



Improvement of Formability of AISI 1006 Sheets by Hydroforming with Die in Square Deep Drawing

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HIGHLIGHTS

- A new hydroforming setup with a die was designed, made, and assembled.
- The new setup enhances the formability of (1006) AISI steel in square deep drawing.
- The hydroforming deep drawing was compared to the conventional one for cup forming.
- Hydroforming enhances low-carbon steel formability by reducing thinning.
- Conventional deep drawing only reaches 70% depth due to corner thinning.

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ABSTRACT

An effort has been made to improve the formability of (1006) AISI steel alloy sheets in deep drawing of square-shaped parts with flat bases through hydroforming. To achieve this goal, the manufacturing process involved the use of a newly developed experimental setup for sheet hydroforming with a die, which was created by the researchers. The key design features of this setup aimed for simplicity and modularity, allowing for potential utilization with oil pressures of up to 100 MPa. The obtained results were compared with those of conventional deep drawing. Both processes were examined under specific conditions to form identical cups up to the full depth of the provided die. Indicators of formability considered for comparison included the minimum possible corner radius, the maximum achievable depth without failure, and the maximum percentage of thinning at the corners. This study demonstrates that hydroforming can enhance the formability of low-carbon steel alloy sheets by improving the flow of metal into the die cavity and reducing thinning at critical regions, when compared to conventional deep drawing processes. In conventional deep drawing, only 70% of the full depth could be achieved before failure due to high local deformations resulting in significantly higher thinning at the corners.

1. Introduction

Deep drawing is a manufacturing operation that involves the plastic deformation of a flat thin sheet metal (blank) to take the form of the punch or the die geometry. This process is increasingly being utilized, particularly in the automotive, aircraft, and aerospace industries, due to its numerous advantages [1-3].

Conventional Deep Drawing (CDD) processes face significant challenges in meeting the requirement of industries currently: improved parts quality, cost reduction, low energy consumption, and the utilization of lightweight materials. Each final product requires appropriate dedicated tools for being formed in conventional deep drawing [4,5]. As a result, new manufacturing technologies have been developed and improved. One of the developed technologies and the most important sheet-forming processes is a Sheet Hydro-Forming (SHF) process [6,7].

The sheet hydroforming process has recently gained significant popularity for sheet metal forming due to its various advantages compared to conventional methods, such as improved formability, reduced need for secondary operations, a significant reduction in springback effects, better surface quality, lower tooling costs, etc.[8]. Additionally, hydroforming utilizes similar materials to those employed in conventional forming processes. This means that a wide range of materials can be effectively used in this process, including low-carbon steel, aluminum alloys, titanium, stainless steel, copper and copper alloys [9].

SHF processes can be further categorized into two main types: hydromechanical deep drawing (hydroforming with punch) and pure hydroforming (hydroforming with die). When the used tool responsible for product shape is the punch, the process is referred to as Sheet Hydroforming with Punch (SHF-P). On the other hand, when the used tool responsible for product shape is the die, it is called Sheet Hydroforming with Die (SHF-D). In other words, in the SHF-P process, the blank takes the shape of the punch, while in the SHF-D process, it takes the shape of the die [10].

The schematic representation of the Conventional Deep Drawing process and the main hydroforming processes can be seen in Figure 1 [11,12]. Several differences regarding the tools used, contact conditions, and forming technology among the presented processes are shown in Figure 1. In conventional deep drawing (CDD) in Figure 1(a), where a rigid tool (the punch) is used to apply the necessary drawing force to push the sheet into the die cavity. This contrasts sheet hydroforming with die (SHF-D) in Figure 1(b) is a technology that utilizes highly pressurized liquid to shape the product according to the die cavity. In this process, sheet metal is formed by fluid pressure in a die to obtain the desired shape. While, in the Hydromechanical Deep Drawing process (HDD) in Figure 1(c), the female die typically used in Conventional Deep Drawing is replaced with a fluid-filled cavity. As the punch penetrates the die cavity, the liquid is pressurized. Hence, counter pressure is applied to the part during drawing by the fluid, pushing the sheet onto the punch surface, thereby increasing the contact surface area between the blank and the punch surface, enhancing formability. The fluid pressure within the cavity can be controlled using a valve [13,14]. Furthermore, using fluid in hydroforming reduces friction. It prevents metal-to-metal contact at the blank-die interface, improving the potential for obtaining better geometry and quality in the final products. A comparative study between sheet hydroforming and conventional deep drawing has been a subject of interest for many researchers in sheet forming. Researchers have conducted various studies to assess these two forming processes' advantages, limitations, and performance characteristics. The following literature survey provides an overview of some key studies in this area.

