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Experimental Investigation of Process Parameters in the Hydrostatic Forming to Enhance a Square Steel Cup Formability

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Keywords:
Formability; Hydrostatic formation; Sheet metal forming; Process parameters; Process window.

Highlights:

- Developing a new experimental setup and investigating key parameters influencing hydrostatic forming for square cups.
- Determining process window, including optimal peak pressures for forming and holding for successful hydroforming.
- Improving formability by reducing achievable minimum corner radius and minimum thinning.

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Abstract: To enhance stability during the forming process and improve the quality of the product, it is essential to analyze and identify the influence of the process parameters on the sheet formability. Therefore, this research investigates the influence of key process parameters, including the forming fluid pressure and the blank holding force, on the formability to produce square cup parts using an AISI 1006 STEEL alloy sheet employing hydrostatic formation technology. The formability evaluation was based on two criteria: the maximum thinning in the formed parts and the minimum achievable corner radius. For this purpose, the authors manufactured an experimental setup for hydrostatic forming and verified this setup's capability to manufacture square cups with specific dimensions. This setup provides and controls the three process pressures (forming, holding, and closing) independently, allowing greater flexibility to maintain process stability. In this regard, a process window with optimum peak fluid pressure and holding force combinations was determined. The experimental results indicated that these combinations allow for the successful formation of cups up to the entire die depth without encountering failures (wrinkling and fracture). Additionally, increasing the peak pressures for forming and holding within the process window reduced the achievable minimum corner radius, thereby enhancing dimensional accuracy. Simultaneously, it contributed to increasing the maximum percentage of thinning at the bottom corners. In particular, the thinning measurement was 23%, near the critical limit. Therefore, this process window helps select the optimal peak pressures based on the desired corner radius and the maximum allowable thinning for a given component.

بحث تجريبي لمتغيرات عملية في التشكيل الهيدروليكي لتعزيز قابلية التشكيل لوعاء مربع من الفولاذ

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الخلاصة

لتعزيز الاستقرار أثناء عملية التشكيل وتحسين جودة المنتج، من الضروري تحليل وتحديد تأثير متغيرات العملية على قابلية تشكيل الصفيحة. لذلك، يركز هذا البحث على دراسة تأثير متغيرات العملية الرئيسية، بما في ذلك ضغط المائع اللازم للتشكيل، وقوة مسك الصفيحة، على قابلية انتاج منتجات على شكل اوعية مربعة بواسطة استخدام صفائح فولاذية ١٠٠٦ AISI بتقنية التشكيل الهيدروستاتيكي. حيث استند تقييم القابلية للتشكيل إلى معيارين: الحد الأقصى من الترقق في الأجزاء المشكلة والحد الأدنى لنصف قطر الزاوية الممكن تحقيقه. لهذ الغرض، المؤلفون صنعوا عدة تجريبية مخصص لتشكيل الهيدروستاتيكي واثبتوا امكانية هذا العدة على تصنيع اكواب مربعة بأبعاد مخصصة، هذا العدة توفر وتسيطر على الضغوط العملية بشكل مستقل (التشكيل، المسك، الاغلاق) بحيث تعطي مرونة أكبر للمحافظة على استقرار العملية. تم تحديد إطار العملية مع التوليفات المثلى لذروة ضغط المائع وقوة المسك القصوى. اشارت النتائج التجريبية على ان هذه التوليفات تسمح بالتشكيل الناجح للأكواب حتى عمق القالب الكامل دون مواجهة إخفاقات (تجعد، كسر). بالإضافة الى ان زيادة اقصى ضغوط لتشكيل والمسك ضمن إطار العملية المحدد يزيد من الحد الادنى لنصف قطر الزاوية الممكن تحقيقه، بالتالي زيادة الدقة الابعاد، بنفس الوقت هذا الزيادة تساهم في زيادة نسبة الترقق عند الزوايا السفلية، حيت وجدت قياس الترقق حوالي ٢٣٪ قريبة من الحد الحرج. لهذا هذا الإطار يساعد في اختيار قيم اقصى ضغوطات المناسبة لإنتاج منتج معين ذو نص قطر زاوية المطلوب واقصى نسبة ترقق مسموح به.

