Investigation of a Modified Hydrodynamic Deep Drawing Assisted by Radial Pressure with Inward Flowing Liquid Process

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Abstract. Hydrodynamic Deep Drawing (HDDRP), the combination of hydroforming and conventional deep drawing, accommodates the advantages of the two processes. A technique, called HDDRP with inward flowing liquid, has been introduced based on the idea of insertion of radial pressure around the blank rim. The radial pressure created on the blank edge, can increase the drawing ratio. Thus, increasing the radial pressure to an amount greater than the cavity pressure, and independent control of these pressures is the basic idea of this research for forming cylindrical parts. To perform the experiments, two independent pumps were used to provide the two pressures independently. The pressure supply system and the die set were designed in a way that provides simultaneous control of the pressures throughout the process. Then, the effects of radial pressure paths on thickness distribution of cylindrical St13 cups were investigated. In addition, a comparison between HDDRP and HDDRP with inward flowing liquid processes has been performed experimentally. Results indicated that using a higher radial pressure than the cavity pressure and controlling their values at any moment of the process enhances the thickness distribution of the formed part in all regions.

Keywords: Hydroforming, Sheet metal, Steel

1 Introduction

Of the various metal forming processes, hydroforming is one of the non-traditional ones. This technique uses a pressurized fluid or gas in place of a conventional solid tooling like punch, die, etc. for manufacturing purpose. So, liquid is used as the medium of energy transfer to form the workpiece. Since 1990s hydroforming has been widely adopted for making metal sheet components in many industrial fields, especially in the automotive, aerospace, electronics and kitchen industries [1-3].

Production of sound parts by using hydroforming, mainly depends on different important parameters such as control of liquid pressure, blank holding force, exact design of tooling and process capability [4, 5] .

By development of technologies, different hydroforming methods have now been proposed such as standard hydroforming [6, 7], hydromechanical deep drawing [8], radial hydromechanical deep drawing (hydro-rim) [9], hydrodynamic deep drawing assisted by radial pressure [10] and hydrodynamic deep drawing process assisted by radial pressure with inward flowing liquid [11].

Kandil [7] carried out an experimentally investigated the effect of process parameters such as sheet material properties, punch geometry, punch load, initial pressure for cylindrical cup forming. The results showed that by using hydroforming deep drawing process compared with conventional deep drawing process, higher limiting drawing ratio can be achieved and uniform strain distribution along the cup wall were obtained.

Bagherzadeh et al. [8] studied the application of hydro-mechanical deep drawing process on laminated sheets. Their analysis includes 3D finite element (FE) simulation with implementing Fortran based code for accurate modelling of non-uniform oil pressure distribution. To verify FE results, some experiments were conducted on the laminated aluminium/steel sheet. Their results showed that higher limiting drawing ratio (LDR) and lower thinning in low formable aluminium sheet would be achieved in Al/St lay-up than St/Al lay-up.

Tirosh et al. [12] exerted external fluid pressure on the blank rim in Hydro-rim process to reduce radial stress and to decrease the interfacial friction. They reported that the most important benefit of this method is that if changes in the material properties can be controlled, by controlling the process speed, higher drawing ratios can be reached.

Gorji et al. [10] studied forming of copper and St14 conical–cylindrical cups in the HDDRP process. The effect of pressure path on the thickness distribution and drawing ratio of the sheet was also investigated. They

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illustrated that for the pressure path with a certain maximum amount, the part was formed with appropriate thickness reduction. They reported an LDR of 9.76 in forming pure copper conical cups. The HDDRP process has been developed by Wang et al. [11], called HDDRP with inward flowing liquid. The key point in this process is that a radial pressure higher than the cavity pressure will be achieved if the liquid flees inward from the rim cavity to the die cavity. They demonstrated that this mechanism can decrease the forming force and increase the LDR, significantly.

In this paper, the HDDRP assisted by radial pressure with inward flowing liquid has been further modified. The effects of different parameters have been investigated by the simulation method in the previous work [13]. In this process, the mechanism of the implementation of the hydraulic circuit and its repeatability are examined. Also, the mechanism of the formation of higher radial pressure and the method of simultaneously controlling the cavity and radial pressures was studied. Eventually, the effect of higher radial pressure on thickness distribution has been examined experimentally.

