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Design, Fabrication and Performance Tests of a Double-sided Sheet Hydroforming Test System

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In this study, a double-sided sheet hydroforming (DSH) test system, which contains dies, sealing, pressure intensifiers, and a control unit, has been designed, built, and tested. The hydraulic numerical control system, which is currently used, has been modified as afour-axis where parameters are forming pressure, back pressure, punch position, and blank holder force. A hydromechanical deep drawing press has been modified in terms of die and sealing. New sealing components have been used to prevent leakage during the forming process because one side of the sheet is exposed to the forming pressure, and the other side is exposed to both the back pressure and the moving punch. Performance tests have been carried out to determine the limitations and capacity of the system. After the performance tests, it has been concluded that; the higher forming rates all along the process curve, the higher the pressure and force differences. However, the resultant error of the corresponding points has been only higher at the beginning of the process curve. In addition, the higher slopes in process curves have increased the pressure and force differences. A conical industrial part has been deformed by using hydromechanical deep drawing and DSH processes to test the performance of the DSH press. The wrinkling defect that occurred in previous hydroformed parts has been reduced remarkably by using back pressure in the DSH process. As a result, a double-sided sheet hydroforming test press has been successfully designed and manufactured. Finally, this study provides technical knowledge and can be used as a guideline for the design and performance evaluation of similar manufacturing systems.

Keywords: Double-sided hydroforming process, Design, Performance test, Sheet hydroforming

1 Introduction

Conventionally, hollow parts that are used in automotive, aerospace, and food industries have been manufactured by the deep drawing process. The deep drawing process has required more than one step for a proper work piece while forming the same final part has been possible with one step in hydroforming process[1]. Hydromechanical deep drawing has been similar to deep drawing except for the usage of pressurized liquid. During the movement of the punch on one surface of the sheet, the pressurized liquid has been applied to the opposite surface of the sheet. The incompressibility of fluids has caused hydrostatic stresses. These stresses have allowed the sheet to draw up to punch. Accordingly, formability has been enhanced, and this process has been also called hydromechanical deep drawing[2-4]. This process has been considered a soft tool forming technology [5,6].

When compared to other sheet forming methods at room temperature, this process has the best formability. Limiting Drawing Ratio (LDR) is the most significant criterion to determine the formability of sheet materials [7-10]. The limiting Drawing Ratio of AA5754 sheet is 2.16 and 2.70 for classical deep drawing and hydromechanical deep drawing, respectively [11]. However, these ratios are valid for cylindrical punch geometries. When different punch geometries, such as conical or half spherical, are used, the formability characteristic is not the same. Because the contact region between the punch and the sheet is not constant in opposition to the cylindrical punch. In this case, the necessity to develop double-sided sheet hydroforming (DSH) process has been developed. The schematic representation of DSH has been given in Fig. 1. In this method, pressurized liquid (back pressure) is applied to the opposite surface of the

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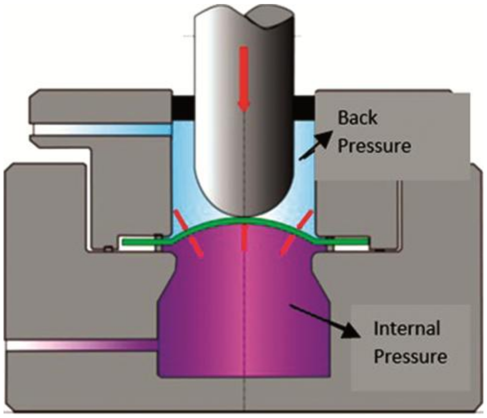

Fig. 1 — Double-sided sheet hydroforming (DSH) process.

sheet where normally no pressure is applied. Thus, material flow can be controlled in a better way during plastic deformation. In addition, undesired contact of sheet and die radius is avoided because of the direction of the back pressure. The thickness distribution of the final part in DSH is also more uniform than in other hydroforming processes. Another advantage of this method is the possibility of forming sheet sat lower pressure levels[12].

Recently, studies related to DSH have focused on the production of more uniform distribution of thickness. In the DSH process, pressure is applied to both sides of the sheet. Thus, axi-symmetrical parts can be manufactured in a more uniform thickness. Hashemi et al[13] have proposed process window diagrams for aluminum alloy, pure copper, and St14 steel using hydrodynamic deep drawing assisted by radial pressure. The final product ensures uniform thickness distribution and has required less initial thickness.

