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 focus 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.

0. Introduction

Sheet hydrodynamic deep drawing is a kind of advanced metal forming technologies, 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 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 then the hydrodynamic deep drawing have some advantages, such as higher limited drawing ratio, higher dimensional accuracy, better surface quality, enhanced ability to form complex shape parts, and so on [1-5].

Conical cup is a typical part of stamping products. Sheet hydrodynamic deep drawing (HDD) method is suitable to form this type of cups. Many researches have been conducted to form conical parts by using sheet hydroforming process. Alireza Jalil et al. [6] found that double layered conical cups could be formed more easily with the process of hydrodynamic deep drawing assisted by radial pressure compared with other traditional methods. Lang et al. [7] investigated into hydromechanical deep drawing of an aluminum alloy components that its shape is similar to conical cups. By means of both numerical simulation and experiment, the forming process in hydromechanical deep drawing of this complicated part is discussed and the key process parameters, such as the blank shape and the loading pressure in the die cavity are optimized. Li et al. [8] used multi-pass hydrodynamic deep drawing method to fabricate a conical cup with deep cavity. By using the suitable working condition during multi step hydrodynamic deep drawing, the conical part with homogenous thickness distribution, desirable surface quality, and high dimensional precision is formed, which illustrated that the multi-step HDD technology is valid for the integration and precision forming of the conical cup of deep cavity with complex feature and high drawing ratio.

During the deep drawing of conical cups, the deformation zone can be divided into three parts: flange plane zone, contact zone between sheet metal and die fillet zone, free surface zone between punch and die gap zone. The free surface is apt to wrinkle when forming conical parts. Then, thin walled deep cone cup is one of the typical difficult stamping parts in stamping industry, which generally adopts multi pass forming. Sheet hydroforming process is one of the advanced forming processes to form thin-walled cone-shaped parts. During the forming process, the liquid pressure acting on the bottom surface of the sheet metal causes reverse expansion of the suspended area, which can reduce wrinkling of the mounting area. During conventional deep drawing process of conical cups, the compression stress among the suspended blank between the die cavity and the punch is apt to lead to wrinkling. This phenomenon is ameliorated by using hydrodynamic deep drawing process because the compression stress reduces and the state of stress changes due to the suspended blank bulged by counter pressure. However, due to the main forming mode is deep drawing, it is inevitable that the compression stress exists in the unsupported blank between the die crater and the punch by means of the soft supporting on the suspended region, especially in the deep drawing process of conical cups with deep cavity. The main issue to improve the forming ability of deep cone parts is how to restrain the wrinkling and improve the forming state. In order to solve this problem, the authors had previously proposed a novel hydrodynamic deep drawing utilizing a combined floating and static die cavity [9]. Its feasibility and effectiveness have been confirmed and verified in previous studies. In this study, the influence of the key process parameters such as pressure loading path and blank holder force on the forming process will be studied in detail.

1. Scheme Of Hydrodynamic Deep Drawing Utilizing A Combined Die Cavity

In order to help readers grasp the technology more conveniently, this section will introduce the Scheme of hydrodynamic deep drawing utilizing a combined die cavity again.

The schematic diagram of hydrodynamic deep drawing process utilizing a combined floating and static die cavity is illustrated in Fig.1. The main components of the setup include a punch, a blank holder, a floating die cavity, and a static die cavity. The combined die cavity composes of a static and floating die cavity. As presented in the Fig.1, the floating die cavity that can be moved up and down freely is inlayed into the static chamber. A set of special hydraulic system is linked to the floating die cavity by a high-pressure rubber hose running through the static die cavity, and the other separate hydraulic system is attached to the static die cavity directly. A sealing device between the static die cavity and the floating die cavity is designed to guarantee the liquids in the static chamber are compressed to levitate the floating die cavity without overflow from the clearances between the combined cavities. When the floating die cavity moves downward along with the punch, the sealing between the floating and the static die cavity becomes invalid and the floating die chamber is connected with the static die cavity.

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.2 (a), at the first stage, the floating die keeps stationary together with the static die cavity, and in fact, the forming process is carried on by using the floating die cavity as the deep drawing chamber. As presented in Fig.2 (b), during the second stage, the floating die cavity keeps moving downward along with the descending punch, and the hydrodynamic deep drawing is conducted by using the static die cavity as a liquid chamber accordingly.

After the experimental setup is assembled, the floating die cavity is supported by a particular spring that provides holding force to tightly contact with the static chamber initially. The filling pump starts up to oil the static cavity until it is time to be filled, and then the liquids are pressured to a preset pressure that can sustain the floating die to keep motionless in the first deep drawing stage. After the floating die cavity is also filled with oil, the punch begins to move downward while the floating die cavity keeps still, which means the hydroforming is executed using the floating die as liquid cavity, as shown in Fig.2 (a). The first stage goes on until the blank moves to contact with the floating chamber bottom. After that, the floating die together with the punch moves downward, and then the second hydroforming stage is conducted using the static chamber as a liquid cavity, as shown in Fig.2 (b). When the floating die cavity begins to descend, the sealing device between the floating die cavity and the static die cavity is no longer works, and the liquids in the static die cavity become connected with the floating die chamber through the clearance between those die cavity. The second forming stage keeps on until the forming process finish. A liquids escape pipe is designed in order to guarantee liquids can overflow from the floating die cavity and no levitating pressure generates beneath the blank during the first forming stage, and on the contrary, the liquids escape pipe will be shut off during the second forming stage.

2. Numerical Analysis

2.1 Contact state at die corner and sealing situation

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. The counter pressure distribution during this modified method has a big difference from that during conventional hydroforming process owing to a floating die cavity introduced to the novel hydrodynamic deep drawing process. As shown in Fig.3, during the first stage of the novel process, the hydrodynamic deep drawing is carried out using the floating die cavity as a deep drawing chamber while the floating die cavity keeps static together with the static chamber. The sealing effect between the floating die cavity and the blank is realized by the contact force between these two bodies caused by deep drawing force. Therefore, the blank cannot be wholly levitating from the floating die corner and a partial tangent contact should be keeping during the first stage of the deep drawing. The floating die would begin to descend together with the punch when the punch presses the blank to touch the chamber bottom of the floating die cavity at the end of the first stage of HDDC. After the floating cavity begins to move, the pressured liquids effecting zone transforms to the domain inside the static die crater as same as that during conventional hydroforming process using the static cavity as a deep drawing chamber.

The liquid pressure is applied on the blank inner the floating die crater during the first deep drawing stage, and the pressure-applying blank will be changed to the domain inside the static cavity crater when the floating die is moving downward. The contacting status between the blank and the floating die is used to diagnose the type of the hydroforming in simulations, 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, otherwise, the simulation would be regarded as invalid. During the novel method, the successful sealing can be realized if the normal contact stress P_{normal} between the blank and the corner the floating die cavity is great than the liquid pressure P_n in the die cavity. This can be illustrated as follow equation:

$$P_{normal} \geq P_s \qquad (1)$$

According to the Fig.10, 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.12, the blank bulged by the liquid pressure is simultaneously tangent not only to the floating die corner between the bottom surface and the but also to the punch wall by upper surface of the blank. The pressure higher, the bulging corner of the blank is smaller. In addition, the least radius of the forming sheet to sustain maximum liquid pressure no leakage simultaneously tangents both to the connected tangent line between the floating die corner and the floating die upper surface. The corner value is defined by the following equation.

$$r_b = \left(\frac{1}{2}d_1 * \cot\alpha - r_{d1}\cot\alpha - h_1 - t_0\cot\alpha\right) \Big/ \left(\sqrt{\cot^2\alpha + 1} - 1\right) \qquad (2)$$

The functional relation between the bulging blank corner and the liquid pressure is described by the vessel theory illustrated as the following equation.

$$\rho = \frac{\sigma_b t_b}{P_i} \qquad (3)$$

2.2. Method to elevate formed part quality

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

The evaluation criterion of wrinkling degree is the key issue to compare the effects of various process parameters on the forming process quantitatively. Experiments and some related researches revealed that the external wrinkle during conical cup deep drawing is always toward outside, which means the wrinkling is one sided. The quality of 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 conical 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 conical cup is low, the source of dimensional accuracy is generally related to material anisotropy. The surface wrinkling of 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 Figure 5, 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 different heights is obtained firstly，Moreover, the shape accuracy, wrinkling number and wrinkling height of the cross-section circle of the conical part are obtained at different heights along the symmetry axis. As shown in Figure 5, the shape accuracy of the cross-section circle is represented by the out of roundness of the cross-section circle, and the wrinkle is marked by used 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 used the vertical distance from the zenith of the wave to the two neighboring troughs connected line, which as illustrated in fig5.

3. Materials And Experimental Methodology

The TA2-M blank with thickness of 0.6mm 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-O are 2.76, 3.56, 3.23 along the rolling directions of 0°, 45°, 90°, respectively.

Table 1 Mechanical properties of TA2-M

Rolling direction	Young’s modulus E(GPa)	Strain hardening exponent n	Yield stress (MPa)	Tensile stress (MPa)	Harding coefficient k (MPa)	Anisotropy Coefficient r
0	105	0.098	490	560	482.9	2.76
45	105	0.104	487	566	472.6	3.56
90	105	0.119	491	588	489.5	3.23

A typical conical cup usually found in 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.6. The blank material used in experiments is titanium alloy which mechanical properties are shown in Tale 1. The blank thickness is 0.6mm. 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.7. Fig.7 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 capacity of 80 ton. The stamping speed is set about 5 mm /s. The part geometric detail is shown in the Fig.6. The die parameters are marked in Fig.8 and those values presented in Table 2.

Table 2 The die parameter value

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

The commercial FEM software Dyna-form is used to simulate the hydrodynamic deep drawing process. The sheet is TA2-M titanium alloy with thickness of 0.6mm. The mechanical properties of TA2-M are shown in Table 1. The flow curve along rolling direction is directly used as the hardening curve and Barlat yield criteria is adopted in simulations. The components of the die are constructed as rigid bodies and the blank is fabricated as deformed body in simulation models. The rigid bodies include the punch, the blank holder, the floating die cavity and the static die cavity. In first stage of the hydrodynamic deep drawing process utilizing a combined die cavity, both the floating and the static die cavity are keeping stationary. Correspondently, the floating die cavity would move downward together with the punch during the second stage of the sheet hydroforming process. The blank holding pattern adopts fixed blank holding force with the value of 400KN. 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 FEM mold, considering the dynamic leakage between the two contacting interfaces exists, and 0.02 is used between the blank and the holder as well as the punch. The sheet was considered as a deformable body and discretized into 13190 elements of BELYTSCHKO-TSAY type. The FEM model is presented as Fig.9.

Pressure boundary condition is one of the key parameters during hydroforming process simulation. During the hydromechanical deep drawing, the liquid pressure is restricted in the domain inner the sealing ring. This pressure boundary can be properly applied in the FE model using the loop function in the Dyna-form preprocess stage. Compared with the HMD process, as shown in Fig.3 (b), the pressure boundary condition during HDD process is more complicated. 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 no matter the forming process is HDD or HMD. Many researches adopted similar strategy to simplify the hydroforming FE model.

Numerical simulations together with a series of principal experiments are executed to verify and explore the proposed method. At first, massive simulations were conducted to explore the possibility to form the part shown in Fig.5 by using conventional hydromechanical deep drawing process, and the successfully working window would be provided if it were possible to form the part successfully. Then, aiming at the proposed novel method, amount of simulations are also carried out to explore the successfully working window for liquid pressure and significant changes caused by introducing the floating die cavity compared with conventional hydrodynamic deep drawing. The difference between the conventional and the modified method is analyzed in detail. Finally, experiments are also conducted to validate the proposed method and the simulation results.

4. Analysis Results

According to the introduction above, 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 regard as the hydrodynamic deep drawing subprocess utilizing the static die cavity. In this method, the essence of the first stage of deep drawing is 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. Therefore, 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.10. During the first stage, the liquid pressure starts from 0MPa 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 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 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.10, 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 agreement with the working condition of hydrodynamic deep drawing based on a combined floating and static die cavity.

Finite element simulation and preliminary experiment 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 obtained 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 0MPa and linearly rises to the maximum value of 16MPa when the die stroke reaches 28mm, and then maintains this value to the die stroke 50mm. In the second stage, the pressure rises linearly from 2MPa and up to 20MPa when the die stroke reaches 75mm, and then remains this value until the end of the process.