2 Experimental Procedure

The schematic of the pressure supply in the modified HDDRP with inward flowing liquid and the dimensioned geometry of the die set are illustrated in Fig. 1.

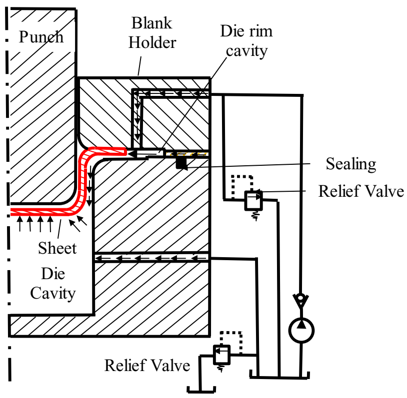

Fig 1-a: Scheme of the die set and pressure unit.

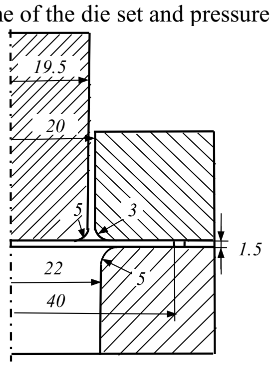

Fig. 1-b. Schematic of the die set with the geometrical dimensions (mm).

Fig. 2 shows the components of assembled die set for the hydroforming of cylindrical cups. A Denison and Mayes Group universal testing machine with a capacity of 600 kN, was used to form St13 circular blanks. For the supply of liquid pressure, a variable flow rate hydraulic pump with the maximum pressure of 50MPa and a constant flow rate hydraulic pump with a maximum pressure of 100MPa were used. Fig. 3 illustrates the typical pressure path used in the experiments for the cavity and radial pressures. In the hydroforming process, a small pre-bulging can be created on the sheet bottom to improve the drawing process. In this research, 1 MPa pre-bulging pressure was applied (path OA). After the pre-bulge stage, the pressure was linearly increased (path AB) to a maximum value (path BC). The slope of this path depends on different parameters such as the punch velocity, sheet thickness and punch profile bottom [14]. The punch speed is about 20 mm/s. The pressure path variation was controlled by a computer system connected to a digital manometer.

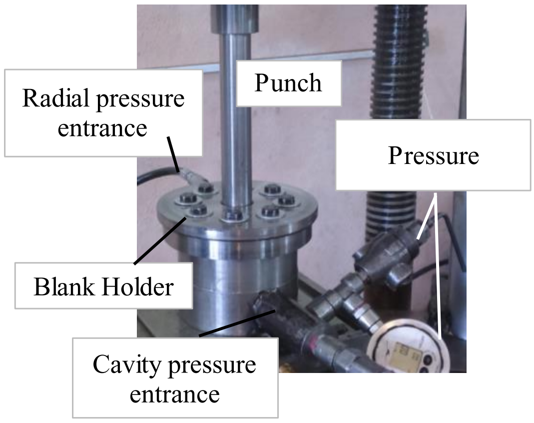

Fig. 2. HDDRP with inward flowing liquid die set.

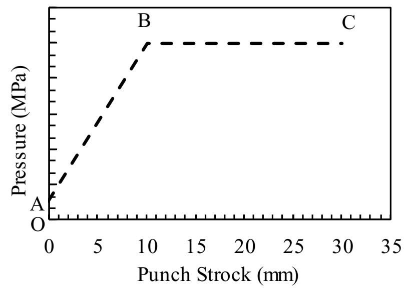

Fig. 3 Typical pressure path in this study.

2.1 Material properties

Table 1 shows material properties obtained from uniaxial tensile tests, where specimens were cut at different orientations to the rolling direction (0°, 45°, and 90°) according to ASTM-A370 standard. The sheet diameter and thickness were 80 mm and 1.5 mm, respectively.

Table 1. Mechanical properties of St13 sheets [13].