Studies regarding the effect of DSH on microstructure have indicated that; DSH increases hydrostatic stresses and prevents the expansion of the gap between grains during deformation. Thus, the beginning of tearing can be delayed, and wrinkling can also be avoided [14, 15]. Wang et al. have compared conventional hydraulic bulge and double-sided hydraulic bulge tests[16]. It has been concluded that double sided bulge test results in Limiting Dome Height (LDH) have increased as much as 31.8% compared to one sided bulge test. Normal stresses have occurred through thickness direction. Thus, bulging height can be increased by double sided pressure, which has been an enhanced formability indicator.

In the DSH process, the liquid pressure has been insufficient because of the sealing problem, particularly in back pressure. The aim of this study is to modify the hydroforming test press for the DSH process in order to solve the sealing problem of the DSH process. The changes made in the press design have included die design, selection of sealing elements, and adding a fourth axis in the hydraulic numerical control system. Finally, performance experiments have been carried out, and sample work pieces are formed in order to indicate that the DSH press operates reliably and safely in high pressure values. Even though the accuracy and repeatability of the pressure sensors and load cell have been specified in the properties, these values have not been valid for high forming velocities and unconventional load curves. Therefore, one needs to ensure that the press has been reliable for high forming rates and unusual load curves in a reasonable tolerance interval. The performance tests have been carried out for this purpose.

2 Materials and Methods

2.1 Design of double-sided sheet hydroforming test system

Double-Sided Sheet Hydroforming (DSH) press consisted of four main design aspects such as the die components, the sealing components, the control system, and the sensor system, as shown in Fig. 2. In addition to the DSH press, hydraulic pressure intensifiers and a software system were also required. Two pressure intensifiers were necessary to generate forming and back pressure. Software that had been connected to the Hydraulic Numerical Control (HNC) unit was also necessary for interaction between the user and the DSH press.

2.1.1 Design of die components

The DSH process is generally applied with double acting pressure intensifiers. However, the process could be applied with a single acting pressure intensifier, providing that proper sealing components are used. If the designer prefers a single acting booster, the lower die (back pressure area) must be redesigned. A disadvantage of this preference was the necessity to design and manufacture a lower die each time part geometry was changed. Because of the movement of the punch, the sealing between the lower die and punch must be possible where back pressure was applied. As the current hydroforming setup contained a single acting pressure intensifier, dies for the DSH process were redesigned, which were given in Fig. 3. Lower die, sealing components that belong to the lower die and spring

