on the forming dimensional accuracy of the formed part is studied by adjusting the second stage blank holder force, and four kinds of second stage blank holder forces of 30 t, 40 t, 50 t, and 60 t are set respectively. The result of forming precision is shown in Figs. 29 and 30. It can be seen from the figures that compared with the influence of blank holder force in the first stage, the blank holder force in the second stage has a significant influence on the forming accuracy of the part. The forming accuracy of the part with larger blank holder force in the second stage is higher, and it mainly affects the forming roundness and surface ripple height of the upper part of the part. It can also be seen from the figure that the forming precision is the highest when the blank holder force is 50 t. Generally speaking, the higher the blank holder force in the second stage, the higher the quality of the formed parts.

5 Conclusion

The modified method, named hydrodynamic deep drawing process utilizing a combined static and floating die, has been proven feasible and suitable to form thin wall conical cups. The modified forming process can depress the wrinkling.

In terms of the effect on the forming accuracy, the influence of the liquid pressure during the second stage is more significant than that in the first stage in hydrodynamic deep drawing utilizing a combined floating and static die cavity. The forming accuracy is mainly affected by the loading path of liquid cavity pressure in the second stage. The initial pressure of the second stage and the moment of the maximum pressure arriving during this stage have a significant impact on the dimensional accuracy of the formed parts, and the lower the initial pressure or the later the maximum pressure of the second stage arrives, the higher the accuracy of the formed part is.

The influence of the blank holder force in the second stage on the forming accuracy is more significant than that in the first stage. The change of the blank holder force in the first stage has little effect on the roundness and wrinkling height of the part. Under the condition of ensuring that the flange does not wrinkle, the smaller the blank holder force in the first stage, the better the forming ability of the drawing part. Correspondingly, the higher the blank holder force in the second stage, the higher the quality of the formed parts. For the improved hydrodynamic deep drawing method utilizing a combined floating and static die cavity proposed in this study, the design of process parameters such as liquid pool pressure and blank holder force in the first stage should mainly consider the forming capacity of parts. Accordingly, the process parameters in the second stage mainly consider the accuracy of formed parts.

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Declarations

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Consent to participate All authors agreed to participate in this research.
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