الكلمات الدالة: إطار العملية، التشكيل الهيدروستاتيكي، تشكيل الصفيحة المعدنية، قابلية التشكيل، متغيرات العملية.

1.INTRODUCTION

Sheet metal forming (SHF) processes are highly significant in the field of metalworking due to their technological importance. These processes are capable of producing a wide range of sizes and shapes. Typical products of such products include aircraft panels, automobile bodies, beverage cans, kitchen utensils, and appliances. Among the different types of SHF processes, hydroforming is one of the nontraditional ones. In hydroforming, a liquid is employed as the medium for transferring energy to shape the workpiece [1]. Hydrostatic formation is a type of hydroforming technology used in sheet metal processing, where a highly pressurized liquid is utilized to shape a part based on the geometry of a die cavity. This technology offers numerous advantages, including the ability to form profiles with complex shapes, high surface quality, and suitability for various materials, such as steel, aluminum, stainless steel, copper, and even nonmetals. Consequently, it has been applied to many sectors, particularly in manufacturing thin-wall products within the automotive industry. The hydrostatic forming used in sheet metal forming is also referred to as sheet hydroforming with die (SHF-D) because the tool responsible for forming a product's shape and dimensions is the die, as depicted in Fig. 1 [2, 3]. The effective forming of a product through hydroforming relies heavily on the design aspects of the tooling and the control of crucial process parameters, such as the fluid pressure required for forming, the closing force, and the blank holding force. However, compared to conventional deep drawing (CDD), hydroforming presents larger process variables, making precise process control more challenging. Consequently, the sheet hydroforming is still under review to decide its general suitability for industrial production [4]. Furthermore, due to its practical versatility, this technology has become a subject of interest to many researchers from different countries. In particular, several researches were performed to study the influence of technological, geometrical, and material parameters on sheet formability to enhance product quality. Önder and Tekkaya [5] compared the influences of sheet hydroforming with punch, sheet hydroforming with die, and conventional deep drawing processes on different cross-sectional shapes of products. The researchers developed working windows of each technique considering the geometric shape parameters, such as circles, ellipses, rectangles, and squares made of ultralow carbon steel.

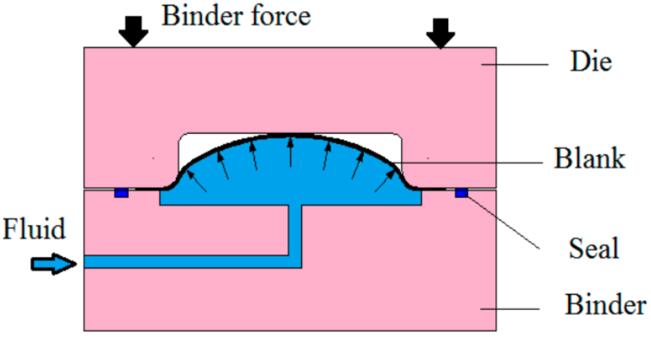

Fig. 1 Hydrostatic Formation Process Diagram.