Adopted the pressure loading curve shown in Fig.11, the conical cups illustrated in Fig.6 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 wrinkle in the upper of the cone wall, as shown in Fig.12(a) and Fig.12(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.12(c) and Fig.12(d). One thing is very clear that the conical wall of the conical cup will inevitably appear 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.

The fracture usually occurs at the small end of the conical part during the conical part hydrodynamic deep drawing process, and the forming limit of the conical part is determined by both of the rupture and wrinkling. The thinning ratio of wall thickness is one of the simple and effective criteria for fracture judgment. Fig.13 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 0.5674mm, while that obtained from the ordinary hydrodynamic deep drawing is 0.5669mm. 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 improve 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 hydroforming process

4.1.1 Influence of maximum pressure in the first stage

The pressure-loading path is one of the key parameters during the HDDC, and has important effects on the forming process. The process of hydrodynamic deep drawing utilizing a combined static and floating die cavity can be divided into two stages, and then the corresponding pressure loading path is adopted two sage stepwise loading. As shown in Fig.14, 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, during the second stage, the cavity pressure starts from a pre-set value and rises lineally to the maximum value. 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 the forming part is studied by using the four pressure loading paths in the first stage as shown in the figure 14.

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 12~18Mpa, the roundness of the cross section of the conical part is lied in the mouth of the conical part, and the maximum value is 0.11mm. The wrinkling height of different height sections of conical parts is shown in Fig.15. It can be seen from Fig.15 that the wrinkling height of the parts is less than 0.09mm 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.16 that the dimensional accuracy and surface quality of the parts obtained under the maximum pressure of 16MPa are higher. The maximum value of the first stage and 16MPa is a best choice for the maximum pressure during the first stage.

4.1.2 The reaching moment of the maximum pressure of the first stage

In order to study the influence of the moment when the maximum liquid pressure arrives on the forming accuracy in the first stage of liquid pressure loading path, four loading paths are designed as shown in Fig.17. All of the maximum pressure in the first stage among the four pressure loading paths is 16MPa. 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 2MPa, and reaches the maximum liquid pressure of 20MPa when the punch stroke is 75mm, and the maximum liquid pressure is maintained until the punch stroke is 80mm.

It can be seen from Fig.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 20MPa, the maximum value is reached when the die stroke is 28mm, and the dimensional accuracy and surface quality of the parts are relatively high. In the first stage, under the premise that the floating punch plays 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 a key parameter during sheet hydroforming process, and the pressure loading path during HDDC process is divided into two stages as illustrated above. In order to investigate the effect of the maximum pressure of the second stage on the forming process, a series liquid loading paths illustrated in Fig.20 is adopted in the following investigations.

It can be seen from Fig.21 that the change of the maximum pressure in the second stage has little influence on the dimensional accuracy of the part. However, the change of the maximum pressure in the Stage2 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 the Fig.22 that when the pressure in the second stage is 20MPa, the wrinkle at the mouth of the conical part is the weakest, and the surface quality is relatively average.

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

In order to study the influence of the maximum liquids pressure arriving moment 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.23. As shown in Fig.23, with the punch stroke increasing, the liquid pressure rises linearly from 0MPa to the maximum of 16MPa when the punch stroke arrives at 28mm, and then maintains this value until to the punch stroke of 50mm while the first stage of hydraulic deep drawing is completed. In the second stage, all the four loading paths increase linearly from 2MPa to the maximum pressure of 20MPa, but there are differences in the time when the maximum pressure reaches and the maximum pressure arrives at 60mm, 65mm, 70mm and 75mm respectively.

Fig.24 shows the influence of the maximum force arriving moment on the roundness and wrinkling height of the formed part in the second stage of pressure loading. As shown in Fig.24, the moment when the maximum liquid pressure reaches in the second stage has a significant impact on the precision of the formed part. As shown in Fig.25, 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 75mm, 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 Figure 26. As shown in Fig.26, in the first stage, the liquid pressure rises linearly from 0MPa and reaches to the maximum value of 16MPa at the punch stroke of 28mm, and then maintains the value until the punch stroke of 50mm, 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 completely finished. The four loading paths are mainly different from the initial pressure, which are set as 0, 4, 6 and 10MPa respectively.

Fig. 27 shows the maximum winkle 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 completed is most beneficial to the dimensional accuracy and surface quality of the formed parts.

4.3. Influence of blank holder force on forming accuracy

As illustrated in Fig.10, a two stages pressure loading strategy for the blank holder force (BHF) is used in hydrodynamic deep drawing process utilizing a combined static and floating die cavity. Three kinds of BHF of the first stage, 30t, 40t and 50t, 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 40t. The simulation results are shown in the Fig.28 and Fig.29. 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.

In the case of the blank holder force for the first stage keeping 40t, 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, 40, 50 and 60t are set respectively. The result of forming precision is shown in the Fig.30 and 31. 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 50t.

5. Conclusion

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

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 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.

The influence of the blank holder force in the second stage on the forming accuracy is more significant than that in the first stage.

Declarations

Ethical Approval：Not applicable.

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

Consent to Publish: All authors have read and agreed to the published version of the manuscript.

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Figures

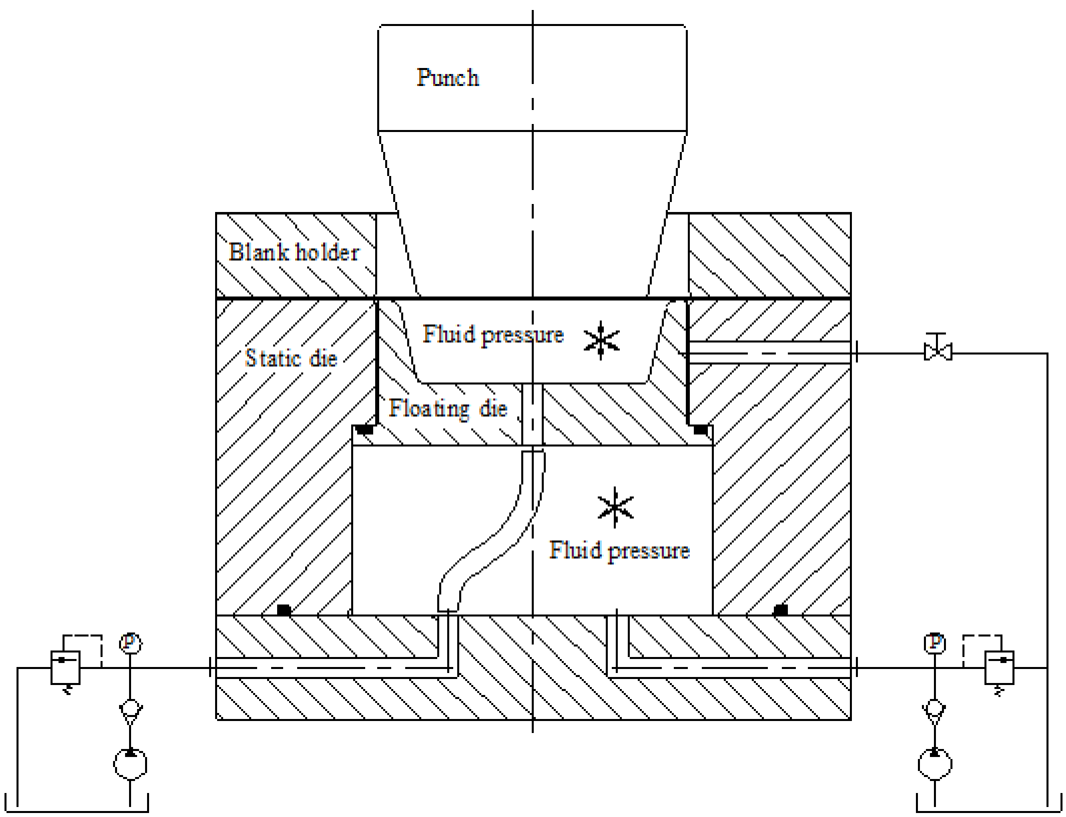

Figure 1

Schematic diagram of hydrodynamic deep drawing utilizing a combined static and floating cavity

Figure 2

The process of the hydrodynamic deep drawing utilizing a combined die cavity

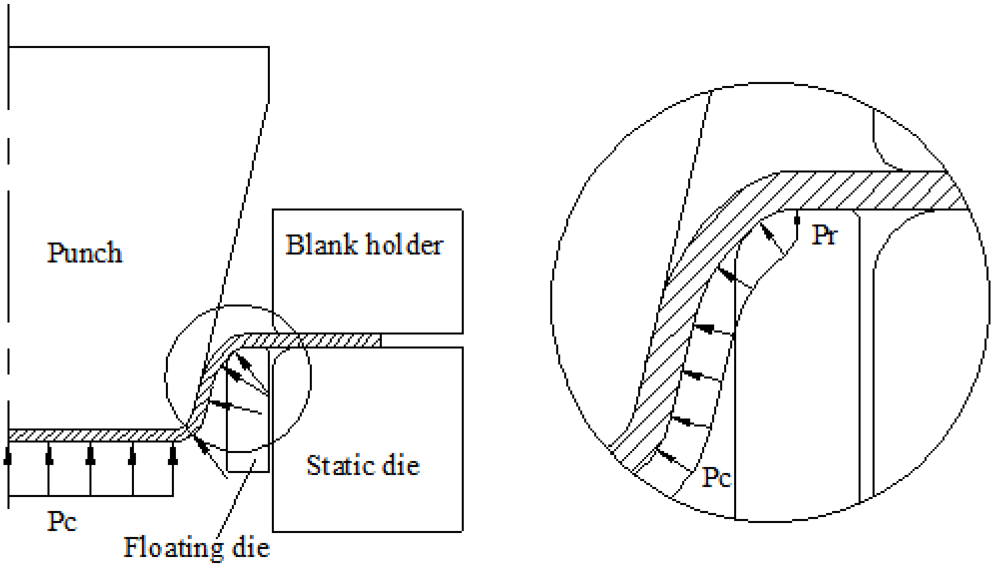

Figure 3

Pressure boundary conditions in the first stage of HDD utilizing a combined cavity

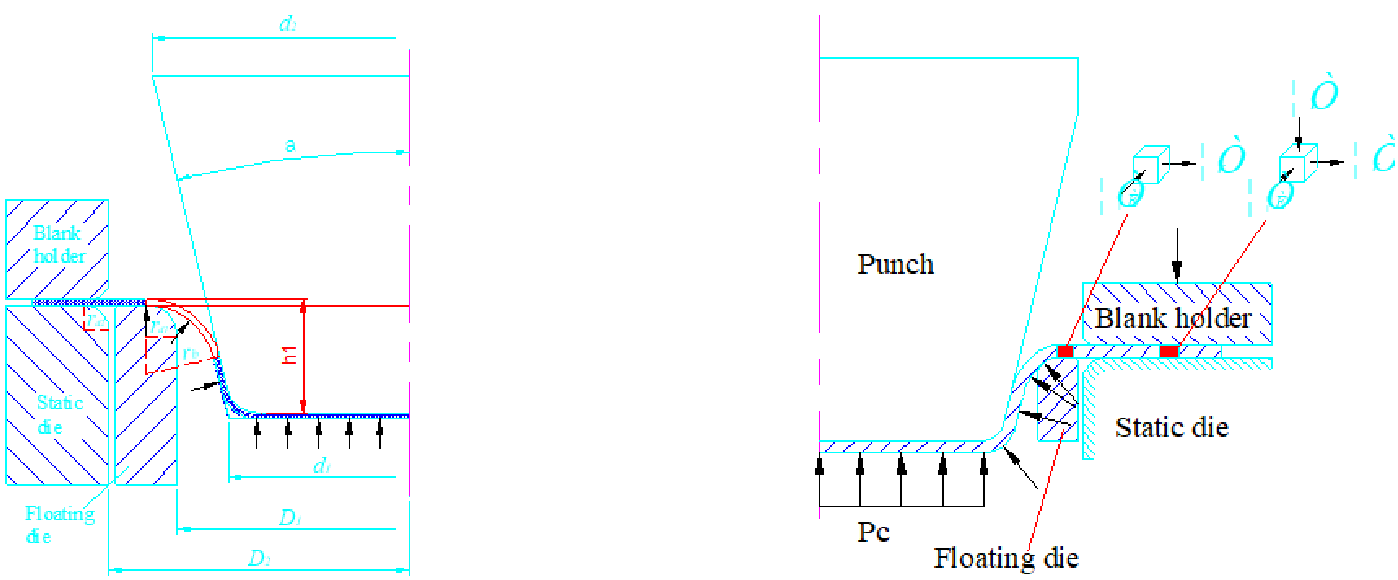

Figure 4

Contact conditions of sheet metal at the fillet of the floating during HDDC process