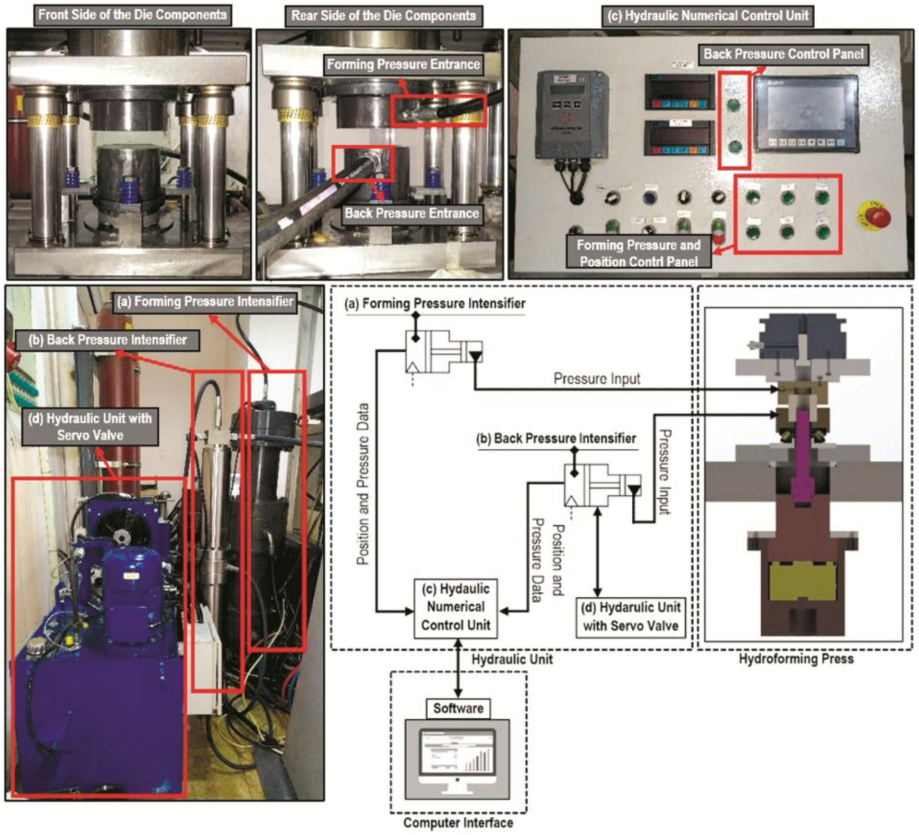

Fig. 2 — Schematic view of the double-sided hydroforming press.

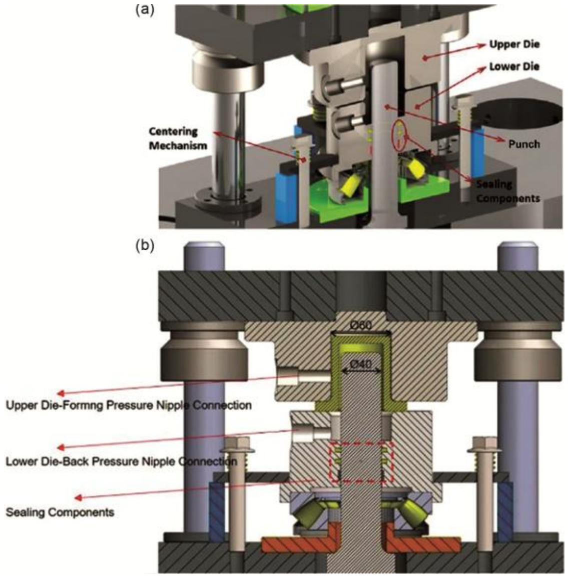

Fig. 3 — (a) Die design of DSH, and (b) detailed view of the upper and lower dies.

shoe planarity mechanism was integrated into the original hydroforming setup.

2.1.2 Design of sealing components

Sealing must be ensured in S1 and S2 areas which were given in Fig. 4. Dynamic sealing in the axial direction was provided by face seal, which is suitable for 50 MPa pressure. Thus, sealing between the moving punch and lower die in the S1 area, which was unique to the DSH process, was provided. Since standard face seals were permissible up to 30 MPa, a special face seal was used in this case. Two face seals were used for reliability. Concentricity of the die and punch must be ensured in order to achieve proper sealing. Therefore, a centering ring was added to the design.

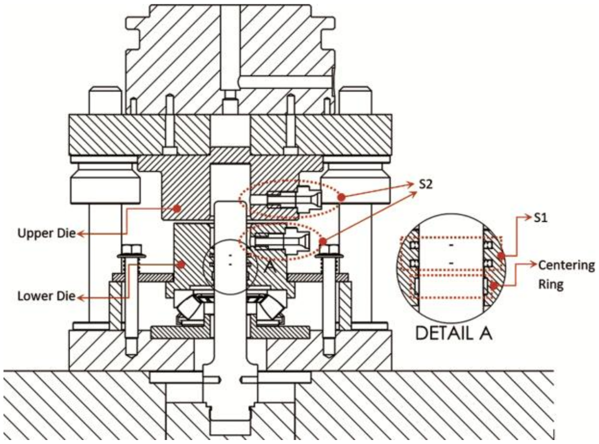

Fig. 4 — Sealing areas (S1 and S2), centering ring between dies and sheet.

The sealing ring was given in Fig. 4. This feature allowed the sheet to compress with high surface pressure on both the upper and lower die. In particular, the plastic deformation behaviour of sheet metal was used instead of any kind of sealing equipment. The S2 area represented the pressurized liquid and die connection region. Copper gaskets were used between hydraulic coupling and dies for better sealing. As well as sealing, concentricity was also important for sealing performance. Concentricity was ensured by a maximum 0.05 mm gap between the centering ring and the punch.

2.1.3 Design of control system

The hydraulic cylinders of the punch and the blank holder, pressure intensifiers that generates internal and back pressure, were controlled by a proportional solenoid valve and direction control valve. In a non-modified hydromechanical deep drawing press, punch position, blank holder force, and internal pressure could be controlled simultaneously via three-axis HNC. 4th axis HNC was implemented in the system in order to control back pressure. The software was modified for the recently updated control unit. Buttons that were used to regulate and start back pressure were added to the control unit, which was shown in Fig. 2 (c). Electronic connections were completed, and G codes were updated to make the communication between software and HNC possible. As a result, four parameters were added to the system in total. These parameters were punch position, internal pressure, back pressure, and blank holder force.