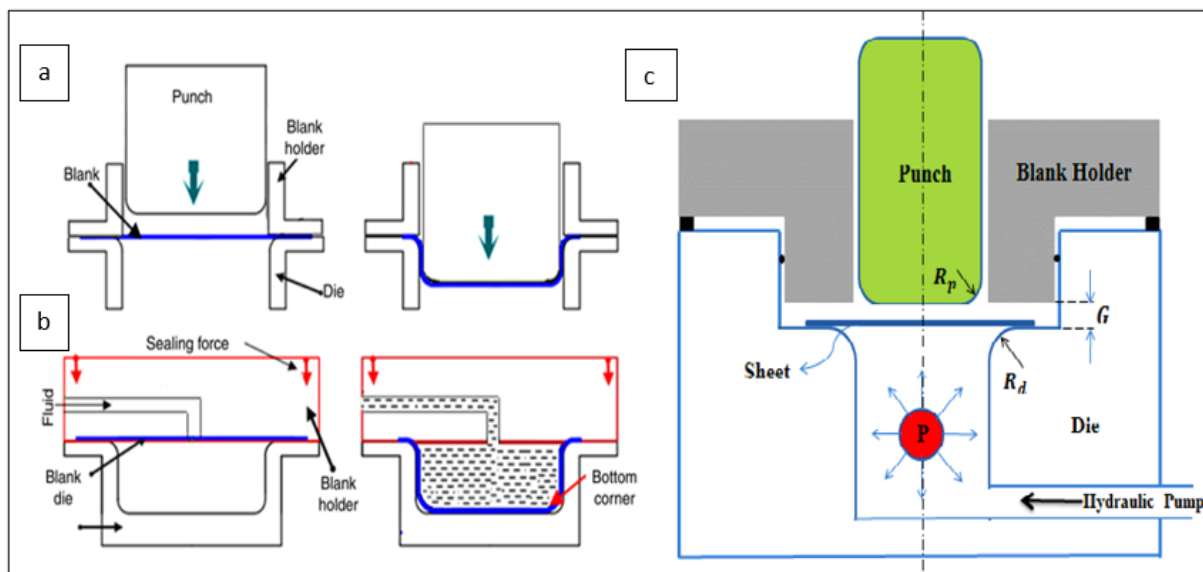


Figure 1: (a) Conventional deep drawing and (b) sheet hydroforming with die [11] (c) hydromechanical deep drawing [12]

Eladl et al. [15] conducted a study comparing the traditional deep drawing process with the hydroforming process in metal sheet forming. They examined the thickness variation and surface roughness of the products produced using both methods, employing numerical and experimental analyses to evaluate the quality of the resulting products. The findings indicated that the hydroforming process, which employs fluid pressure, was developed to address issues with conventional deep drawing. In another study [16], sheet hydroforming simulations were conducted to compare SHF-P and SHF-D methods. The results were analyzed to determine the more suitable method, which was then discussed and introduced. Zahedi et al. [17] compared the deformation force and sheet thickness distributions of two cylindrical parts produced using the processes mentioned (CDD, SHF). In hydroforming deep drawing, the calculation and proper application of pressure in the pressure chamber are crucial to increase the drawing ratio. Finally, a cup with a drawing ratio 2.3 was successfully drawn using the investigated pressure path. The results demonstrate that while hydroforming deep drawing requires higher forces, it allows for achieving higher drawing ratios. In their study, Abbadeni et al. [18] conducted a comparative analysis between the CDD process and the HDD process using finite element analysis. The research focused on examining the effect of fluid cavity pressure on formability, plastic strain, and thickness distribution. The findings revealed that the presence of pressurized fluid in HDD was an effective lubricant, facilitating the flow of the blank. So, the HDD process exhibited a more uniform distribution of plastic strain and lower maximum strain values, leading to improved formability and drawing ratio; in addition, a reduction in thinning was observed in the HDD process compared to the CDD process. FE simulations of CDD and SHF-D were carried out by [19]. The maximum depth of the cup and maximum thinning were predicted from the simulations and taken as indicators of formability. It can be concluded that this hydroforming process has excellent potential to produce complex sheet metal parts due to enhanced formability.

Due to that, few comparative studies have been performed between CDD and SHF-D. Moreover, most of these studies focused on improving the sheet formability at simple forming conditions, such as forming cups with large diameters and small heights. So, focusing on developing an experimental setup with respect to the SHF-D process for improving the sheet formability in relatively complex conditions for forming (a cup with a small diameter and large depth) and comparing it with conventional forming must be done to fill the research gap it has been noticed.