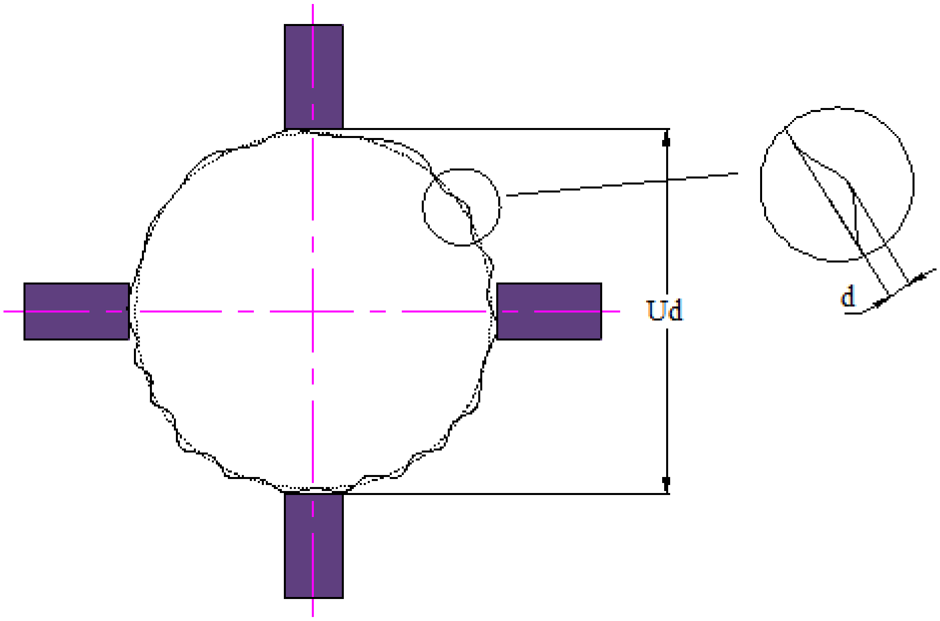

Figure 5

Schematic diagram of evaluation method for roundness and wrinkle height of the formed parts