Kim et al. [6] proposed a multi-stage hydroforming technique for improving the formability of structural components. The research concluded that this method is the most effective solution for reducing the incidence of thinning by 30% and even higher. Furthermore, Zhang et al. [7] conducted a study on the sheet hydroforming process by using a movable die to maintain contact with the deformed zone of the blank. This technique prevented the areas already deformed from further excessive deformation, resulting in uniform thickness areas than those observed in the freely hydro-bulged components. Furthermore, it substantially increased the limiting drawing ratios of the SS304 stainless steel. The key factor in successful hydroforming is the control of blank holder force (BHF), which guarantees the final product high quality. To overcome these challenges, Geiger et al. [8] and Novotny and Hein [9] established the process windows include an optimal combination of the forming fluid pressure and blank holder force for successful hydroforming of the pairs of sheets manufactured from DC04 extra-low carbon steel and AA6016 aluminum alloys. The process parameters that influenced the formability in square deep drawing using hydroforming have been studied in detail. To optimize these parameters to maximize formability, the Taguchi method was used [10]. Additionally, Yaghoobi et al. [11] studied the effect of different parameters on the forming process and product quality. This study focuses on applying a genetic algorithm (GA) and adaptive neuro-fuzzy inference system (ANFIS) to optimize the pressure path in the hydrodynamic hydroforming process of cylindrical cups. Nguyen and Nguyen [12] and Le et al. [13] studied the role of the forming fluid pressure and its effects on the part quality for DC04 materials during the sheet hydroforming with the die process. A relationship between the required forming fluid- pressure and the input parameters has been established. The goal has been to enhance the cylindrical cups forming. Modi and Kumar [14] discovered that utilizing a variable blank holding force (BHF) instead of the constant BHF enabled improved product geometry with smaller radii and reduced thinning. In addition, Kitayama et al. [15] optimized the blank holder force trajectory to ensure producing high-quality products. Feyissa and Kumar [16] studied enhancing the formability of high-strength sheets in square-deep drawings by hydroforming with a die. Experimental works and numerical simulations were conducted to examine the influence of significant process parameters, including the sealing force and the fluid pressure, on the formability. The results were compared with those from conventional deep drawing. A process window (PW) with the optimum combination of the maximum fluid pressure and the maximum sealing force was determined to form the parts without any failure. Wang et al. [17] established the pressure path for forming conical, cylindrical, and irregular parts in the hydrodynamic deep drawing process. Additionally, through experimentation, the process windows for the draw bead height were determined by adjusting the height of the draw beads to form irregular products. Despite the valuable works regarding sheet metal hydroforming processes published recently, as mentioned above, which highlighted developing flexible forming techniques, the effect of the process parameters on the formability and process window identification was unconsidered. Therefore, several research gaps have been noticed. Consequently, in this work, the researchers have addressed these gaps through manufacturing, assembling, and developing a new, simple, cost-effective experimental setup concerning the SHF-D technique that accomplishes the forming processes without relying on expensive conventional stamping presses. The key points of the design of this setup, which have been sought to be achieved, are simple and modular design, possible exploitation of oil pressures of up to 1000 bar, providing and controlling the four process pressures (forming, holding, closing, and radial pressures) independently, and the possibility of manufacturing specific several components of the experimental setup in small workshops using universal machinery. In this context, comprehensive studies regarding the manufacturing aspects of such setups are still noticeably absent in the existing literature. In particular, forming square-shaped parts with a significant depth-to-diameter ratio is a noteworthy challenge due to the process limitations in producing such parts' dimensions. This challenge was faced, and square cups with these specific dimensions have already been formed. Determination of the process window, including suitable combinations of peak fluid pressures for forming and holding that produce successful cups without fracture and wrinkling, has been experimentally performed. This experimental approach aims to avoid inaccurate numerical predictions caused by the difficulty of modeling fluid leakage in most simulation software packages. In this regard, the most available literature dealt with this topic numerically. Overcoming some challenges, such as the dimensional accuracy (smaller bottom corner radius) and optimizing the forming process parameters related to SHF of steel alloys with experimental analysis, have been studied more comprehensively in this work.

2.EXPERIMENTAL PROCEDURE

2.1.Sheet Material and Chemical Composition

Plain carbon steel is widely utilized as one of the most commonly employed steel types. Particularly, low carbon steel (LCS) is one of the most common kinds of plain carbon steel, deriving its name from its low carbon content. It is the mainly used steel in sheet metal operations to form automobile parts and many other appliances. In this study, low-carbon steel was selected as a workpiece material due to its ease of formability, low cost, and availability. Furthermore, it shows excellent forming performance during hydroforming. The chemical composition of the AISI 1006 steel alloy used in this study is listed in Table 1. Specifically, the chemical composition was studied according to the ASTM E415 standard in State Company for Inspection and Engineering Rehabilitation activities (S.I.E.R). It is important to note that this sheet was supplied as a rolled sheet produced by cold rolling.

2.2.Determination of the Rolling Direction

The rolling direction has been defined by an optical microscope with 125X magnification power. Figure 2 illustrates the rolling direction of the (1006-AISI) low-carbon steel.