Parameter	Value
Poisson's ratio	0.32
Young's modulus, (GPa)	210
Strain hardening exponent	0.29
Harding coefficient, (MPa)	539
Yield stress, (MPa)	158
Anisotropy value (r_0)	0.972
Anisotropy value (r_{45})	1.1761
Anisotropy value (r_{90})	1.361

2.2 Die and hydraulic circuit design

In designing the die of this process, the most important goal was to create a radial pressure higher than the cavity pressure. For this purpose, according to Fig. 1-a, the die should be sealed to prevent oil leakage and pressure drop. Therefore, as shown in Fig. 1, an O-ring was used for sealing in the die using the standard mentioned in [16] to prevent fluid leakage. Moreover, because of high pressure and leakage prevention, the blank holder was fastened to the die by eight high strength screws (Fig. 6).

Fig. 6 The O-rings used for sealing the die.

The second most important point in creating higher and controllable radial pressure at any moment is that the radial pressure be created independently by an additional pump (Fig. 1). Therefore, the pressure from the second pump should be transferred in a way to around the blank rim. For this purpose, as shown in Fig. 7, the conventional balnkholder is redesigned. Inside the blank holder, a path was embedded to flow liquid from the pump toward the gap between the die and the holder.

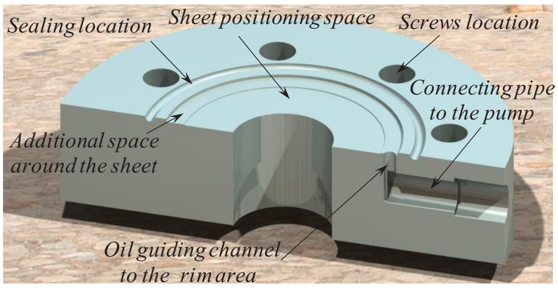

Fig. 7 The different sections of blank holder.

The hydraulic circuit of this process is shown in Fig. 8. As can be seen, this process uses two independent pumps to create pressure. The cavity pressure path is also controlled at any moment through a digital manometer connected to a computer. Also, the radial pressure path is measured and controlled by the analog manometer in the pump at any time. Two relief valves were attached to the die cavity and the blank rim cavity to control the maximum pressure values of the cavity and radial pressures. After the pressure in the cavity and rim area reached the maximum values, the relief valves were opened, and the process continued with the constant pressure. Utilization of two independent pumps provides the possibility of controlling the radial and cavity pressure paths, simultaneously[13].

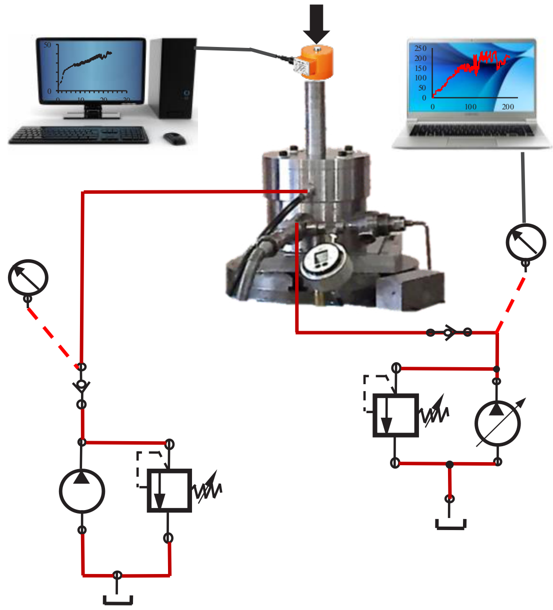

Fig. 8 Hydraulic circuit of modified HDDRP with inward flowing liquid.

3 Process simulation

For the process simulations, the commercial software, ABAQUS 6.13 /Explicit, was used. Fig. 4 shows the FE model of the die set. By considering the symmetry of the process, only one-quarter of the sheet and the die set is modelled [15]. The blank was modelled as 3D deformable with C3D8R element. The die components were considered rigid and R3D4 element type was assigned to these parts. The thickness distribution of the formed cylindrical cup is the most important parameter investigated in this paper. So, five elements were used in the thickness direction to measure precisely the thickness variation. The anisotropy property for St13 sheet was simulated based on the parameters shown in Table 1. Thus, the Hill yield criterion was used to define anisotropic yielding [13]. The friction coefficient was assumed to be 0.14 between the sheet and punch surface but for other surfaces, it was considered 0.04 [14]. The contact algorithm between the sheet and die components, was modeled as penalty method based on Coulomb law. During the process the punch could only move in the z-direction parallel to its central axis and the other die components were fully constrained. In HDDRP with inward flowing liquid, the liquid pressure distribution under the blank flange area is different from that in the conventional Hydroforming deep drawing (Fig. 5). Based on the fluid model proposed by Wang et al. [3] the non-uniform distribution of the fluid pressure under the blank flange area was considered and embedded into the FEM model by a suitable subroutine *VDLOAD based on Visual Fortran code and implemented in ABAQUS.