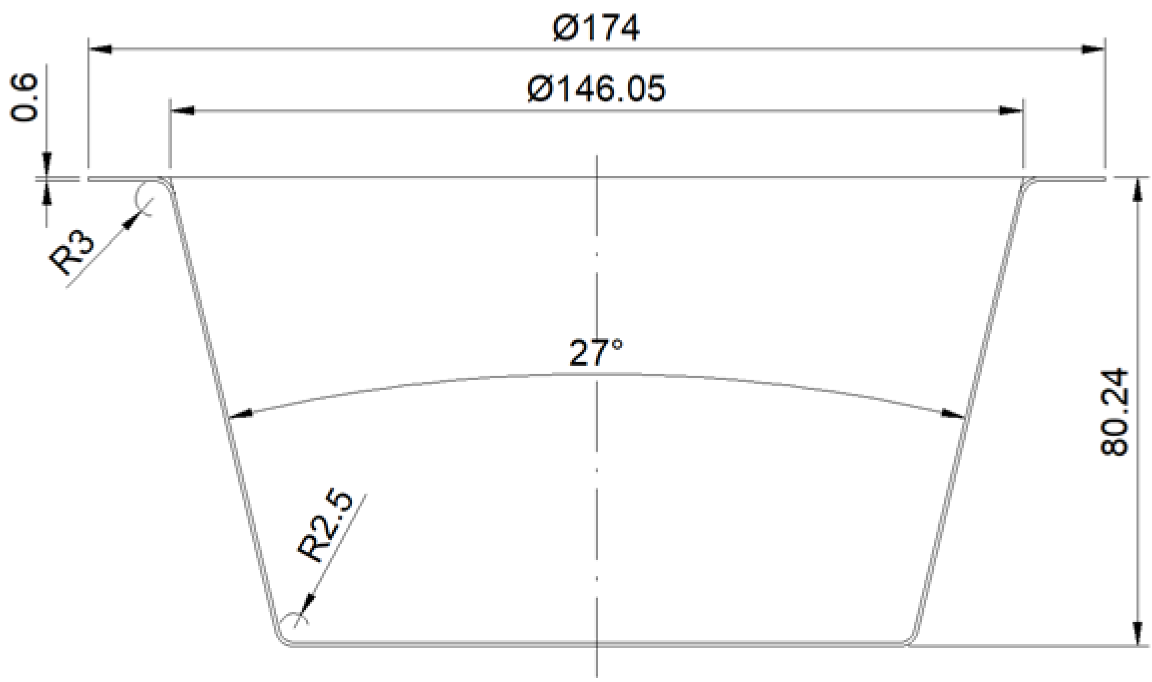

Figure 6

Dimensional scheme of the parts used in this study

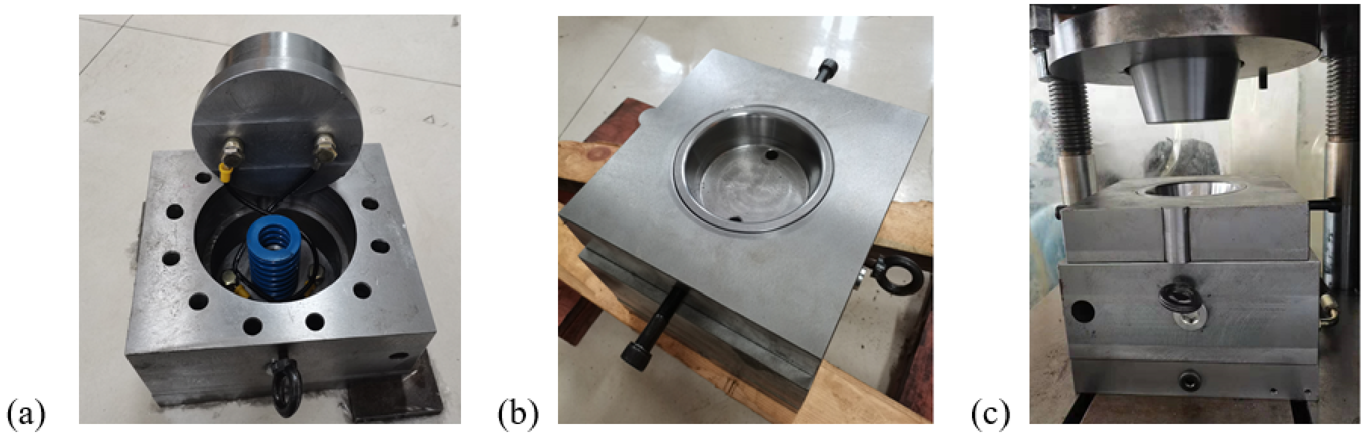

Figure 7

The combined die cavity used in this study

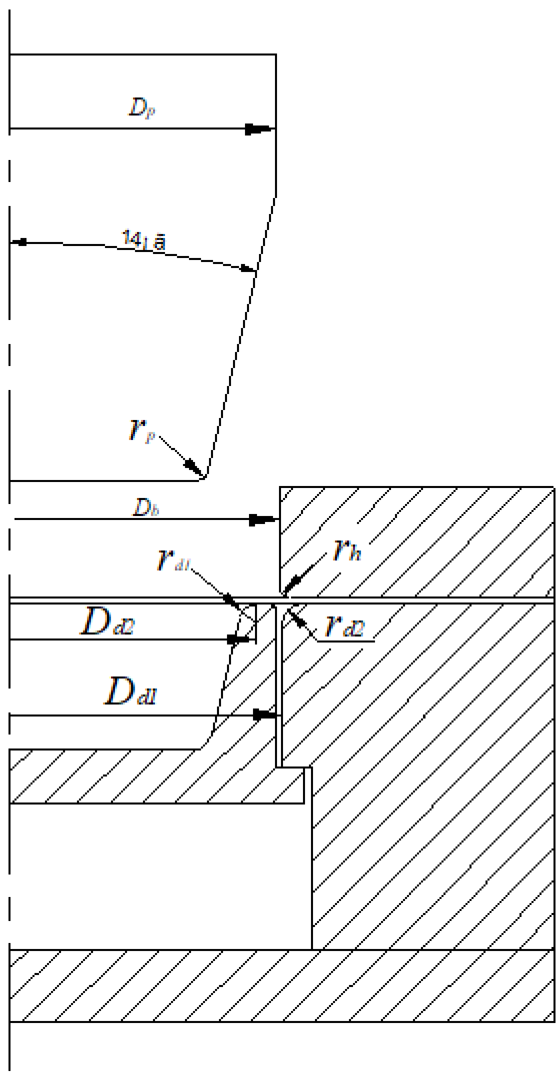

Figure 8

The marked parameters of the setup used in this research

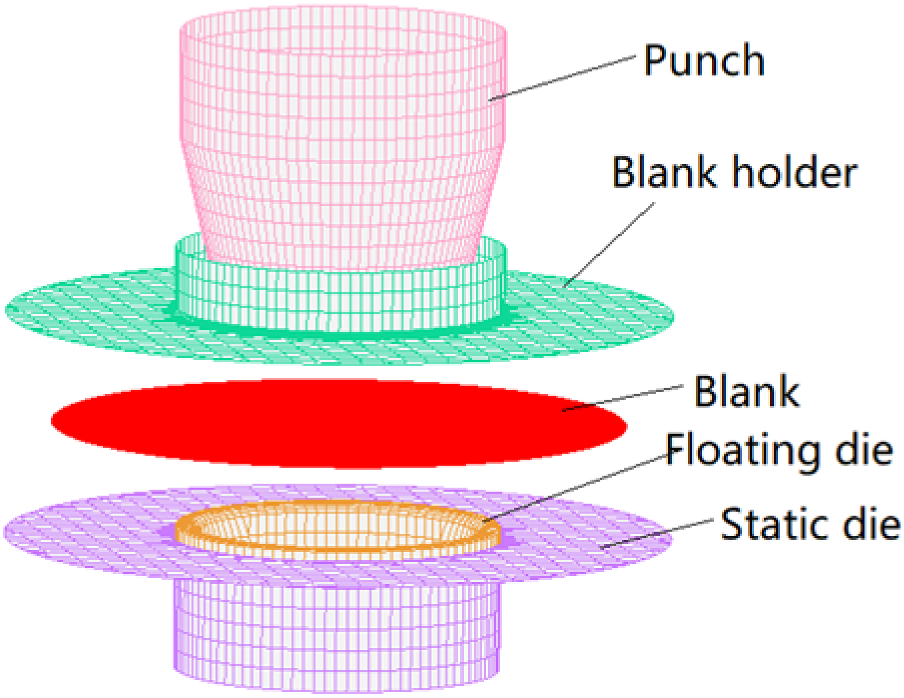

Figure 9

FEM model for HDDC

Figure 10

A typical loading pressure path used in HDDC

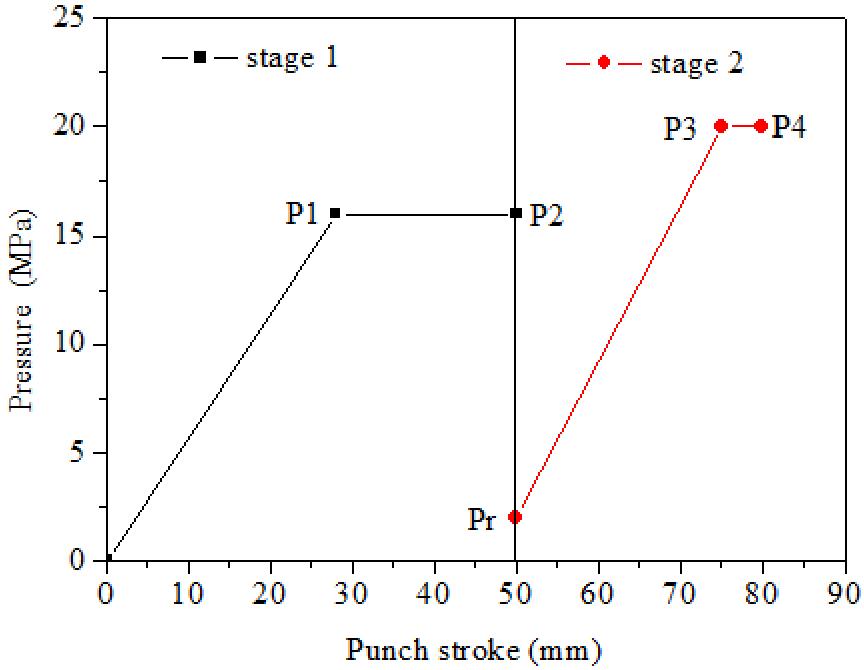

Figure 11

The pressure loading path used in the preliminary simulation and experiment

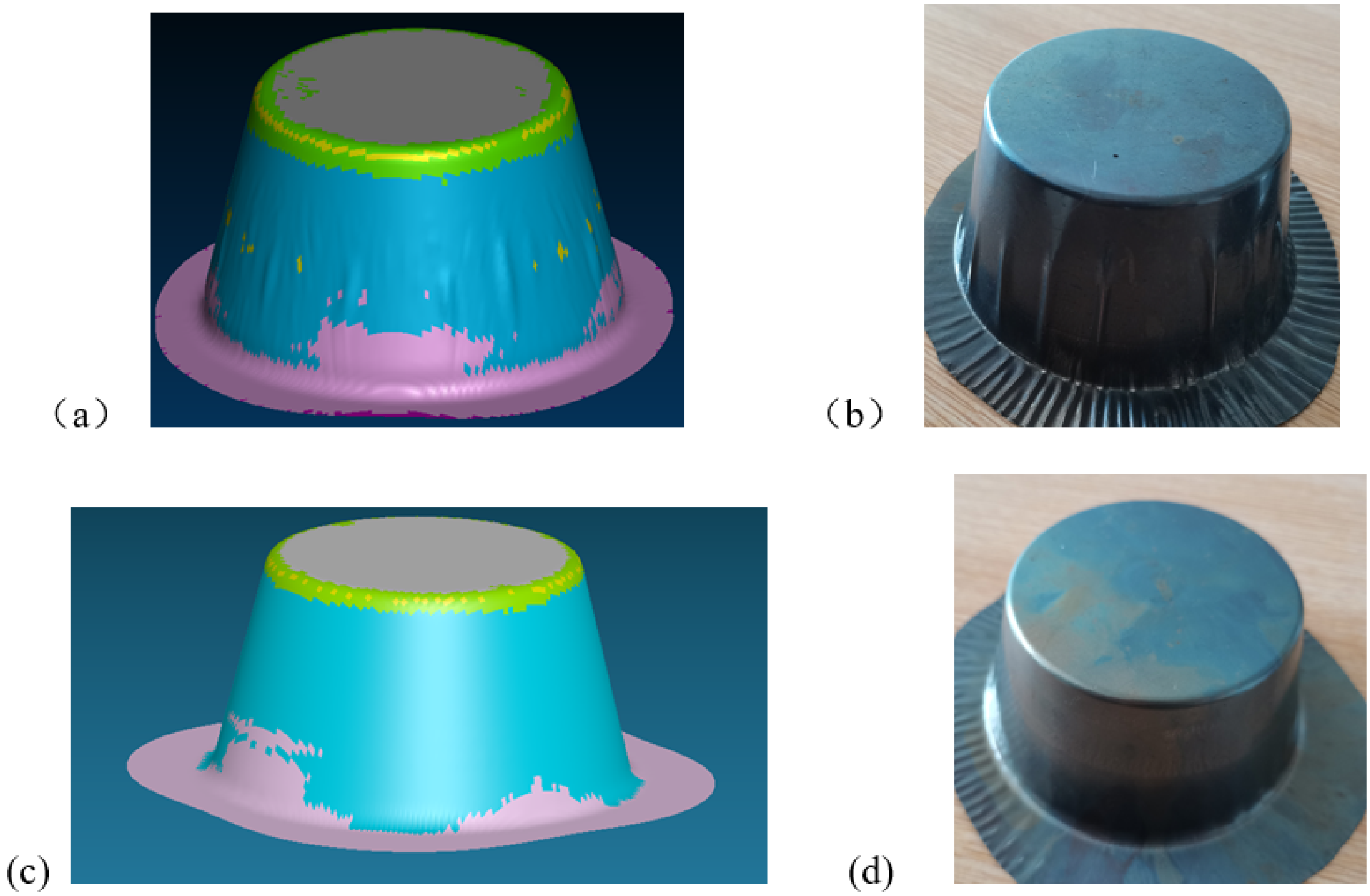

Figure 12

The comparison between the parts obtained by simulation and experiment of two different forming methods

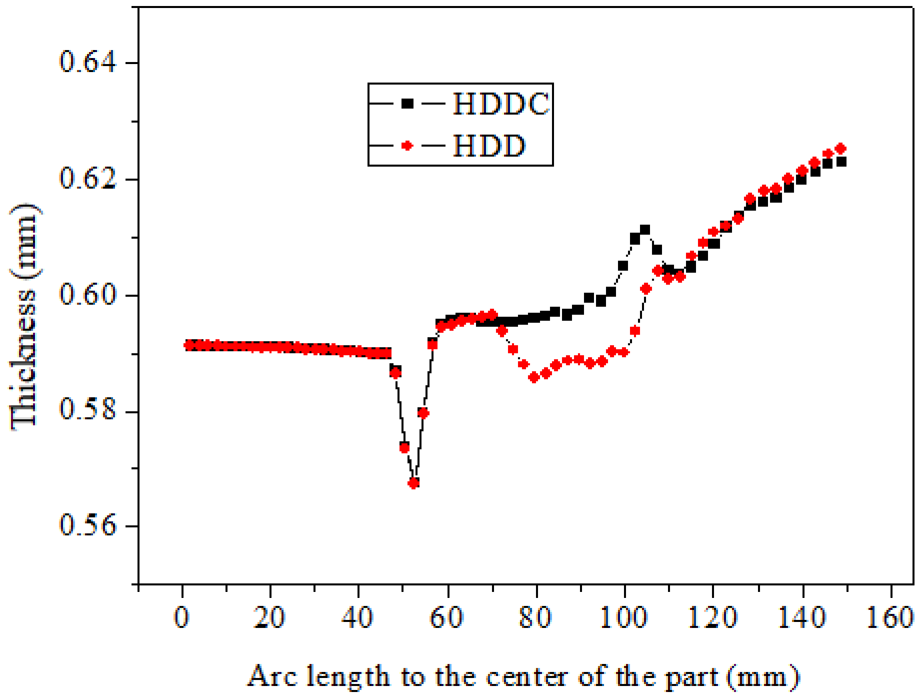

Figure 13

Comparison of the wall thickness distribution of the parts formed by HDD and HDDC

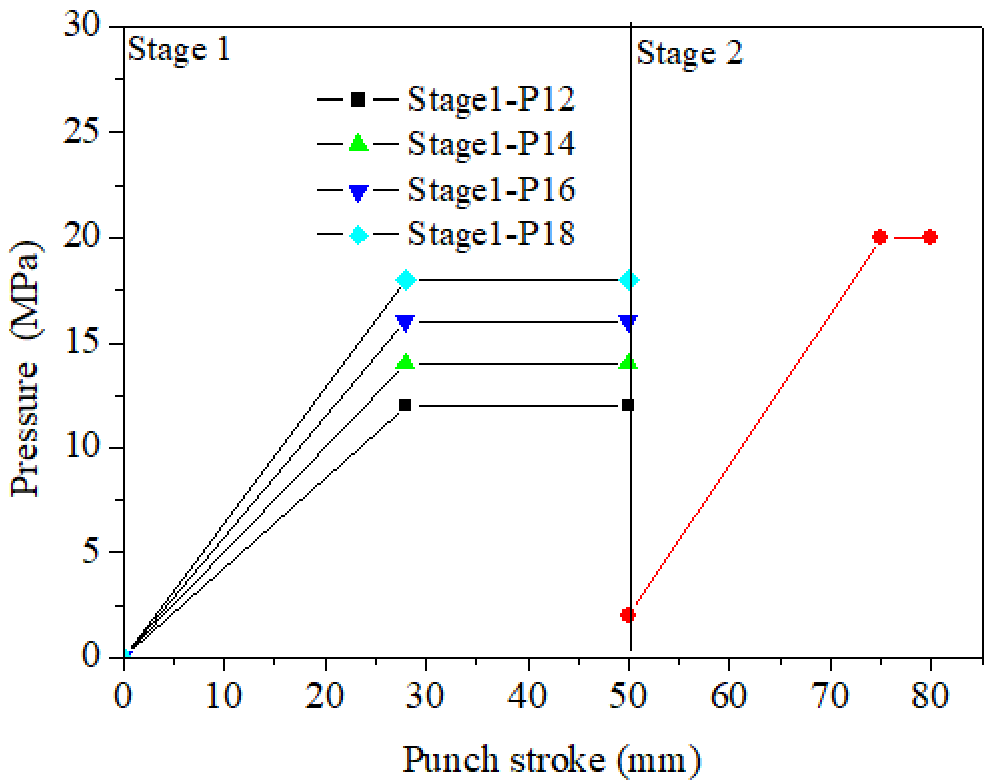

Figure 14

Pressure loading paths with different maximum pressures in the first stage

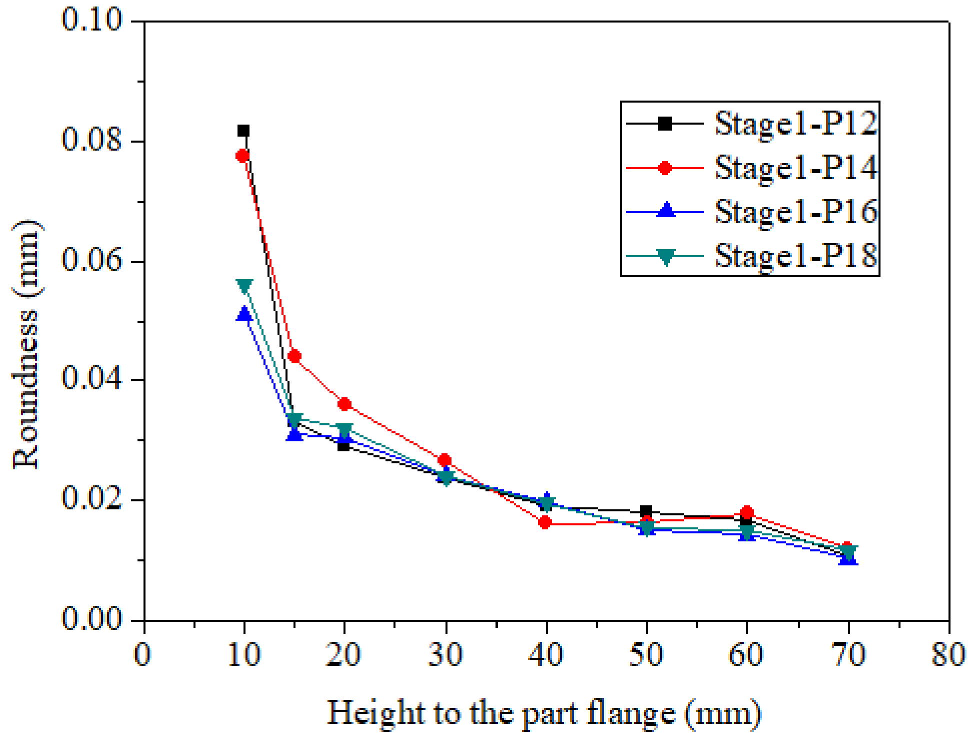

Figure 15

Influence of the maximum pressure in stage1 on the roundness of the formed parts

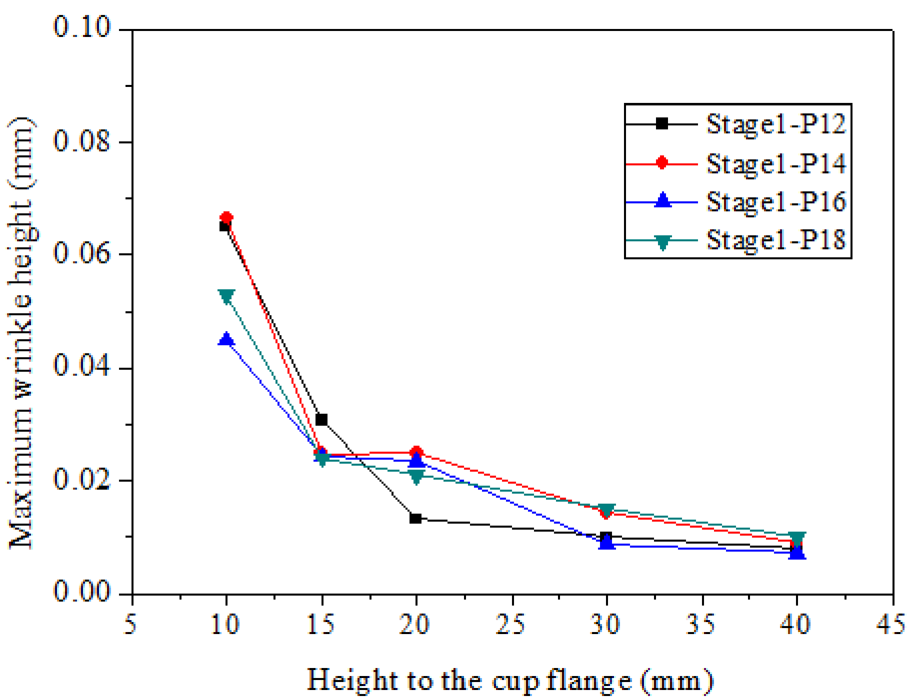

Figure 16

Influence of the maximum pressure in stage1 on the maximum wrinkle height of the formed part