2.3.Microstructure of the Used Specimen

The procedure used for the microstructure examination of the used specimen is as follows:

1- Grinding process with rotating discs using abrasive papers with several grains per square inch, i.e., 120, 320, 500, 1000, and 2000 grit.

2- Polishing process: The polishing discs were covered with soft cloth impregnated with abrasive alumina particles and water lubricant for high-carbon steel to remove scratches produced from the grinding process.

3- Etching process with Nital (2% HNOu + 98% alcohol) for high-carbon steel.

4- Using optical microscope type (MBL2000, German, Kruss), as presented in Fig. 3, to determine the substrate's microstructure.

5- Imaging samples using a digital camera strapped on an optical microscope.

Table 1 Chemical Composition of (1006) AISI, Content in [wt%].

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

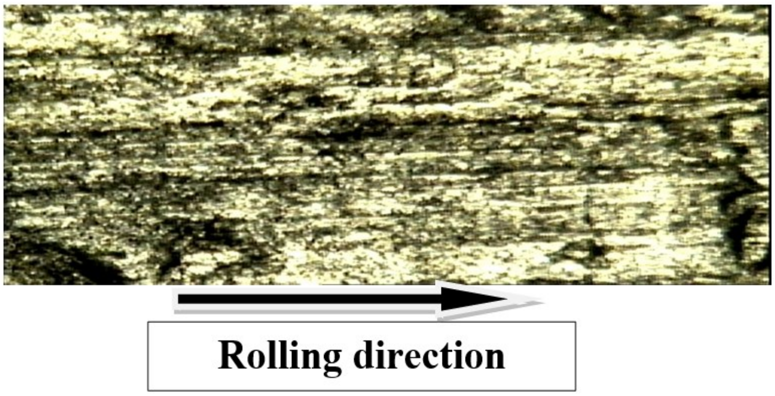

Fig. 2 Rolling Direction of the 1006-AISI Low Carbon Steel.

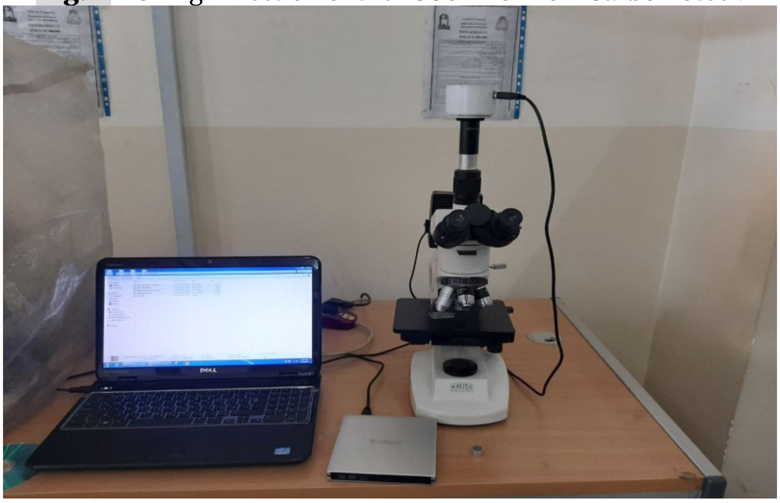

Fig. 3 The Optical Microscope Used to Determine the Microstructure of the Specimen.

2.4.Determination of the Mechanical Properties

The stress-strain curve serves as a graphical representation of the deformation amount experienced by a material under a specific load. This curve is obtained by subjecting a standard specimen to a uniaxial tensile test, where the specimen was pulled until a fracture occurred. To this end, three standard specimens were prepared using the water jet machining process (a water jet machine with model no.3020, Yonoda, China) along the 0°, 45°, and 90° to the rolling direction (RD), respectively. They were designed according to the ASTM A370 standard, as shown in Fig. 4. The tensile tests were performed on the universal testing machine (UTM) model (WDW200E), as shown in Fig. 5, with a crosshead speed kept constant at 5 mm/min, giving an engineering strain rate of 0.0017 s^{-1}. The tensile tests were performed at the Department of Production Engineering and Metallurgy/ University of Technology. The mechanical properties of the used material in this study are presented in Table 2. Moreover, the details of the devices, i.e., the spectrometer, the optical microscope, and the universal testing machine, used in the tests are presented in Table 3.