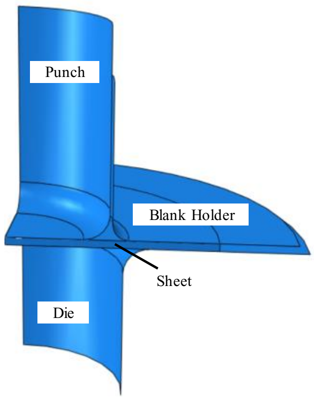

Fig. 4. FE model of the die set.

The pressure distribution in the r-direction can be obtained by Eq. (1) where the boundary conditions can defined as $P = P_R$ at $r = R$, where R is the instant radius of the sheet flange and $P = P_C$ at $r = R_1$, that R_1 is the die entrance radius [11].

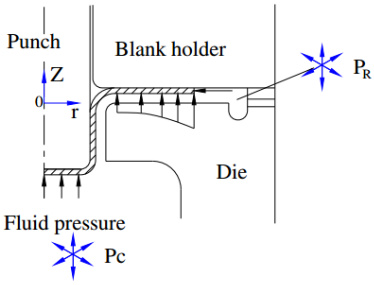

Fig. 5 Pressure distribution in the flange area[11].

$$P_r = P_R - (P_R - P_C) * \frac{\ln(r/R)}{\ln(R_1/R)} \qquad (1)$$

Since increasing the radial pressure to a value higher than the cavity pressure depends on the parameters such as die design, pump power and oil properties and leakage, it should be determined that how much the radial pressure can be increased. So, to illustrate this issue and to more closely examine the process, the Fluent software was used.

4 Results and Discussions

The results of the simulations showed that for forming an St13 cylindrical part in HDDRP with inward flowing liquid, the maximum pressure of 20 MPa is required at least. In order to determine the maximum possible radial pressure, based on the specifications of the pump and the die, the Fluent software was used. The simulation was performed based on the geometric dimensions of Fig. 1-b. The results of this investigation are shown in Figure 9. As can be seen, according to the dimensions of the die and the minimum forming pressure of the cavity as input data, radial pressure up to 65 MPa can be created.

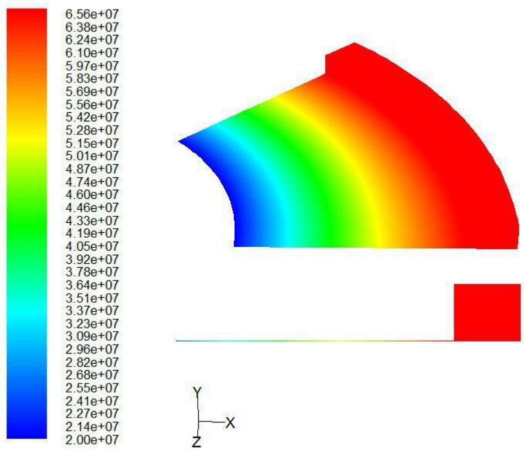

Fig. 9 Fluid Analysis of process with Fluent software, Pressure distribution diagram in the flange area, (MPa).

By Increasing the size of the gap between the punch and die : the part does not contact to die properly so it does not fully form. Also, reducing the size of the gap causes the part contact with die become increases and the wall thickness decreases.

An experimental test was carried out at the cavity pressure of 30MPa and the radial pressure of 57MPa. The 57MPa pressure was the maximum radial pressure that obtained in the experimental state. Because of not reaching the pump to its maximum power the difference with the maximum value of the experimental results and the Fluent software was existed. Figure 10 shows the thickness distribution obtained from experiment and simulations at the same punch stroke for St13 material. As it is shown in the figures, there is a good agreement between the simulation and experimental results.