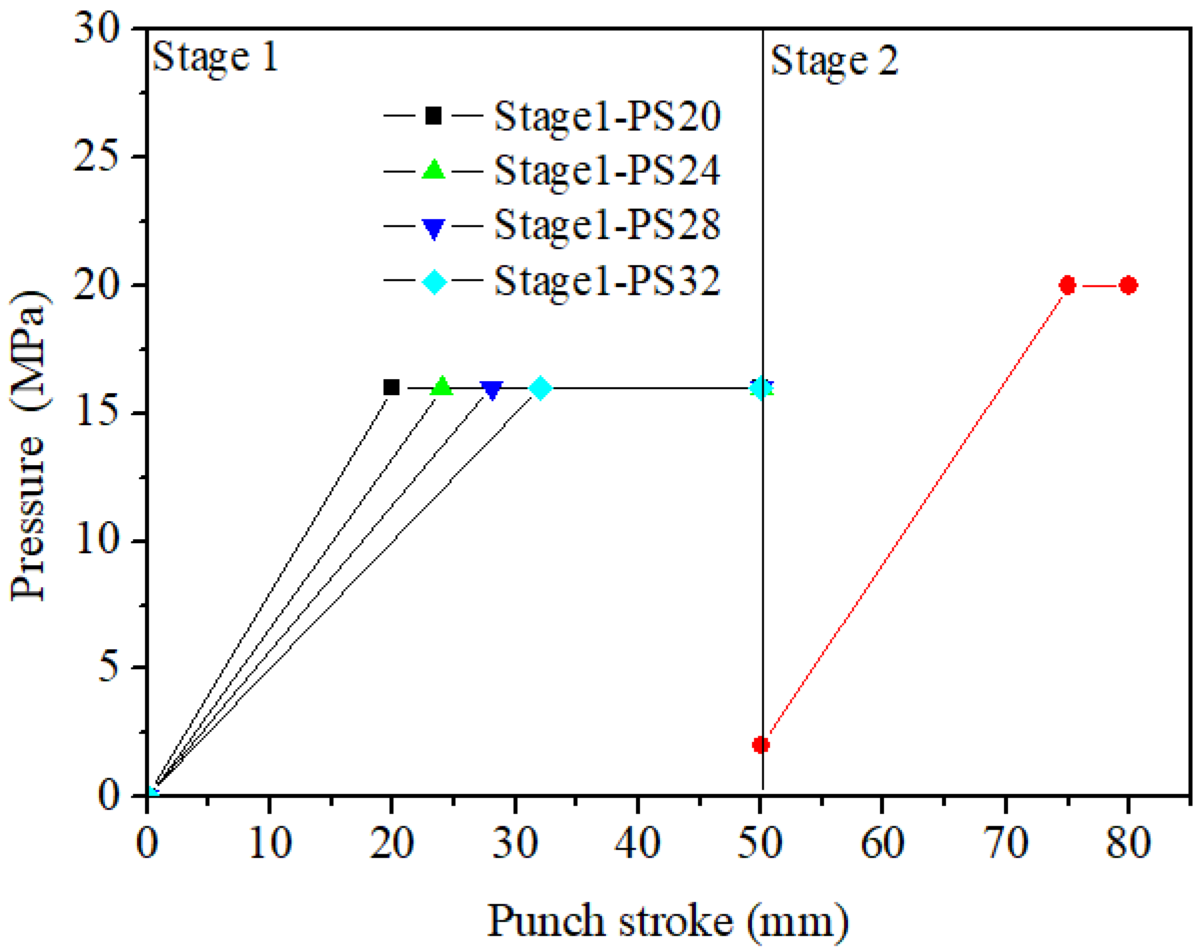

Figure 17

Pressure loading paths with different maximum arriving moment of stage2

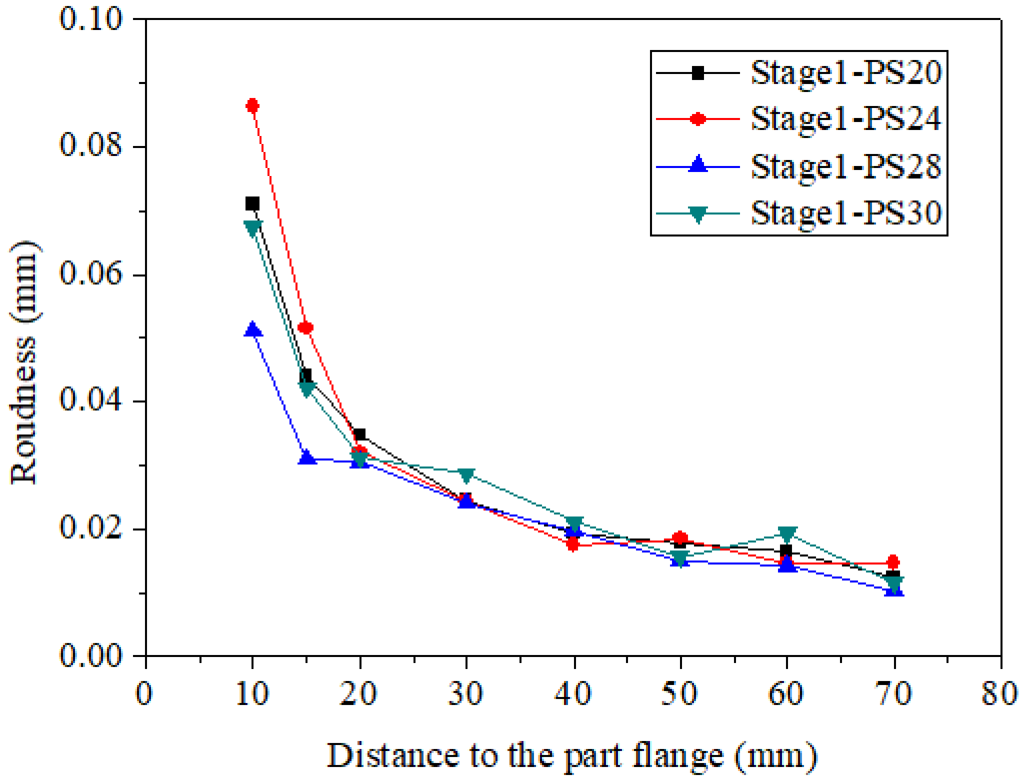

Figure 18

Influence of the arriving moment of the maximum pressure in the first stage on the part roundness

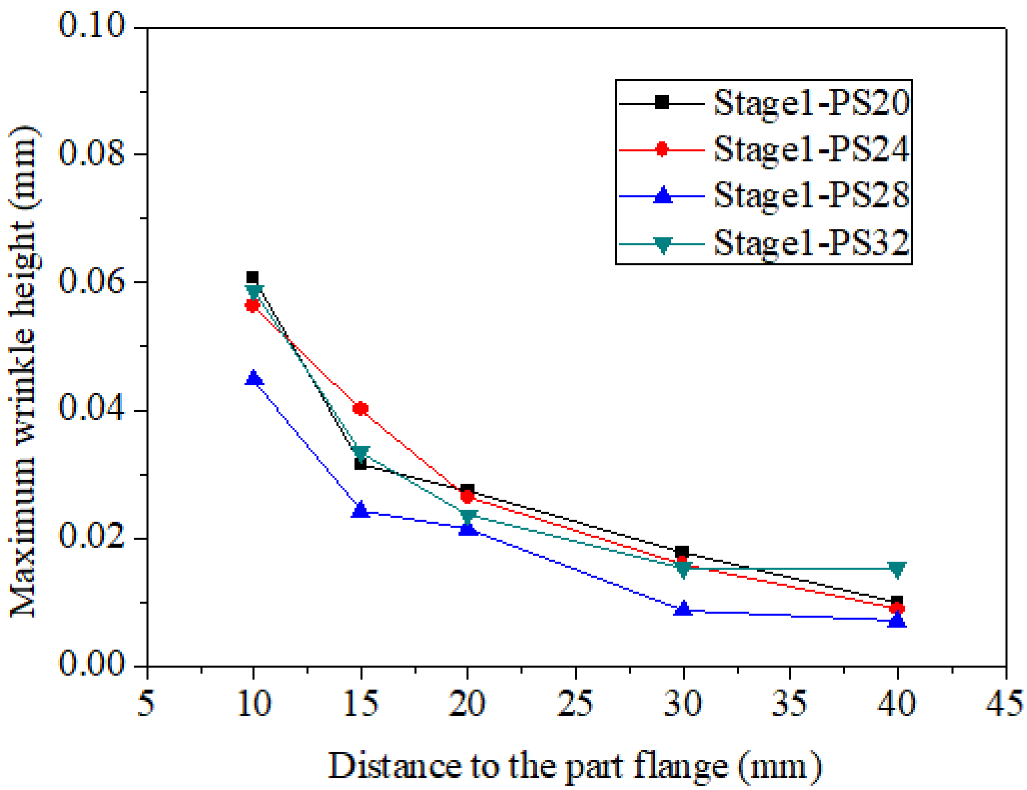

Figure 19

Influence of the maximum pressure arriving moment in stage1 on the maximum wrinkle height of the formed part