Table 2 The Mechanical Properties of the Low Carbon Steel (1006) AISI.

Used Alloy	Yield Stress, MPa	Ultimate Tensile Stress, MPa	Young Modulus, GPa	Passion Ratio	Strain Hardening Exponent	Strength Coefficient,MPa
1006 AISI	225	351	201	0.3	0.208	438

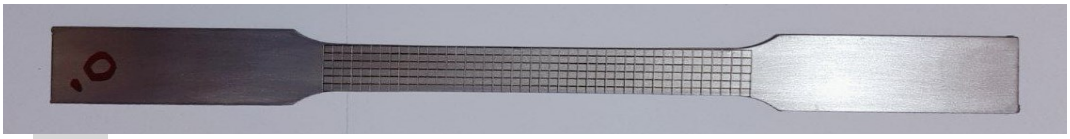

Fig. 4 Standard Uniaxial Dog-Boned Style Tensile Specimens Along the 0° to the RD.

Fig. 5 The Computerized Controlled Tensile Testing Machine with (WDW200E) Model.

Table 3 The Devices' Details Used in the Tests.

Name	Model number	Country of origin	Manufacturer
Spectrometer	SPECTROMAXx	German	AMETEK
Optical Microscope	BLP2000	Japan	MEIJI TECHNO
Universal Testing machine	WDW-200E	China	JINAN KASON TESTING EQUIPMENT CO., LTD.

2.5.Experimental System for Hydrostatic Formation

A newly developed experimental setup for the hydrostatic formation process was designed, fabricated, and assembled by the author. Figure 6 illustrates the experimental system diagram, consisting of four major modules:

1- A CP1000 constant displacement hydraulic pump with the electrical model SMS 9, manufactured by (SANWA TEKKI CORP. MITSUBISHI, JAPAN) to generate process pressures up to 1000 bar, and the working fluid was oil with a motor oil label of 5W-30 and a viscosity of 10.98 cSt at 100°C.

2- Closing containers, including a lower container containing a blank holder and an upper container that contains a die.

3- A hydraulic 60-ton jack (453360K, JET, China), applying a force to close the lower container on the fixed upper container to prevent liquid leakage outside the die set.

4- In addition, the setup included other necessary supplies, such as valves for controlling the pressure value and the fluid flow direction (CIT-03, Kemus, China), flexible hoses for fluid transfer, and a measurement system comprising pressure gauges (ML0100063SHG, Tameson, England) to monitor the forming pressure and the blank holder pressure, as well as a digital caliper to measure the height of the final product.