2.1.4 Sensor design

The sensitivity of sensors was significant for process performance. Parameters such as force, pressure, and position were measured via sensors in the press. Measured signals were transferred to the HNC control unit, and the analog signals were transformed into numerical signals. Thus, these values could be viewed ona personal computer. Several sensors were used in this DSH process for force, pressure, and position. Punch force was measured as 6 kN with the load cell. Clamping force was measured with two load cells, each of which was 4kN. Pressure sensors were used to measure internal and back pressure. Capacities of the sensors were variable in accordance with the state of the pressure. For the low pressure region, a total of six pressure sensors were selected. The capacity of each of these sensors was 25 MPa. For the deformation zone, two pressure sensors were used for forming pressure and back pressure regions with a capacity of 100 MPa and 50 MPa, respectively. Position sensors were used to measure the position of the punch. The velocity of the punch was also important in some cases during the DSH process. Therefore, velocity was also measured accurately by this type of sensor. Specifications of the sensors were given in Table 1.

2.2 Performance Tests

The specimen that is used in the experiments was chosen to be thick enough in order not to cause any fracture during the experiments. Therefore, a cup-shaped part with a 7 mm thickness was used in the experiments. In order to increase the duration of the performance tests, a cup-shaped specimen, which was given in Fig. 5, was used instead of a flat sheet specimen. The main parameters of experiments were forming pressure, back pressure, and blank holder force. Pressure and force values were obtained against the punch position instead of time. Because the forming process was actually performed by increasing punch position and pressure simultaneously.

3 Results and Discussion

Loading profiles were applied to the press via a computer interface to test and evaluate the performance of the DSH press. The main characteristic of a hydroforming experiment was the type of loading profile. The loading profile that was used to evaluate the performance of the DSH press was given in Fig. 6. This profile was determined by the trial and error method.

Table 1 — Specifications of the pressure sensors and the load cell

Specification	Load Cell	Forming Pressure Sensor	Back Pressure Sensor
Maximum Capacity	0-550 kN	100 MPa	50 MPa
Total Error	0.02 %	-	-
Accuracy	-	±0.1 MPa	±0.1 MPa
Repeatability	-	±0.03 MPa	±0.03 MPa
Output	4-20 mA	0-10 V	0-10 V

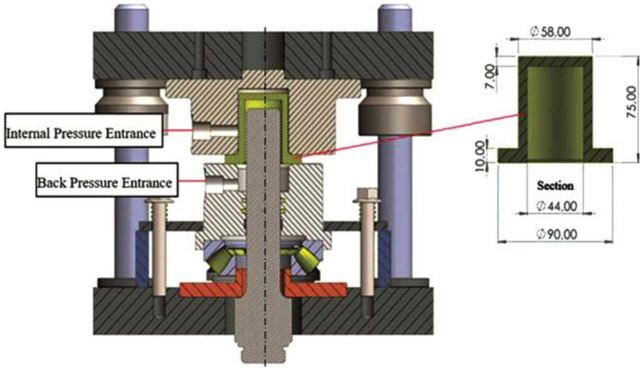

Fig. 5 — The cup shaped part that is used in performance tests.