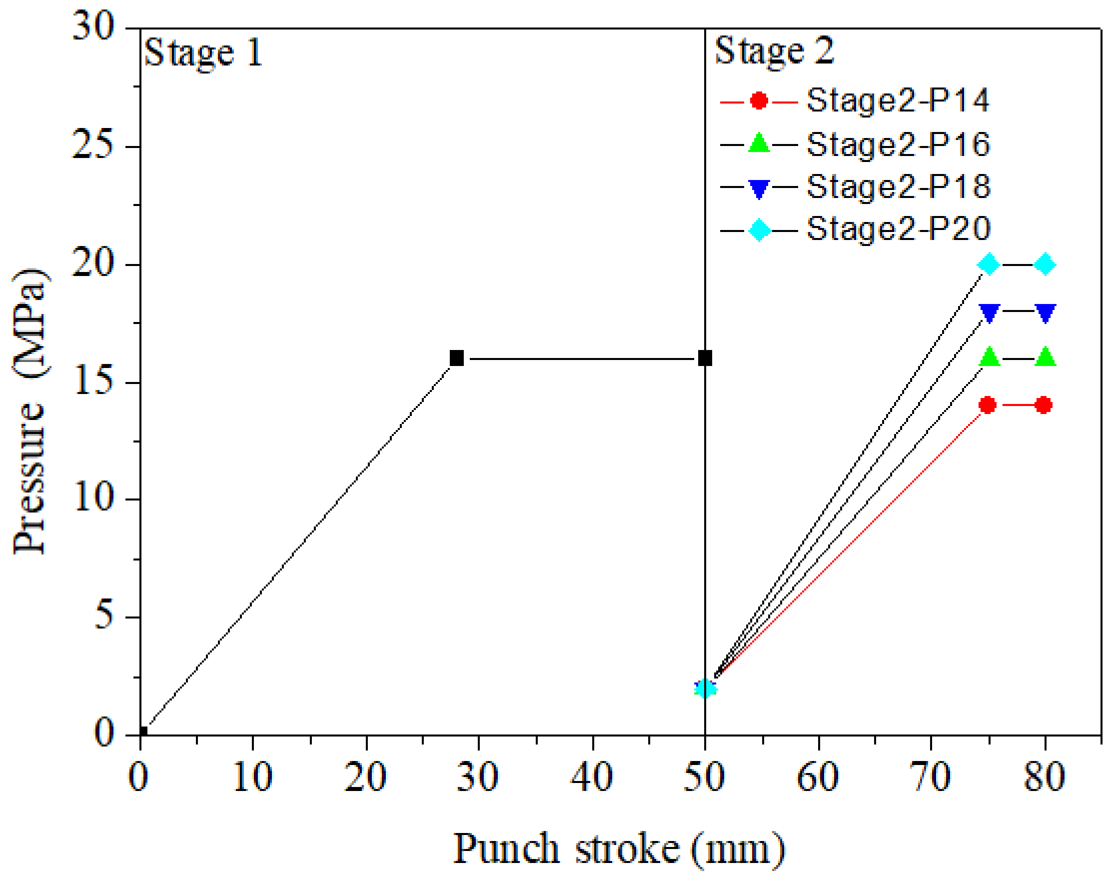

Figure 20

Pressure loading paths with different maximum pressures in stage 2

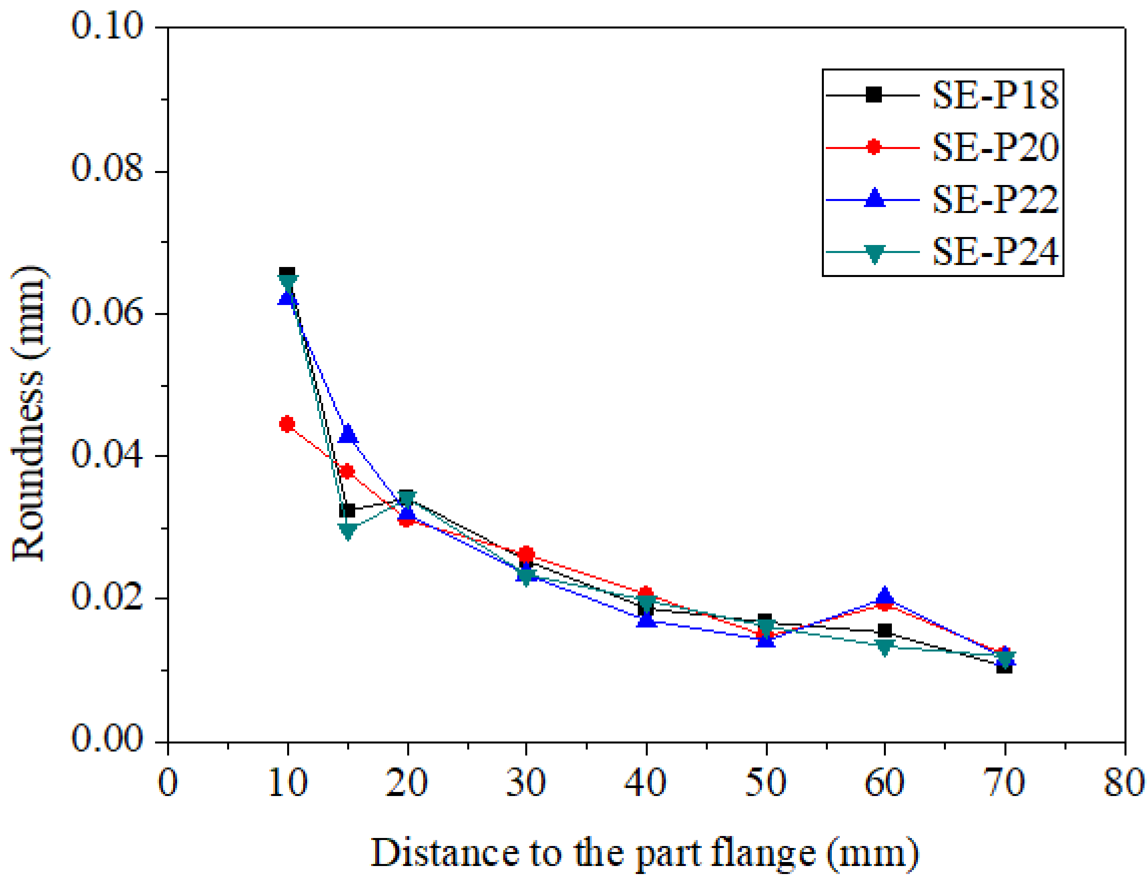

Figure 21

Influence of the maximum pressure in stage2 on the roundness of the formed parts

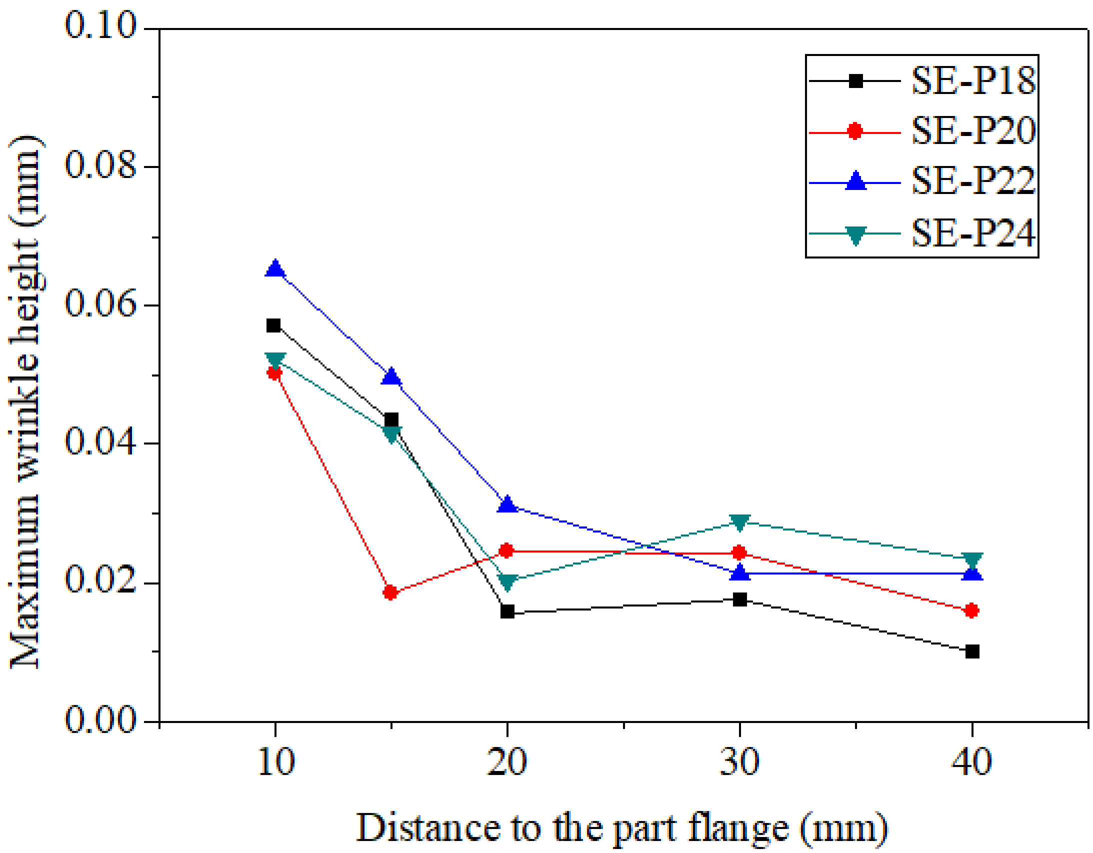

Figure 22

Influence of the maximum pressure in stage2 on the maximum wrinkle height at different heights of the formed part

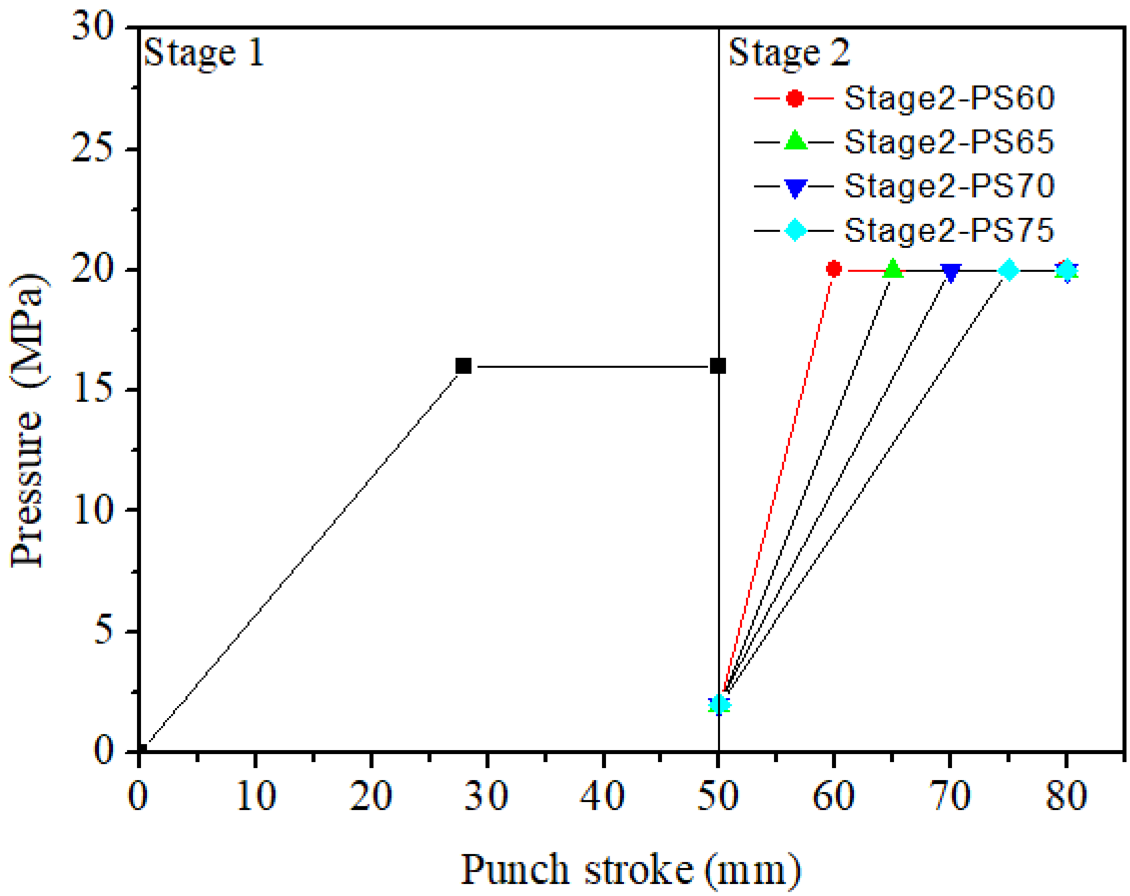

Figure 23

Pressure loading paths with different maximum pressure arriving moment during stage2