The present research study focuses on conducting a comparative analysis between conventional deep drawing and hydroforming with die through experimental works. The main objective is to investigate the formability of sheets made of (1006) AISI low carbon steel alloy, which has a thickness of 0.5 mm, in the deep drawing process for creating square cup-shaped parts with a flat base using hydroforming. The most challenging region to form is the bottom corner of the cup, as it undergoes the highest degree of thinning. Consequently, the parameters used to evaluate the formability in square cup hydroforming include the minimum possible corner radius, the draw depth without failure, and the maximum percentage of thinning at the corner. The obtained results are compared to those of conventional forming, and based on these findings, a more suitable method is proposed.

2. Workpiece Material and Material Properties

Plain carbon steel is one of the most commonly used types of steel. It has a variety of applications, from automotive components to tools and construction materials. Low-carbon steel is one of the most common types of plain carbon steel; its name comes from its low carbon content. Steel is used mainly in sheet metal operations to form automobile parts and many other appliances. In this study, low-carbon steel was selected as a workpiece material. This choice was based on several factors, including its ease of formability, low cost, and availability. Also, it shows rather good forming performance during hydroforming, owing to its slow strain hardening rate, high elongation possibility, and great drawability. These material properties contribute to the delaying of necking during plastic deformation, although it does require relatively high process pressures during the forming process. The chemical composition of the AISI 1006 steel alloy used in this study is listed in Table 1.

Uniaxial tensile tests were performed on specimens prepared through water jet cutting, following the E8/E8M ASTM standard, as illustrated in Figure 2. Tensile samples of low carbon steel alloy sheets were examined using a WDW-200E Universal Testing Machine (UTM) at room temperature, with a constant crosshead speed of 2 mm/min. This equates to an initial strain rate of $0.67 \times 10^{-3} \text{ s}^{-1}$. The mechanical properties of the material sheet are provided in Table 2. $Y_{S0.2\%}$ is an offset yield strength, UTS is an ultimate tensile strength, Ag is an elongation at failure, Ra is a reduction of area, n is a strain hardening exponent, and K is a strength coefficient.

Table 1: Chemical composition of (1006) AISI, content in [wt%]

	C%	SI%	Mn%	P%	S%	Cr%	Ni%	Mo%	Al%
<i>Test</i>	0.0636	0.0355	0.195	0.016	0.006	0.0177	< 0.005	< 0.004	< 0.002
<i>AISI</i>	≤ 0.08	≤ 0.04	0.25-0.4	≤ 0.04	≤ 0.05				

Table 2: The mechanical properties of the low carbon steel (1006) AISI

Alloy	$Y_{S0.2\%}$ (MPa)	UTS (MPa)	Ag (%)	Ra (%)	n	K MPa
<i>1005AISI</i>	225	351	23	52	0.208	438

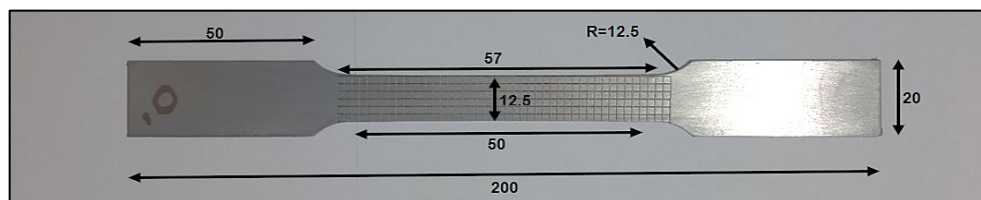


Figure 2: Standard uniaxial dog-boned style tensile specimen, all dimensions in (mm)

3. Experimental Procedures

3.1 Experimental Sheet Hydroforming Setup

A sheet hydroforming with die (SHF-D) arrangement has been designed and fabricated to produce cup-shaped parts. The objective is to draw a square cup of 40 mm side length with 22 mm depth in one stage by sheet hydroforming with die (SHF-D) process. Figure 3 presents a schematic diagram illustrating the dimensions of the die set used in the experiments. While Figure 4 (a and b) depicts and models the newly developed experimental setup, which has been developed by the researcher. Pressurized fluid is pumped by a hydraulic pump (100 MPa) through rubber hoses, which connect the hydraulic circuit to the die set via channels machined inside the containers. These channels divide the pressurized fluid into different paths to do various actions (forming, holding, closing). The blank holder force is applied to the sheet flange against the die surface, while the forming fluid pressure is applied to the lower sheet surface's center, enabling the product to form according to the die cavity's shape. Pressure and directional control valves are employed to control the flow and values of these pressures throughout the forming process, with the assistance of pressure gauges for monitoring.