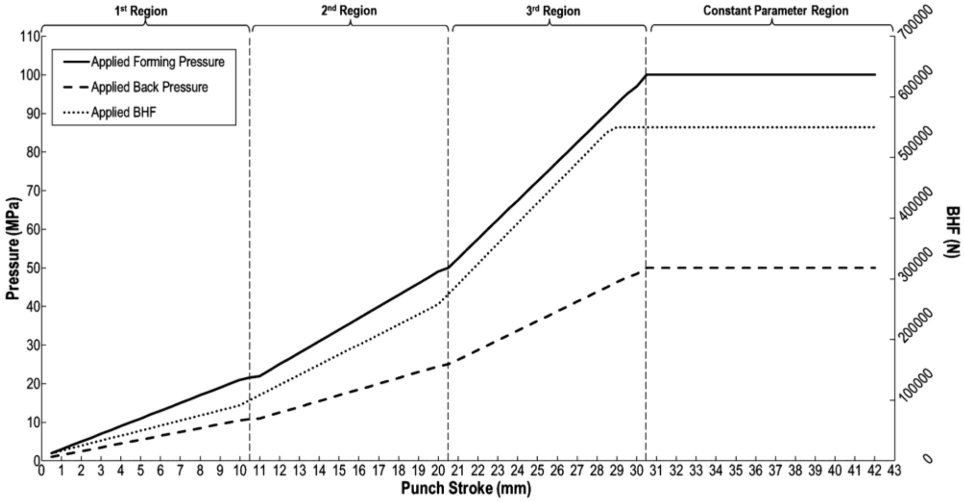

Fig. 6 — The loading profile of an industrial part.

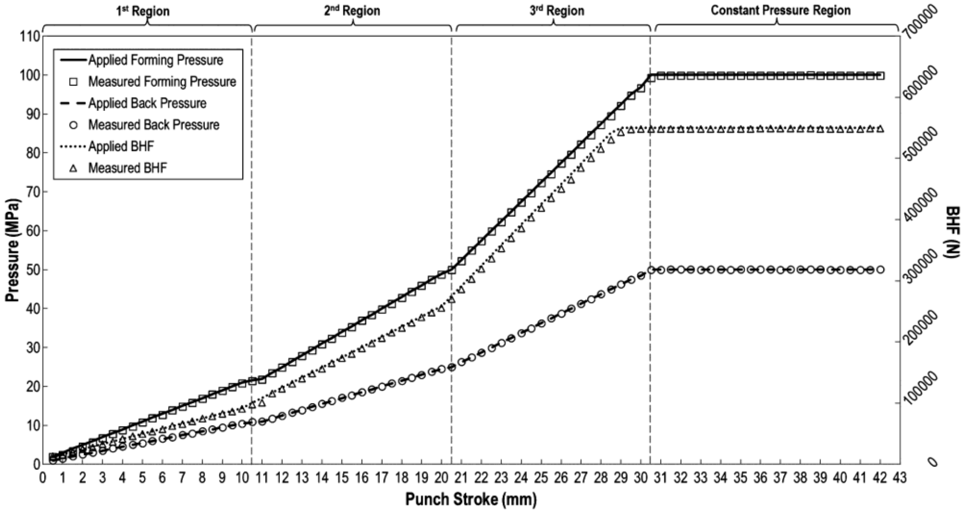

Fig. 7 — Applied and measured loading profiles of forming pressure, back pressure and BHF for 1 mm·s-1 punch velocity.

Three main parameters of the DSH process were carried out in response to the punch stroke. Four different punch velocities, such as 1, 3, 5, and 7 mm·s^{-1} were used in order to evaluate the performance of the control system. The results of measured loading profiles against the applied profile were given in Fig. 7 for forming pressure, back pressure, and blank holder force (BHF). Fig. 7 presents the profiles for 1 mm·s^{-1} punch velocity[17].

Each profile represented a typical hydroforming curve which was also a single multi-linear curve. Forming and back pressure was applied up to 100 MPa and 50 MPa, respectively. Each experiment was carried out with three repetitions. The same loading profiles are applied for 7 mm·s^{-1} punch velocity, and the results were given in Fig. 8. Similarly, a single multi-linear pressure profile was applied to the system. The difference between applied and measured loading profiles was given in Fig. 9. Measurements of the other punch velocities were in between the maximum and the minimum profiles. Therefore, the error distribution of each velocity was analysed in the next section[17].

In the following section, the difference between applied and measured values of both pressures and BHF was visualized. The percentage error of each punch step was also found. When considering the performance of the system, both the pressure difference and percentage error of the parameters were more comprehensible than the comparison of loading curves. On the other hand, the effect of different slopes and different punch velocities could be clearly seen in these graphs. The results of the pressure difference between applied and measured forming pressure were given in