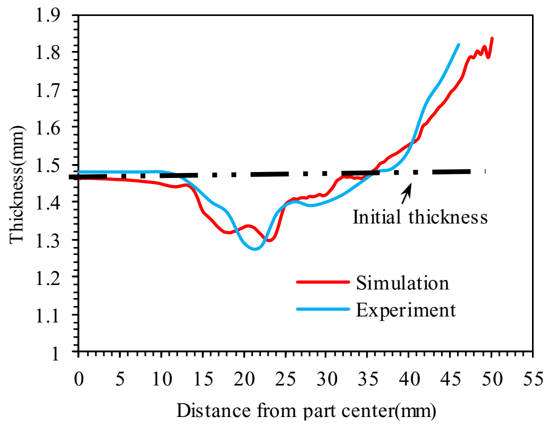

Fig. 10 Thickness distribution curves of formed St13 parts: radial pressures, 57MPa; cavity pressure, 30 MPa; Punch stroke, 29.5 mm

To ensure the repeatability of the test, this test was performed again (radial pressure (55MPa) is approximately equal to the first time (57MPa)).

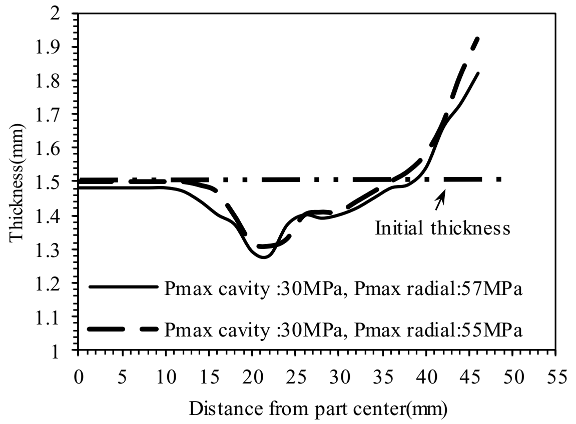

Fig. 11 Thickness distribution curves of formed St13 parts with same pressures; cavity pressure, 30 MPa; radial pressures, 57 and 55MPa Punch stroke, 29.5 mm.

The maximum radial pressure depends to the specifications of pressure supply system, the die geometry and initial blank thickness. Also, the effect of the radial pressure depends on the parameters such as the gap between the blank holder and the die, the gap between the punch and the die, the thickness of the sheet, and so on. Fig.12 shows the effect of the gap value variation between punch and die on part thickness distribution. The effect of gap variation between the punch and the die shows before value of 1mm, the thickness distribution improves but more than 1 mm (for the gap values of 1.5 to 2mm), the workpiece was not formed successfully in the end of wall area as shown in Fig13."

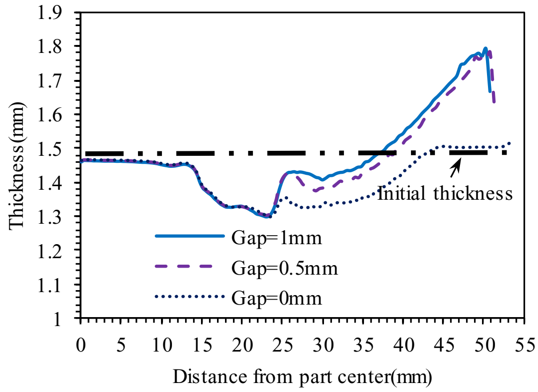

Fig. 12 Thickness distribution curves of formed St13 parts for different gap: radial pressures, 57MPa; cavity pressure, 30 MPa; Punch stroke, 29.5 mm

By Increasing the size of the gap between the punch and die, the part does not contact the die properly. Therefore, it does not fully form. Also, reducing the size of the gap increases the part contact with die. Therefore, the wall thickness decreases.

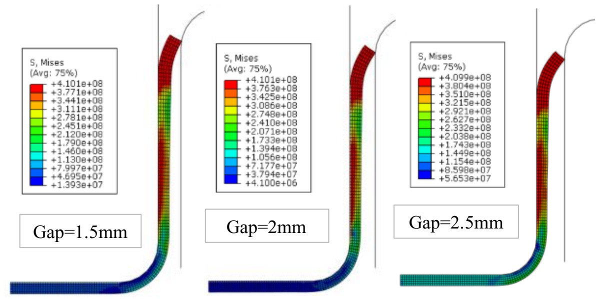

Fig. 13 Sectional view of the formed part St13 at stroke of 29.5 mm at maximum cavity and radial pressures of 30 and 57 MPa, respectively.