A laser cutting machine with 1500W laser power cut rectangular strips into circular blanks to prepare low-carbon steel blanks. These circular blanks have a diameter of 110 mm and a thickness of 0.5 mm. In the SHF processes, it is generally preferred to use inexpensive, readily available lubricants that are easy to apply and remove. However, in this hydroforming process, the blank holder force is often of great value for preventing wrinkling. When wet commonly lubricants such as hydraulic oil are employed, the high blank holder force can displace the oil at the contact surface between the die and the workpiece. As a result, the area under the blank holder may remain unlubricated, making it difficult to pull the workpiece into the die and form

the product without significant thinning. This study utilizes a thin polythene sheet coated with a layer of solid lubricant (grease) to process this issue and avoid direct contact between the die and workpiece surfaces. This polythene sheet's primary function is to fix the grease layer, making it less likely to be displaced by the force exerted by the blank holder. Additionally, it plays a crucial role in preventing leakage, allowing the workpiece to slide smoothly into the die cavity, resulting in closer conformance with the shape of the cavity. The lubricated workpiece is then placed on the blank holder surface between the blank holder and the die.

Initial experimental tests have been carried out of the setup to verify the functionality of the setup elements and to observe the deformation behavior of the sheet under different conditions. These tests served as a preliminary assessment of the setup's performance. Based on the remarked results from these tests, initial perceptions were consisted, and certain related issues were addressed. Consequently, the values range of the geometrical factors and process parameters were determined, which were used for successful hydroforming. The main experiment procedures involve maintaining a fixed closing pressure at a specified value (25MPa) to prevent oil leakage. Simultaneously, the forming pressure is incrementally increased to reach the predetermined peak pressure (71MPa) while carefully adjusting the required, blank holder forces (150KN) to avoid excessive thinning and wrinkling. These values have been previously determined depending on initial tests). It is important to note that flexibility is one of the key characteristics of this newly developed experimental setup. So that its primary components, namely the drawing die and blank holder, are designed to be interchangeable. This feature allows for easy replacement of these components, facilitating the study of various scenarios or cases.