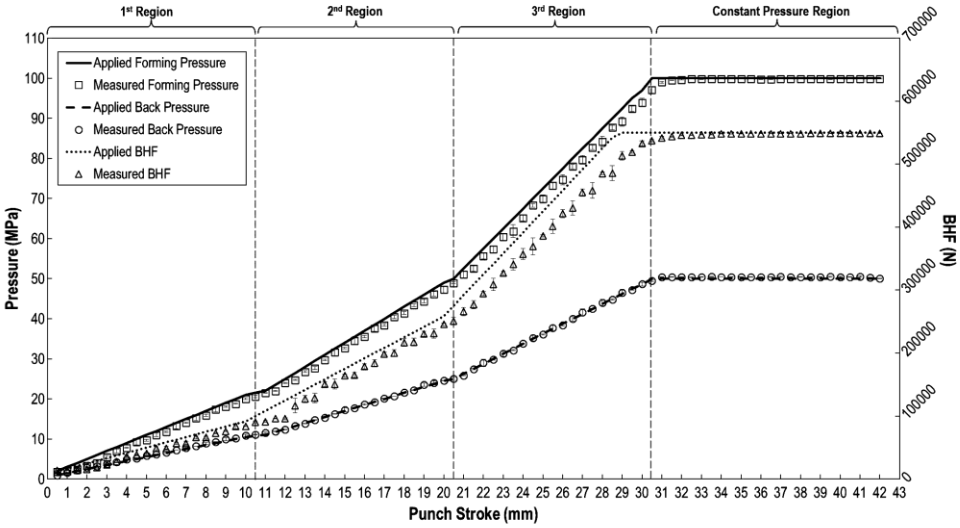

Fig. 8 — Applied and measured loading profiles of forming pressure, back pressure and BHF for 7 mm·s-1 punch velocity.

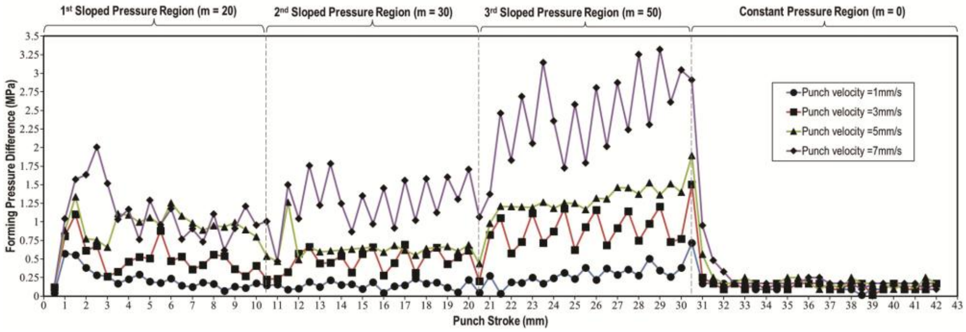

Fig. 9 — Difference between measured and applied forming pressure values for different punch velocities.

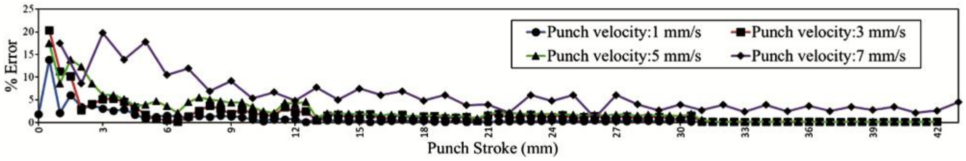

Fig. 10 — Percentage error distributions of each measured forming pressure point for different punch velocities.

Fig. 9. It was clear that high-pressure differences could be misleading without considering the corresponding error. The percentage error distribution of each measured point for forming pressure was given in Fig. 10. The results of the pressure difference between applied and measured back pressure were given in Fig. 11. The percentage error distribution of each measured point for back pressure was given in Fig. 12. The results of the force difference between applied and measured BHF was given in Fig. 13. The percentage error distribution of each measured point for BHF was given in Fig. 14.

In literature, Liu et al.[12] expressed that the challenge for the experiments was the sealing of back pressure because of the relative movement between a punch and a blank holder. It was stated that this problem was solved by using V-ring seals, where the inner diameter of the V-ring was smaller than that of the punch. So, the seals were compressed elastically to ensure successful sealing. In this study, the same problem was solved by using two copper seal elements that were suitable for back pressure. It was shown that the sealing between the moving punch and lower die in the DSH process was ensured. Different from the literature, a centering ring was added to the design, and concentricity of the punch was provided.