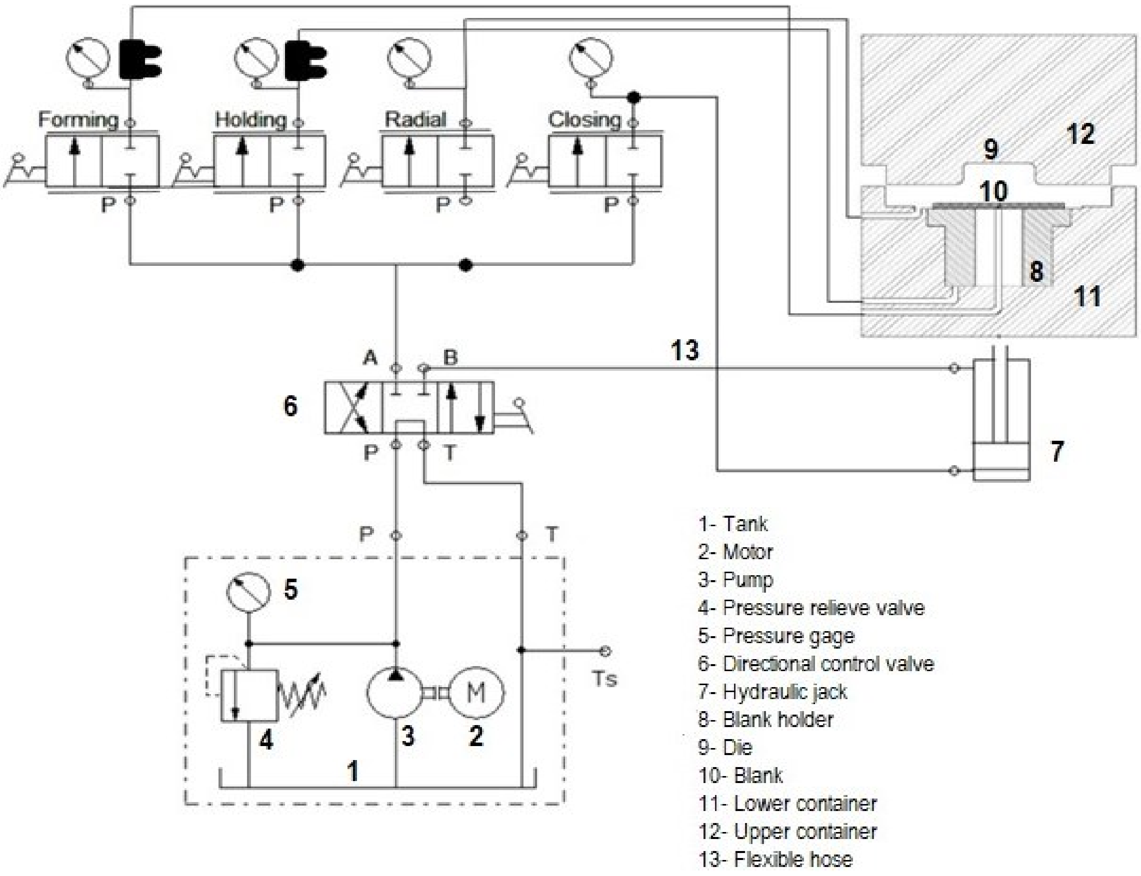

Fig. 6 A Diagram of the Experimental System of the Hydrostatic Formation Process.

2.6.Steps of Experimental Setup Preparation

Before starting the process, it is essential to check the fluid level in the tank with a sight glass to observe the liquid level and ensure enough fluid to complete the process. Then, the power to the hydraulic system was turned on, i.e., turning on the electric motor that activates the hydraulic pump. The pump created a vacuum that drew the hydraulic fluid from the tank through its inlet port and then pumped it through the main line to the system components. To protect the system from damage due to overpressures, the installed pressure relief valve at the main line was adjusted to 850 bars. When the pressure reached this value, the valve opened and allowed the fluid to return to the tank, ensuring the process pressures did not exceed the limit value. The directional control valve, also installed on the main line having four ports and three positions, controlled the fluid flow paths to perform various functions. The operator can manually switch between valve positions using a handle to perform three actions: working, idle, and returning. Thus, when the operator switched between the valve positions, three cases would arise, as follows. Case 1: When the valve position is neutral (the center position), the fluid passes from the pump to the valve and returns to the tank, resulting in no action in the system (idle action). Case 2: When the operator switches the valve position from the center position to the right position (working action), the pumped fluid in the main line enters the valve and flows toward the distribution assembly. The distribution assembly then divides the fluid into four main paths: closing, holding, forming, and radial (if any). To ensure the successful completion of the hydroforming process, the following steps must be conducted in the correct order. Firstly, the valve responsible for the closing pressure was opened, causing the fluid to flow into the hydraulic cylinder's lower channel and lifting the jack's piston ram, thereby lifting the lower closing container attached to it. The lifted lower container contacted the upper one, creating a closing pressure that must be high enough to prevent fluid leakage. Subsequently, the control valve was closed to maintain this value. Secondly, the control valve responsible for the holding pressure was opened, allowing the fluid to flow into the area under the blank holder. This action caused the blank holder to lift and apply pressure on the sheet flange against the die surface. The pressure of the blank holder can be monitored using a pressure gauge. When the pressure reached a predetermined value, the control valve was closed to maintain it at the desired level. The blank holder force could be determined by calculating the flange area subjected to the pressure and the applied fluid pressure measured above. Thirdly, once the closing and holding pressures were fixed, the valve responsible for forming was opened, allowing the fluid to flow into the space under the blank. This action applied pressure to the blank center, causing it to deform and take on the shape of the die cavity. It is worth noting that at each of the three mentioned paths, the operator manually controlled the pressure using the secondary proportional directional control valve installed at each path (to open/close the path and control the amount of fluid flow) and monitored the pressure readings using the pressure gauge. Case 3: After completing the hydroforming operation, the operator switches the valve position to the returning action (left position), causing the pump to enter a drain state and return the fluid to the tank. As a result, the jack and the lower container mounted to it lower. Finally, the operator turned off the power to the hydraulic system once the process is complete.