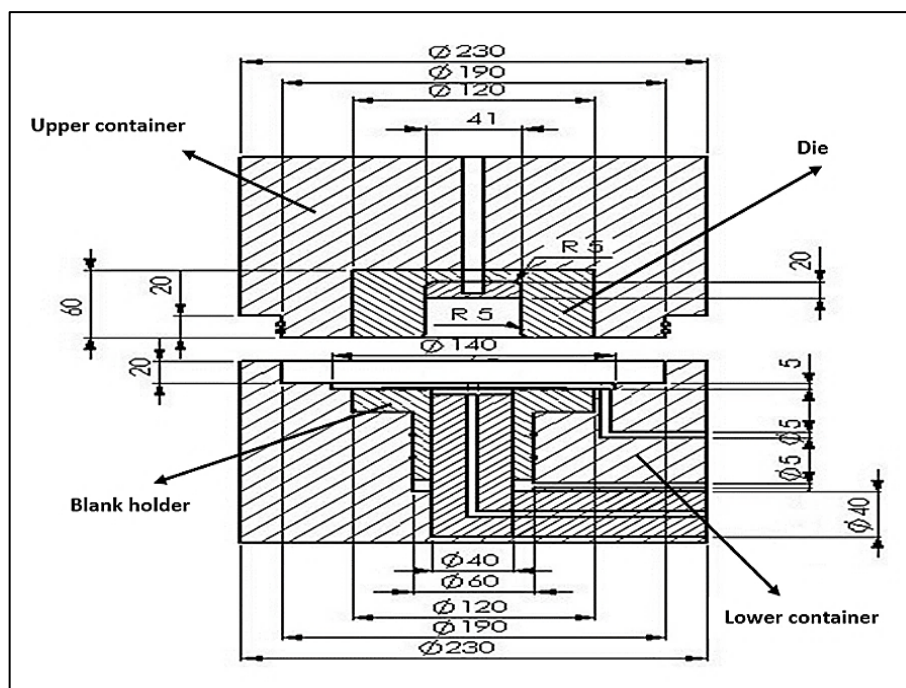


Figure 3: The schematic diagram of the die set dimensions

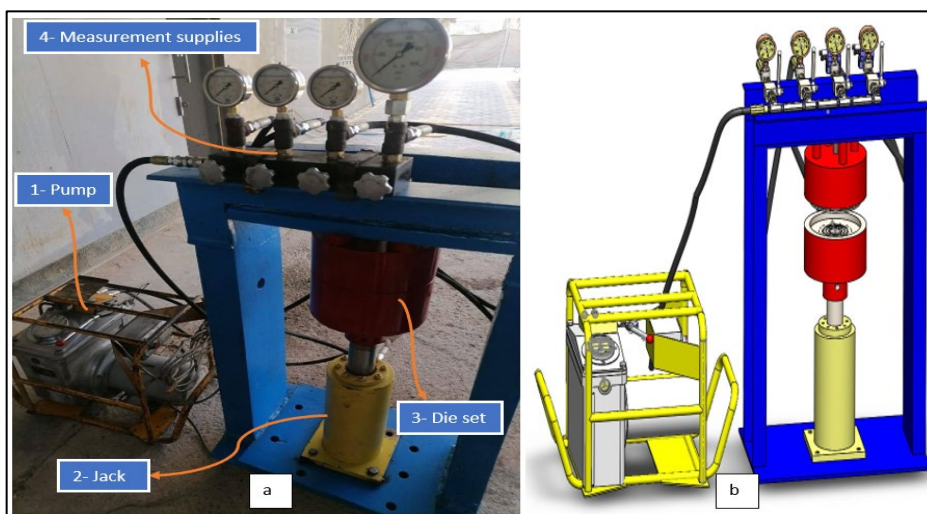


Figure 4: Experimental setup used in this study: (a) actual picture (1. Pump 2. Jack 3. Die set 4. Measurement supplies), (b) schematic modelling

3.2 Conventional Forming

In order to make a comparison, the conventional deep drawing technique was also utilized to draw deep low-carbon steel alloy sheets. To achieve this, a die, punch, and blank holder were designed and fabricated that would be used to draw square cups with identical dimensions to those produced in the hydroforming process. The experiments were conducted under dry and lubricated conditions, with the latter involving a thin polythene sheet coated with grease between the die and the blank, as has already been done in the SHF-D process.

The tools used in the experiments were manufactured from CK45 steel and were machined using a wire electro-discharge milling (EDM) machine. Once the machining process was completed, these components underwent polishing to achieve a smoother surface finish. These tools were assembled on a 20-ton single-action universal testing machine, as shown in Figure 5 (a), to carry out the deep drawing experiments. The hard square punch used had dimensions of 39.9 mm by 39.9 mm, with a punch profile radius and side corner radius of 5 mm each, giving a radial clearance of $(1.1t_0)$ when assembled with the die. On the other hand, the die featured a flat surface with a square cavity 41 mm by 41 mm, along with a profile die radius and side corner radius of 5 mm each. Pins were employed to ensure the accurate alignment of the blank holder and die, thus maintaining tool straightness. The tools used are depicted in Figure 5 (b). Circular blanks with the same dimensions as those used in hydroforming were utilized for the conventional deep drawing process. The process parameters and conditions utilized in both the hydroforming and conventional forming experiments are outlined in Table 3.

It is important to note that all values of the die and punch radii and the clearances between the die and punch and blank holder and punch have been chosen according to relevant standards and handbooks [20]. Additionally, the springback allowance was taken into account in the design of the die, both for conventional and hydroforming processes. This allowance might be incorporated during the die design stages based on previous literature sources related to metal sheet deformation processes or through modeling of the die dimensions using software such as SOLIDWORKS. The software automatically calculates and compensates for the springback allowance value in the die dimensions design.

In order to investigate the variation in thickness in square cups formed using hydroforming and conventional methods, measurements were taken at various locations throughout the cup wall. These measurements were taken using a ball-end anvil micrometer with a minimum measurement increment of 0.001mm. The micrometer is equipped with a ball anvil with a curved surface, so only one point of the anvil actually makes contact with the test position, allowing for precise measurements of the curved corner surfaces of the cup.

Table 3: The process parameters and conditions used in both hydroforming and conventional forming experiments

Parameters	Hydroforming	Conventional forming
Die cavity dimensions	41 mm X 41 mm	41 mm X 41 mm
Punch dimension	-	39.90 mm X 39.90 mm
Die profile radius, side corner radius	5 mm, 5 mm	5 mm, 5 mm
Bottom corner radius of the die	5 mm	-
Bottom corner radius of the punch	-	5 mm
Closing pressure	25Mpa	-
Blank holder force	150 KN	15 KN
Forming pressure	71 MPa (Max)	43KN (max. punch force)
Lubrication condition	Dry, grease	Dry, grease