Figure 14 shows the formed parts obtained from experiments at a typical punch stroke for St13. The thickness of the formed parts was measured after cutting, the results of which are shown in the following figure.

Fig. 14 Formed part sample for thickness distribution measuring at punch stroke 29.5 mm.

Finally, to compare the thickness distribution of the formed part in the case where the radial pressure exists, and in the absence of radial pressure, (or in the case radial pressure is almost equal to the cavity pressure) another experiment test is carried. To ensure repeatability, this test has also been repeated two times as shown in fig 15(cavity pressure (34MPa) is approximately equal to the first time (35MPa)).

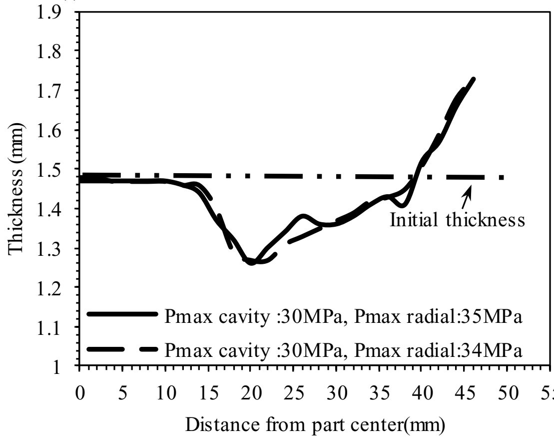

Fig. 15 Thickness distribution curves of formed St13 parts with same pressures; cavity pressure, 30 MPa; radial pressure, 35 MPa, Punch stroke, 29.5 mm

The experimental result of the effect of increasing radial pressure on the thickness distribution curve is shown in fig.16. Radial pressure paths with maximum values of 34 and 57 MPa were used, while the cavity pressure path was kept constant at the maximum of 30 MPa. By increasing the radial pressure, thinning decreases along the formed part. Because of contact inner surfaces of the part with the corner radius of the punch, the maximum tensile stresses occur in this region. Consequently, maximum thinning occurs in punch radius region. By increasing the radial pressure, tensile stresses occurred in this area decrease. So, by increasing the radial pressure, thinning decreases along the formed part. In other words, radial pressure variation has a significant effect on the formed cup thinning. This agrees with the finding of the previous studies [17,18].

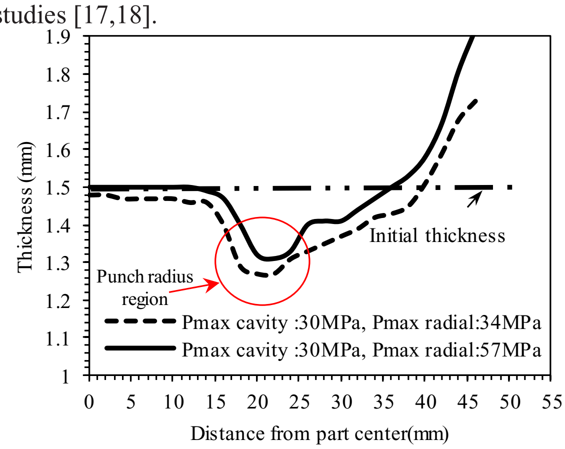

Fig. 16 Thickness distribution curves of formed St13 parts with same pressures; cavity pressure, 30 MPa; radial pressures, 57 and 55MPa Punch stroke, 29.5 mm

5 Conclusion

In this study modified Hydrodynamic deep drawing assisted by radial pressure with inward flowing liquid was investigated.

1. In the experimental section, two independent pumps have been used to provide cavity and radial pressures and the pressure supply system and die set was designed to provides simultaneous change and control of the radial and cavity pressures throughout any time during the process.

2. Results showed that by redesigning the conventional die set and pressure supply system, higher radial pressure can be achieved.

3. It was experimentally shown that by using higher radial pressure than the cavity pressure and controlling their values at any moment improves the thickness distribution of the formed part in all regions.

4. The simulation results by the Fluent Software also showed that the amount of radial pressure, according to the geometry of the die increased up to 3 times of maximum cavity pressure.

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