2.7. Experimental Tests

Once the primary setup operations for the experimental equipment system have been completed, the experimental tests should be conducted to confirm the capability of the sheet hydroforming setup in forming square parts with a side length of 40mm, a height of 20mm, and all radii equal to 5mm, using steel sheets. Figure 7 depicts and models the newly developed experimental setup. It should be noted that the experimental works were conducted using this setup at the Department of Production Engineering and Metallurgy/ University of Technology. Initially, preliminary experimental tests were conducted on the setup with free runs without any pre-measurement to verify the setup elements' functionality and notice the materials' deformation behavior under various conditions. Based on the results observed from these tests, initial conclusions were drawn regarding these issues. In this study, circular blanks were utilized to form square cups in a single stage through sheet hydroforming utilizing the die (SHF-D) process. To prepare the low-carbon steel blanks for the experiments, rectangular strips were cut using a laser cutting machine with a laser power of 1500W, as illustrated in Fig. 8. The resulting blanks had a diameter of 110mm and a thickness of 0.5mm. The hydraulic circuit was connected to the die set through rubber hoses. Then, the pump pumped a high-pressurized fluid through these hoses to reach the die set through channels machined in the lower container. The blank holder force was applied to the sheet flange against the die surface, while the fluid pressure required for forming was applied to the lower sheet surface to form the cup according to the die cavity shape. The pressure and directional control valves were used to control and monitor these pressures during the forming process using the pressure gauges. During the experiments, the closing pressure was maintained at a specified value of 250 bars as measured on the pressure gauge (determined through preliminary experiments) to ensure no oil leakage. The forming pressure gradually increased linearly over time until it reached its maximum value. Furthermore, the necessary blank holder forces were adjusted to prevent excessive thinning and wrinkling. The formed parts were then carefully cut, and the cup's thickness was measured at different locations using a ball-end anvil micrometer. This micrometer had a minimum measurement increment of 0.001mm.