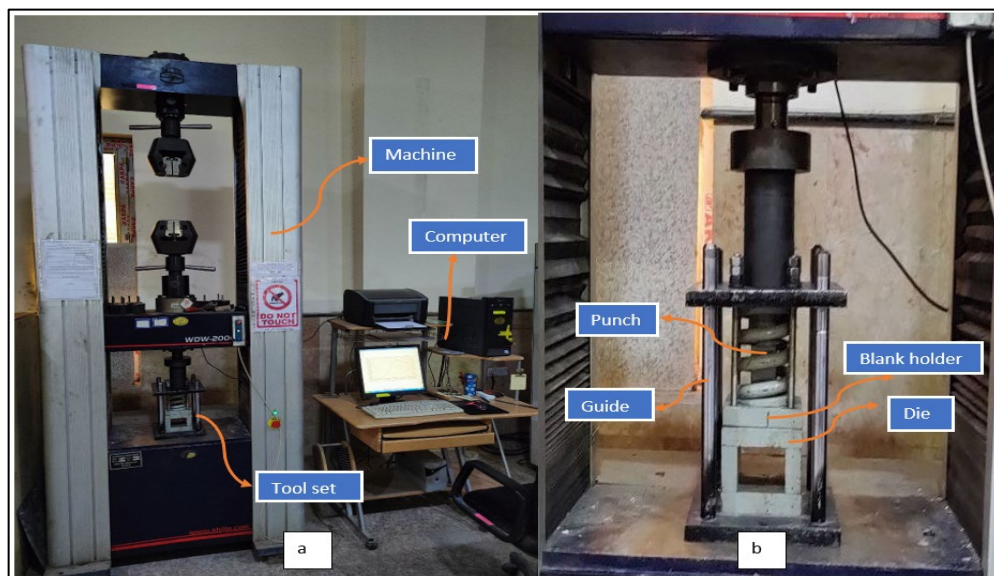


Figure 5: a) The tools were assembled on the universal testing machine (WDW-200E), b) shows the die set

4. Results and Discussion

Both hydroforming and conventional deep drawing experiments were conducted using their specific conditions as defined in Table 3 to create square cups with identical dimensions. These conditions were applied to both the dry and lubricated cases, allowing for further comprehensive analysis during comparison of the two processes. The maximum cup depth and maximum thinning were measured during these experiments and taken as indicators of formability. Figure 6 illustrates the maximum achievable depths in both the SHF and CDD processes under two frictional conditions: dry and lubricated. The results demonstrate that the conventional deep drawing process resulted in failures of drawn cups. In contrast, the hydroforming process successfully formed the cups with desired depth under both dry and lubricated conditions. In the failed cups from the conventional deep drawing, the fracture was observed at the four bottom corners of the part, as shown in Figure 7, which is a normal mode of failure when the draw ratio exceeds the limiting draw ratio. This failure is attributed to the high local deformations characterizing this process, causing significant thinning and eventual failure in the cup wall near the punch bottom corner. Under the dry condition, failures in conventional deep drawing occurred at the bottom corner with a 5 mm radius, and the maximum depth achieved at failure was 14.5 mm. Even when lubrication was applied, the maximum depth achieved at failure increased to 16 mm. On the other hand, hydroforming successfully produced cups with a full depth of 22 mm but with a minimum corner radius of 11 mm in dry conditions. However, when hydroforming was performed with lubrication, the entire depth of 22 mm was achieved with a reduced minimum corner radius to 8 mm. These findings clearly indicate that conventional deep drawing cannot attain the desired part's full depth. Although smaller corner radii are achievable in conventional deep drawing, the achievable draw depth is lower compared to hydroforming, particularly at high drawing ratios. These results were in good agreement with the preceding literature [19].

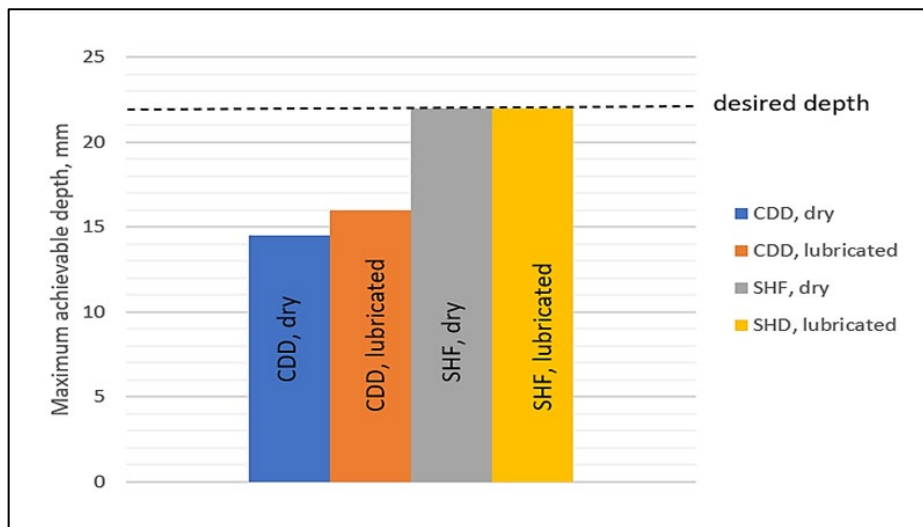


Figure 6: The maximum achievable depths of CDD and SHF for dry, lubricated conditions