A sample conical industrial part was formed by using the curves in Fig. 6 in order to test the performance

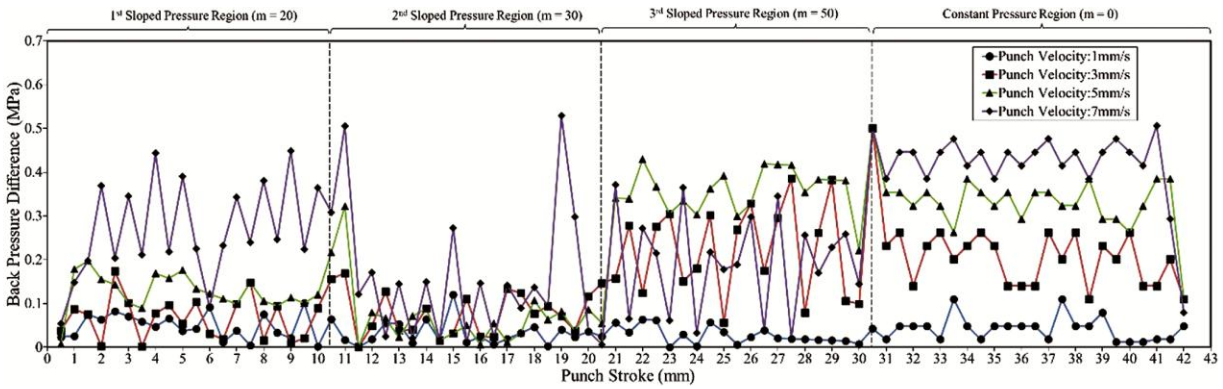

Fig. 11 — Difference between measured and applied back pressure values for different punch velocities.

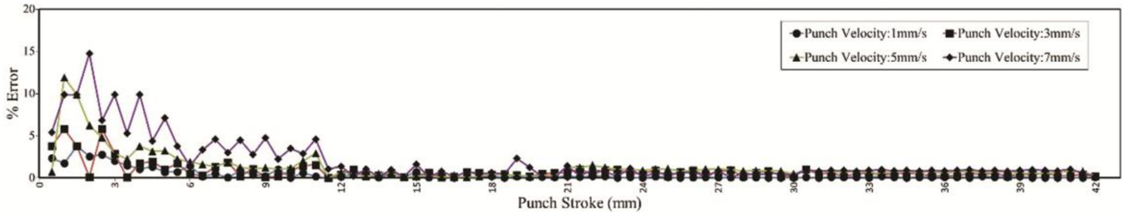

Fig. 12 — Percentage error distributions of each measured back pressure point for different punch velocities.

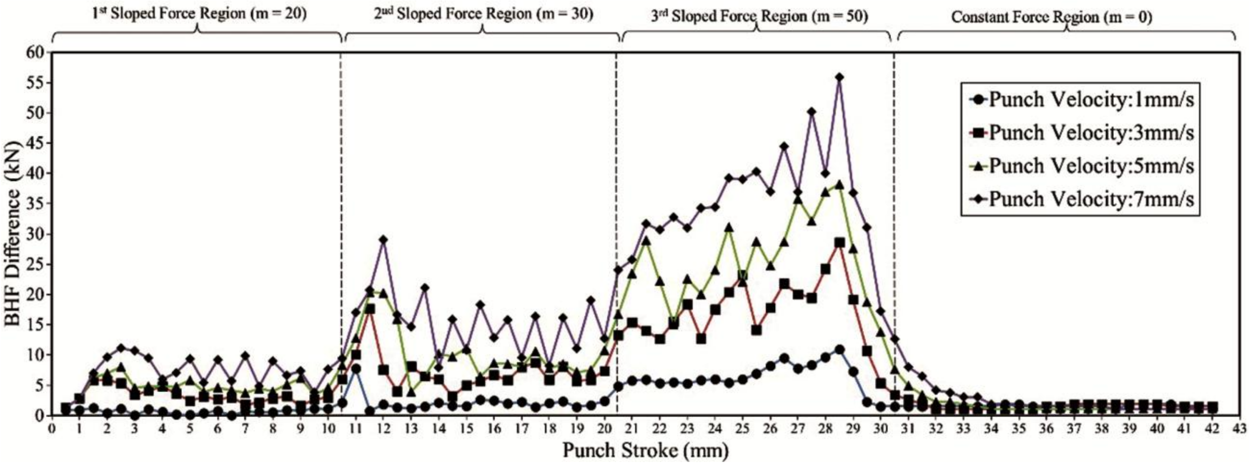

Fig. 13 — Difference between measured and applied BHF values for different punch velocities.