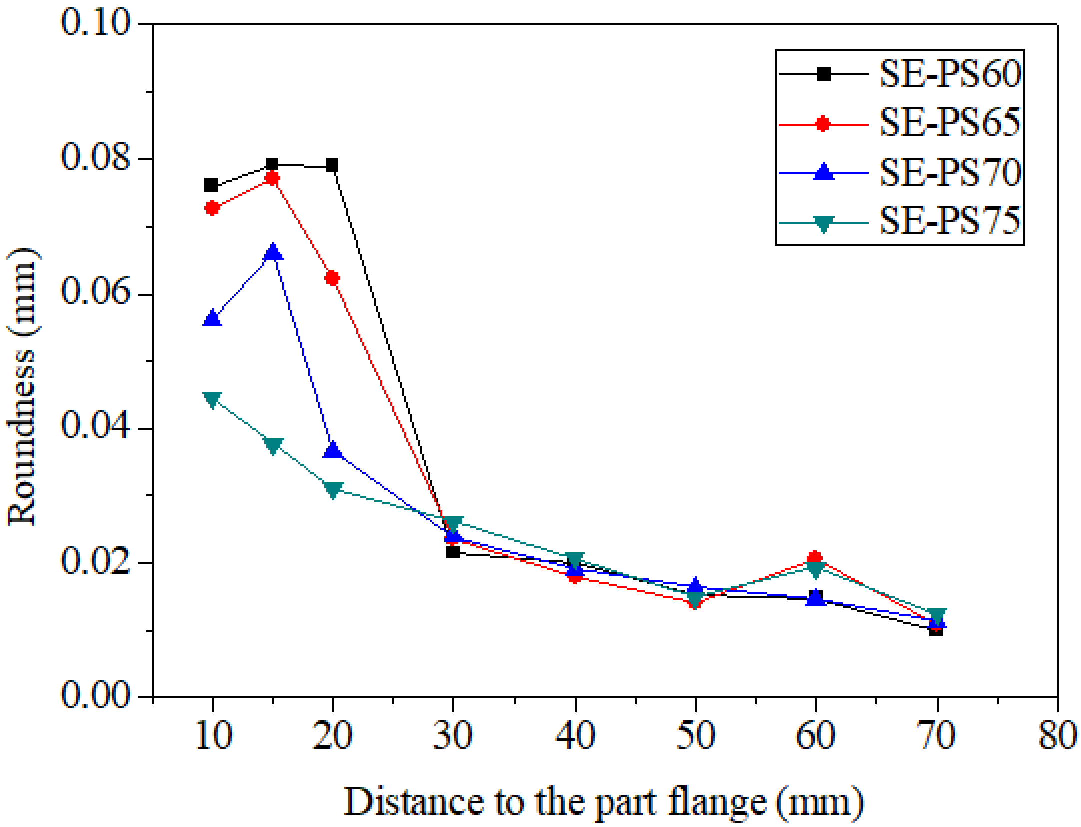

Figure 24

Influence of maximum pressure of the second stage arriving moment on roundness at the different height of the part

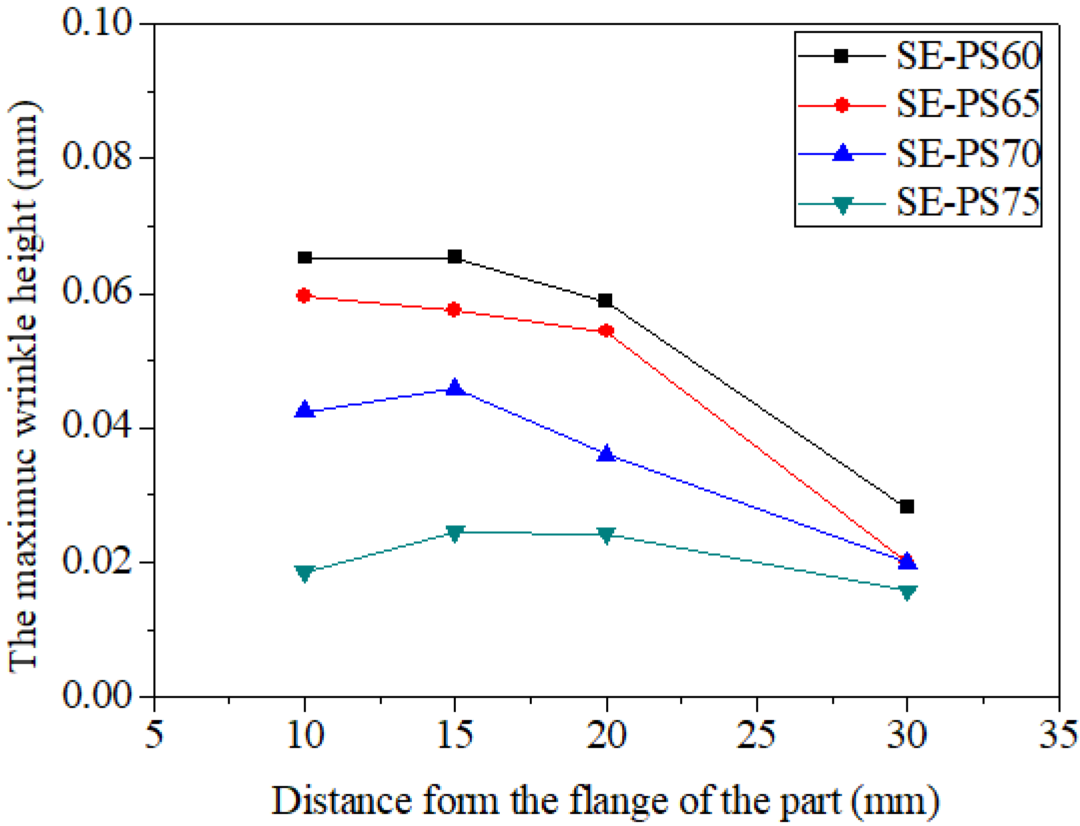

Figure 25

Influence of the maximum pressure reaching moment in stage 2 on the wrinkle maximum height of the formed part at different heights