Figure 7: The failed cups from the conventional deep drawing lubricated conditions

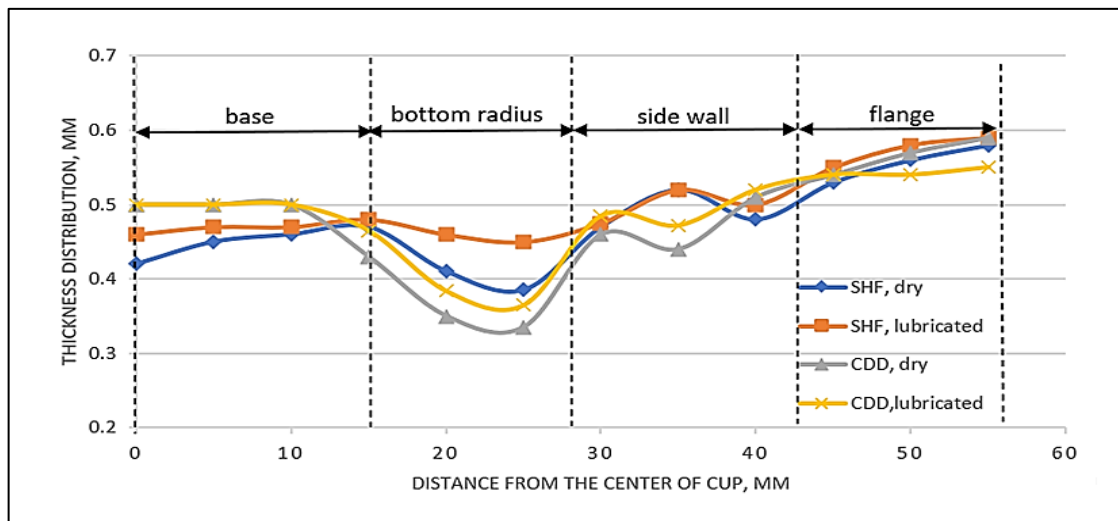
Figures 8 (a and b) compare the thickness distribution along the straight and diagonal zones, starting from the bottom center to the flange edge of the drawn cups. This comparison is based on experimental data obtained from conventional forming and hydroforming processes, considering dry and lubricated conditions. The Figures clearly illustrate that when the dry condition is applied, the maximum thinning at the bottom corner along the diagonal zone (thinnest side) in hydroforming of 23%, which is lower than the 33% observed in conventional deep drawing. Additionally, when the lubrication condition is applied, the

maximum thinning at the bottom corner along the diagonal zone in hydroforming is significantly lower at 10%, compared to the 27% observed in conventional deep drawing.

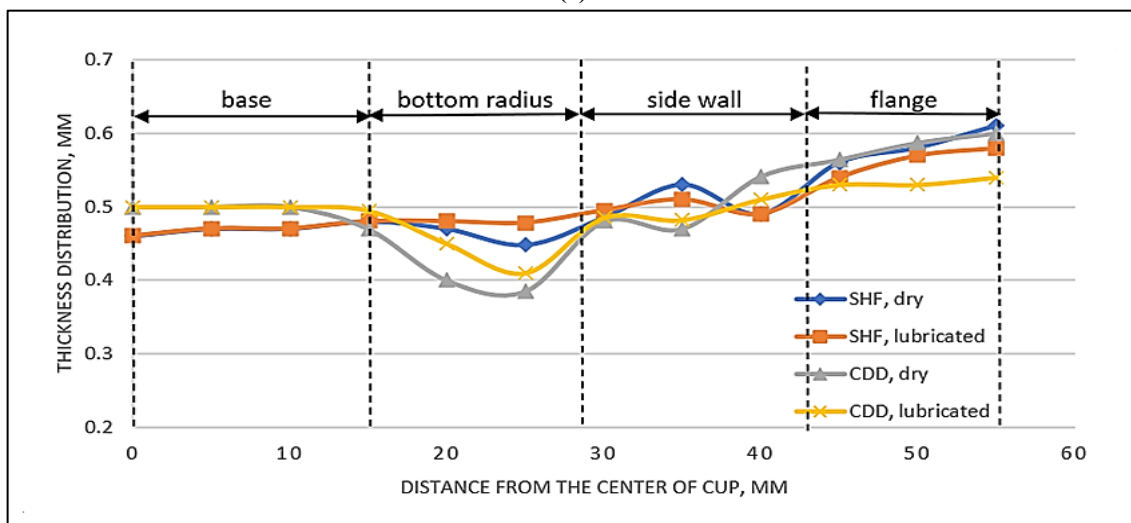
Furthermore, in hydroforming, low thinning is observed in the flat bottom region due to initial bulging. Conversely, this region retains its initial thickness in conventional forming as no deformation occurs in this area. Consequently, hydroforming's thickness distribution appears to be more uniform compared to conventional deep drawing. This phenomenon can be attributed to the fact that a low thinning in both the flat and corner bottom regions exists in hydroforming. At the same time, in conventional deep drawing, there is no thinning in the flat bottom, followed by excessive thinning in the corner. Consequently, hydroforming's more uniform thickness distribution allows for a larger overall depth before failure occurs.