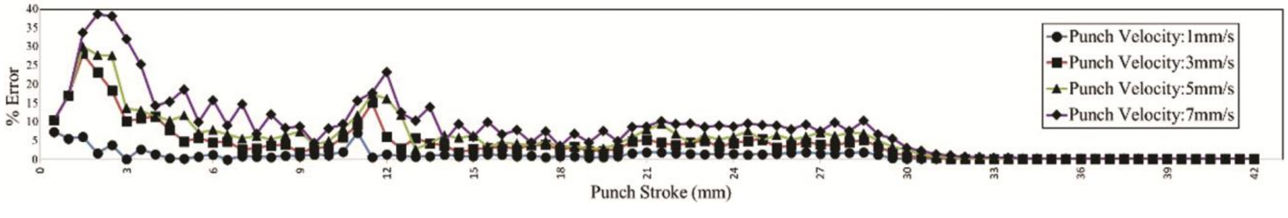

Fig. 14 — Percentage error distributions of each measured BHF for different punch velocities.

of the DSH press. The formed parts with both hydromechanical deep drawing (HDD) and DSH were given in Fig. 15[18, 19]. The starting sheet diameter and the sheet thickness were 85 mm and 0.18 mm, respectively. The material of the sheet was AISI 304 stainless steel. As can be seen in Fig. 15, the wrinkling defect was reduced remarkably by using back pressure in the DSH process.

Fig. 15 — The sample conical industrial parts that were formed with both hydromechanical deep drawing (on the left) and DSH process.

4 Conclusion

In this study, the hydromechanical deep drawing test press has been modified to a double-sided sheet hydroforming press. An improved lower die which has been required for double-sided pressure process, has been designed and manufactured. A newly generated sealing design has been made in order to prevent leakage at high pressures and achieve a decent concentricity of the punch die system. Performance tests have been carried out for forming pressure, back pressure, and BHF. The following results have been found;

- The effect of the forming rate on the accuracy of the process curve has been made by performing for the lowest (1 $\text{mm}\cdot\text{s}^{-1}$) and the highest (7 $\text{mm}\cdot\text{s}^{-1}$) punch velocity that has been possible for the press. The results of the process curves for the lowest punch velocity have been obtained. This velocity (1 $\text{mm}\cdot\text{s}^{-1}$) has been a typical forming rate for the conventional hydromechanical deep drawing process. It has been clear that the accuracy of the applied process curves for forming pressure, back pressure, and BHF has been decent. On the other hand, the accuracy of the highest punch velocity has implied that the accuracy has been reduced for higher forming rates in the DSH process.
- The performance of the DSH process has been evaluated in further detail. The difference between measured and applied curve points has been calculated. In addition to the difference graph, the corresponding error graph has been also generated. When the results of the difference and error values for forming pressure have been evaluated, the difference between measured and applied forming pressure has been increased with the slope of the relevant curve. When a zero-slope pressure region has been applied, the difference has been extremely low. This finding suggests that the difference has not been a performance criterion alone. Because the resultant error of each measured pressure point has been acceptable for overall of the process. It has been worth noting that the earlier phase of the process curve has indicated a relatively high error rate. It has been also clear that the error rate has increased with punch velocity at the very beginning of the process.
- It has been shown that there has been no correlation between the slope of the curve and pressure difference when the results of the difference and error values for the back pressure have been analyzed. However, the pressure difference has been increased with punch velocity. The resultant error has been increased with punch velocities which have been limited at the beginning of the process. A similar trend has been found for back pressure. However, the difference graph has not been consistent with the previous results.
- Difference between measured and applied BHF values has been increased with the slope of the relevant curve. Similarly, the difference has been increased with punch velocity. The error is extremely low for the zero slope curve.
- In conclusion, it has been clear that the overall error rate has been acceptable even if the corresponding pressure difference has been high, especially in the latter phases of the process. However, the error rate of the earlier phase has been higher than the rest of the process. An implication of this finding has been that both pressure difference and the corresponding error should have been taken into account when analyzing the accuracy of the process. Future studies that are related to the numerical analysis and the experimental validation of the DSH process are going to reveal the true effect of this earlier phase error rate on the experimental accuracy.
- A sample conical industrial part has been formed by using both hydromechanical deep drawing and DSH processes. The wrinkling defect has been reduced remarkably by using back pressure in the DSH process. As a result, it can be said that the double-sided sheet hydroforming test press has been successfully designed and manufactured.

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