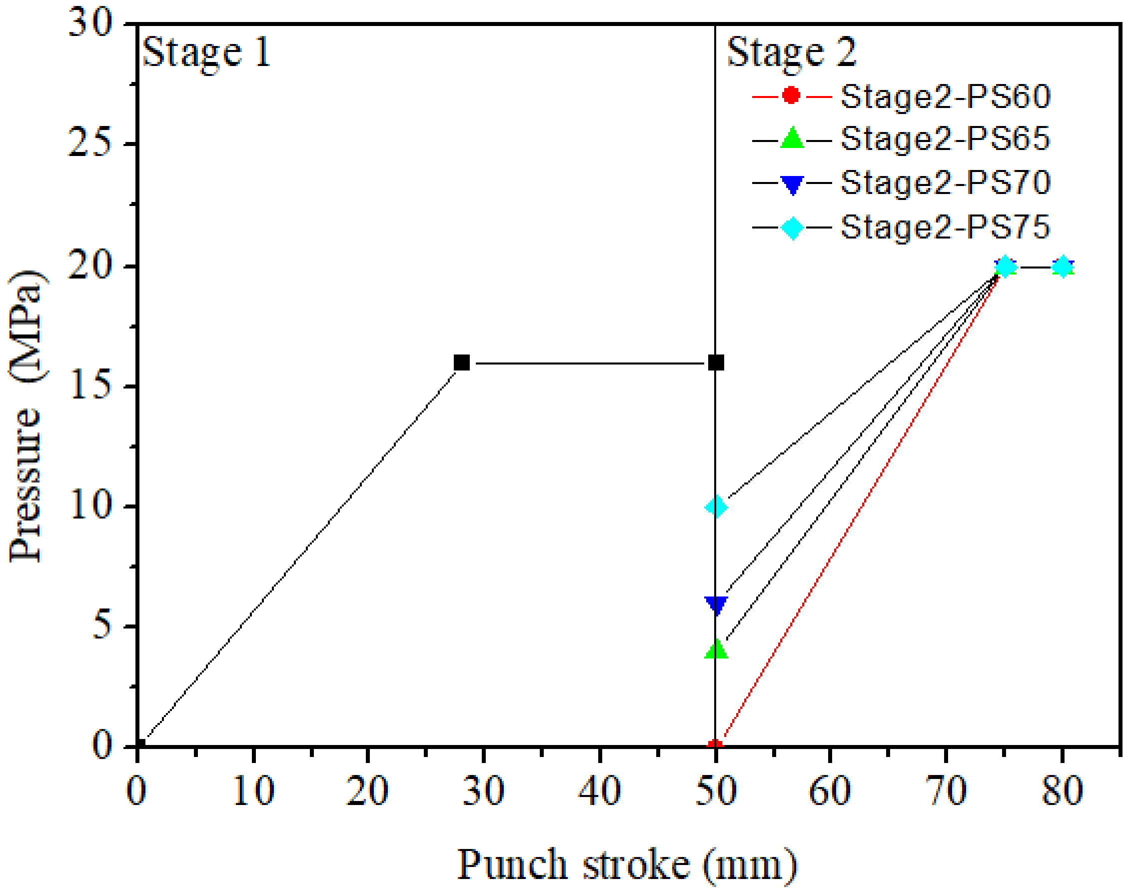

Figure 26

Pressure loading paths with different initial pressure of the second stage

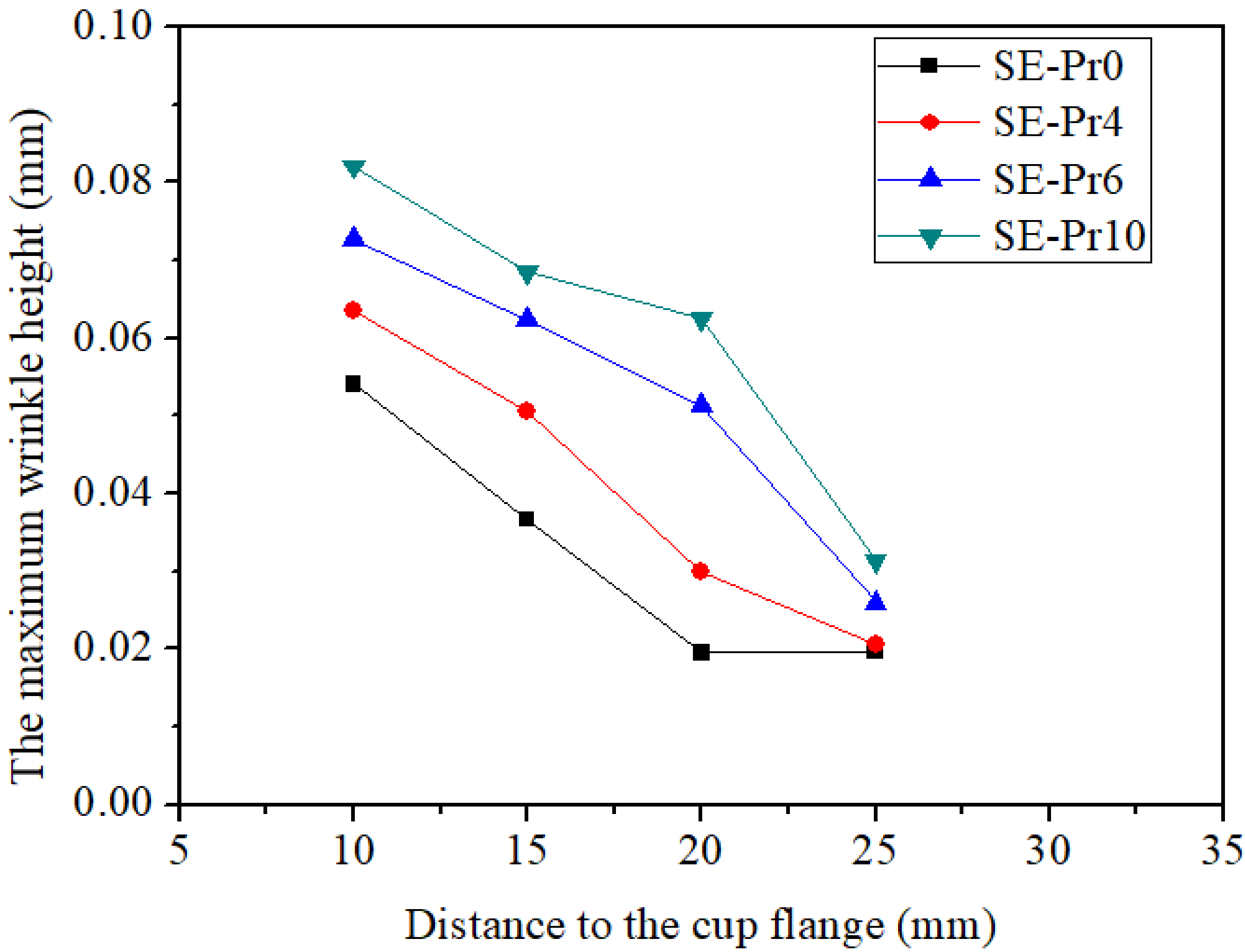

Figure 27

Maximum wrinkling height of the formed parts at different heights

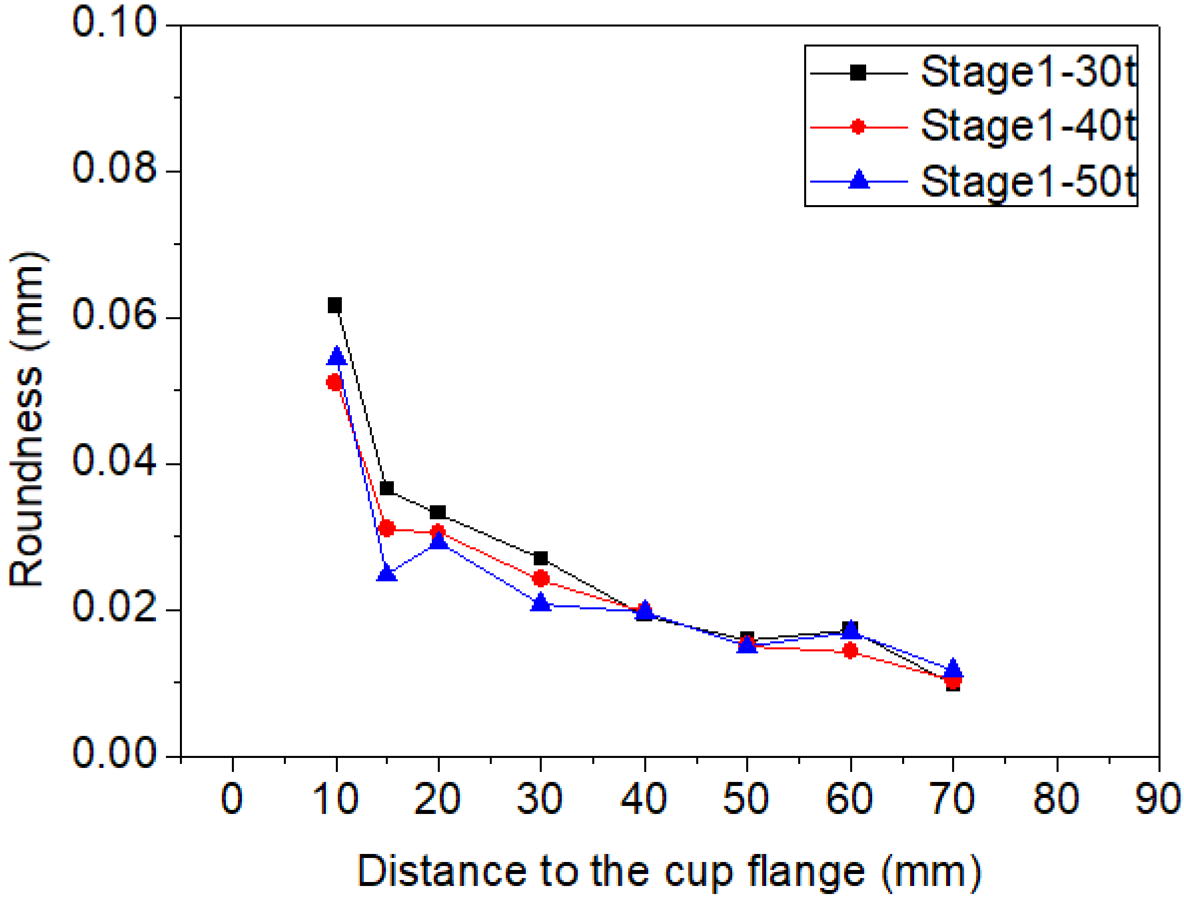

Figure 28

Influence of the blank holder force of stage1 on roundness of the formed parts

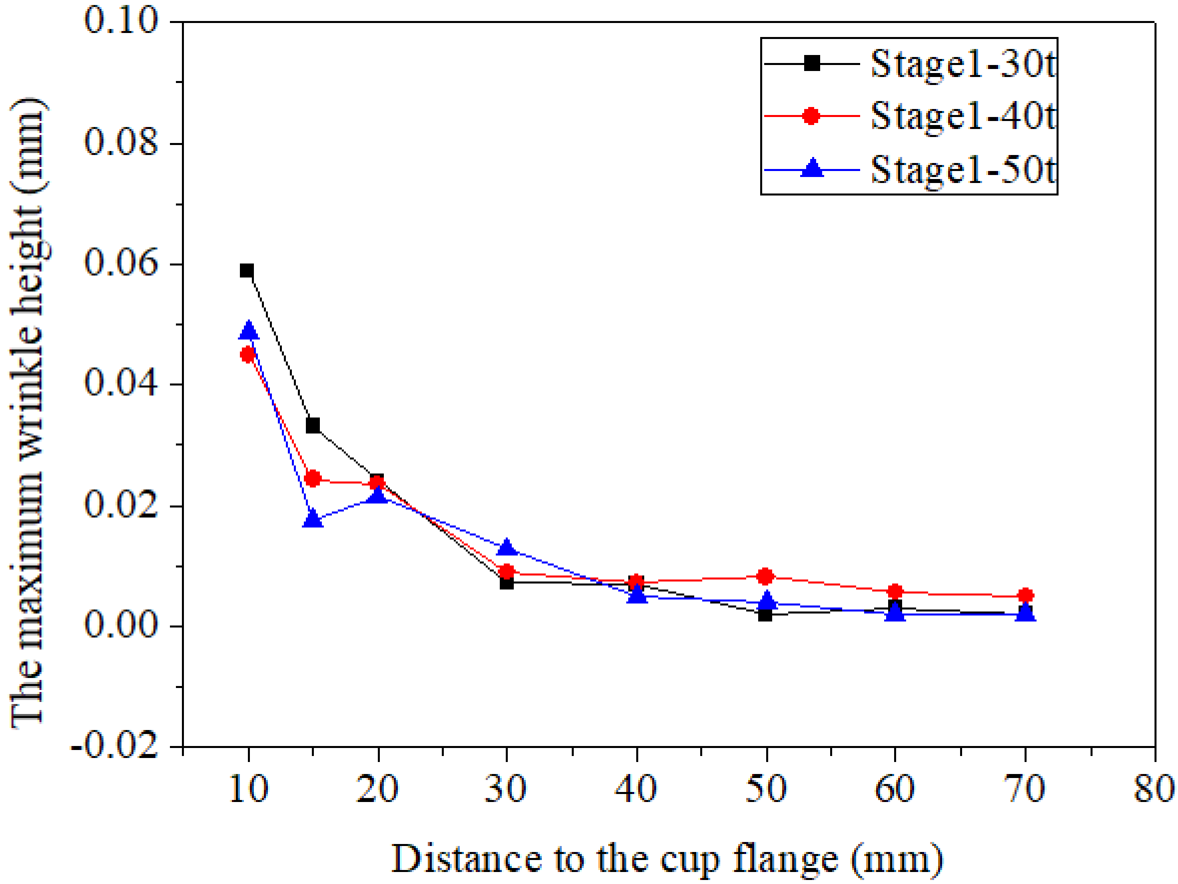

Figure 29

Effect of blank holder force of stage1 on maximum wrinkle height of formed part at different heights

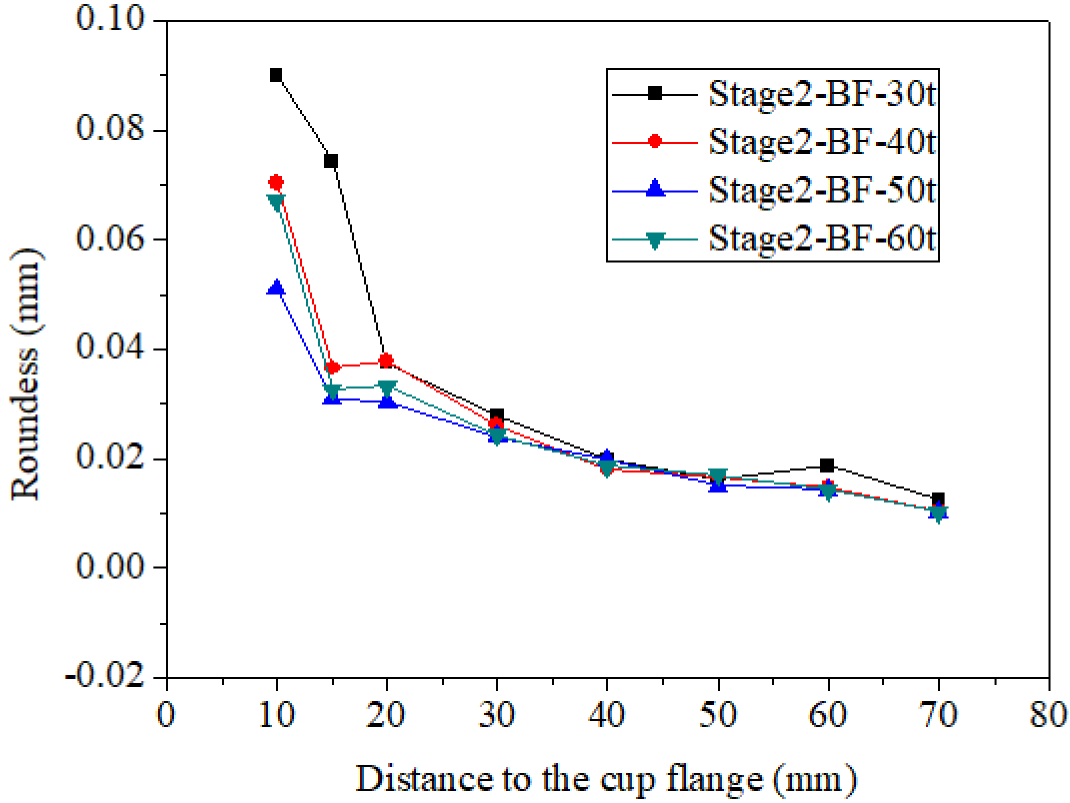

Figure 30

Influence of BHF of Stage2 on roundness of formed parts

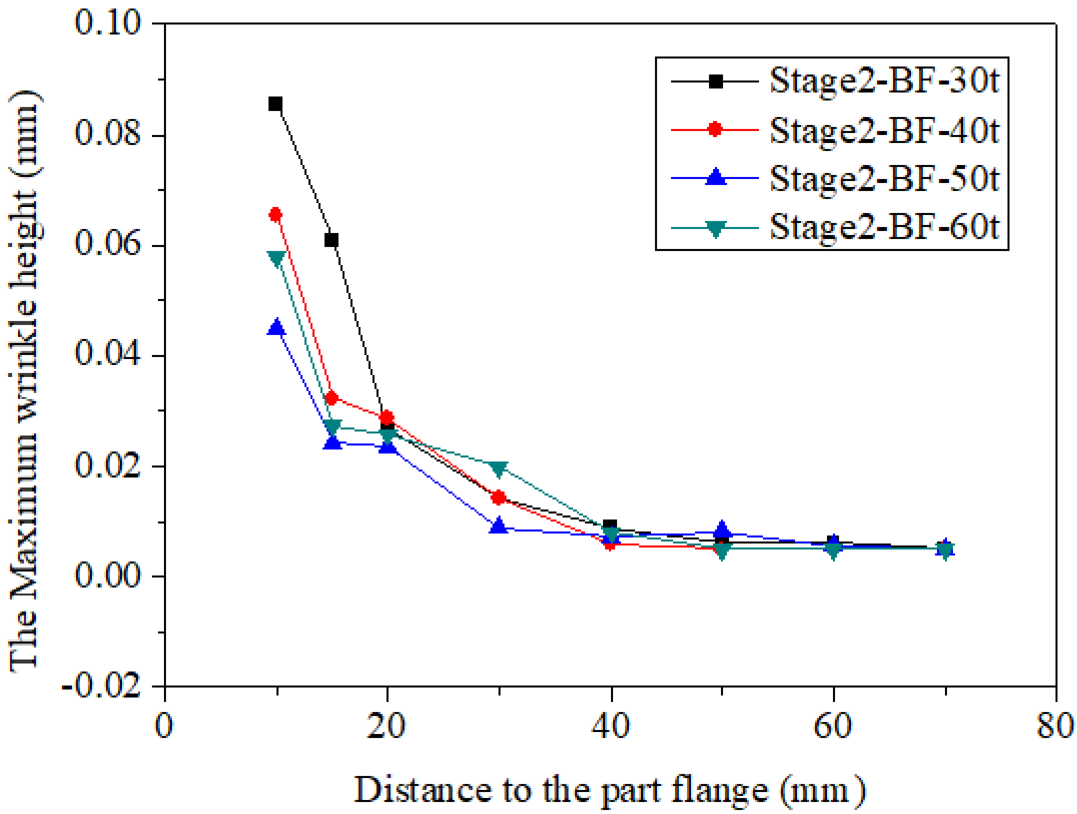

Figure 31

Effect of the BHF of Stage2 on maximum wrinkle height of formed parts at different heights