Across all cases, it is evident that the material flows into the square die during the deformation process, which is more difficult in the diagonal zones of the cavity contour than in the straight zones. This discrepancy is attributed to the sheet during flowing being subjected to different deformation modes along the square cavity contour. Consequently, a greater degree of thinning is observed in the diagonal zones due to the excessive deformation occurring in this area compared to the straight zones. Also, the most significant thinning occurs at the bottom corners, and the reductions in thickness are decreased when lubrication is present. In general, failure typically occurs at the punch corner in conventional deep drawing due to excessive thinning. Conversely, the sheet hydroforming process can successfully produce the desired part without encountering this defect. These results were in good agreement with the preceding literature [21].

It can be summarized that; the results clearly indicate that the drawability of 1006AISI low carbon steel alloy in deep drawing of square cups can be significantly improved through the hydroforming process. The enhanced drawability in hydroforming can be attributed to several reasons when compared to conventional deep drawing: the always presence of the fluid medium, which is a thin film of lubricant between the blank and dies surface easing the deformation, improving material flow into the die cavity and reducing the likelihood of failure. The loading is distributed uniformly throughout the entire blank surface. This helps to reduce localized stress concentrations, resulting in more controlled and uniform material flow, thus enhancing drawability.



(a)



(b)

Figure 8: Thickness distribution along the drawn cups by SHF and CDD (dry, lubricated), a) diagonal zone, b) straight zone

Furthermore, the uniform application of hydraulic pressure ensures that the strain is uniformly distributed across the entire sheet. This allows for higher levels of deformation without premature failure. The low-carbon steel alloy used in the process exhibits a relatively high strain hardening exponent (n -value), indicating its stretchability. Consequently, this alloy can withstand higher limit strains in the biaxial strain stretching states, which are the normal prevailing deformation modes during both bulging and calibration stages. Moreover, the hydrostatic stress generated by the hydroforming process helps suppress the void growth rate, thereby delaying the onset of necking or failure during plastic deformation.

5. Conclusion

This work involved conducting a comparative study between sheet hydroforming and conventional deep drawing. The objective was to examine the performance of both methods in creating identical square cups under specific conditions, including dry and lubricated scenarios. The experimental results revealed that lubrication between the die and the blank significantly reduced the maximum percentage of thinning in hydroforming from approximately 23% (dry) to 13% (lubricated). Furthermore, hydroforming allowed for achieving a successful cup with a minimum corner radius of approximately 8 mm with thinning of 10%; These results were in good agreement with the preceding literature [19]. On the other hand, conventional drawing exhibited the ability to obtain smaller corner radii compared to hydroforming, but the maximum achievable draw depth was lower. In conventional forming, failure occurred when approximately 70% of the full depth was reached using a 5 mm punch corner radius due to significantly higher corner thinning.

As a result, the formability of 1006AISI steel alloy sheets in square cup deep drawing was successfully enhanced through hydroforming. This enhancement can be attributed to the free bulging effect in hydroforming, which enables uniform biaxial strain stretching, as opposed to the localized deformation experienced in conventional forming. Additionally, the uniform loading distribution in sheet hydroforming facilitates the increased metal flow into the die cavity, leading to a more uniform strain distribution and reduced corner thinning. Finally, the findings of this study highlight that the sheet hydroforming with die (SHF-D) process is a highly effective technique for producing square parts with significant depth from low-carbon steel alloy sheets. This process improves formability and may allow for successfully forming complex shapes with greater depth than conventional deep drawing methods.

Author contributions

Conceptualization, A. Jaber. A. Mohammed and K. Younis; methodology, Adil. Jaber; software, Adil. Jaber; validation, Adil. Jaber. A. Mohammed, and K. Younis; formal analysis, A. Jaber; investigation, A. Jaber; resources, A. Jaber; data curation, A. Jaber; writing—original draft preparation, Adil. Jaber; writing—review and editing, Adil. Jaber; visualization, A. Jaber; supervision, Adil. Jaber; project administration, Adil. Jaber. All authors have read and agreed to the published version of the manuscript.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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