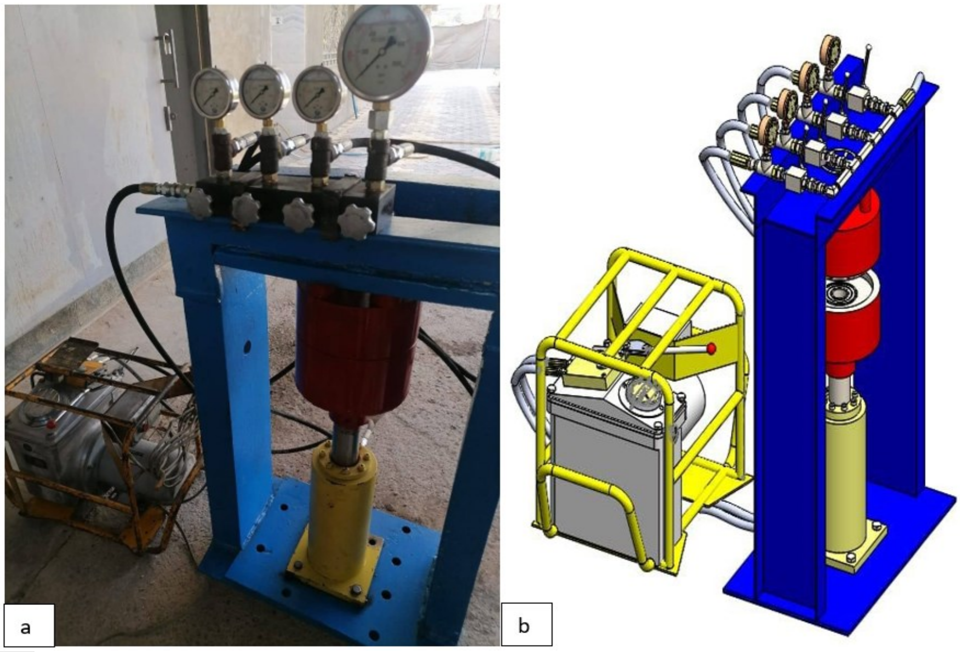

Fig. 7 Experimental Setup Used in this Study, (a) Actual Picture, (b) Schematic Modelling.

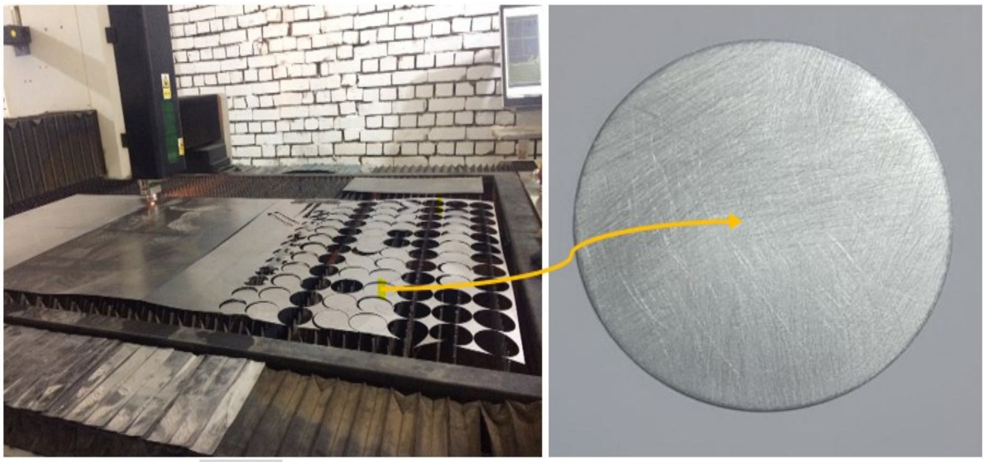

Fig. 8 Preparing the Process of the Initial Blanks.

3.RESULTS AND DISCUSSION

The primary objectives of this study involve the design, manufacturing, and verification of the capability of the experimental setup developed by the authors for hydrostatic formation in the deep drawing process of square cup-shaped parts with a flat bottom. Besides, another significant aim is to improve the formability of (1006 AISI) low-carbon steel alloy sheets by utilizing this experimental setup of the SHF-D process. In this paper, the intention was to form a square-shaped cup of 40 mm side length, with all corners having a radius of 5 mm and a depth of 20 mm. Experimental works investigated the influence of crucial process parameters, such as the forming fluid pressure and the blank holder force, on the process feasibility and sheet formability. The process feasibility indicators included successful forming the final parts without wrinkling or fracture. This goal was achieved by generating and maintaining the high necessary process pressures and ensuring the absence of oil leakage until the forming process was completed. Since the bottom corners were the most challenging zones for forming because of the forming mechanism of the SHF-D, which could impose the largest thinning at these zones, the minimum corner radius that could be achieved without failure and the maximum thinning at the corners were taken to be the assessing formability parameters. These parameters serve as crucial indicators in evaluating the formability of the square cup hydroforming. For the process feasibility investigation, many preliminary experiments have been conducted to determine a process window that includes optimal combinations of the peak blank holder force and the peak fluid pressure necessary for forming. This process window allows for the successful formation of square parts up to a specified depth of the die without experiencing failures, such as fractures at the die entry region or bottom corners and wrinkling at the flange region.

3.1.Microstructure Analysis

Figure 9 (a, b) depicts the low-carbon steel microstructure used in this work before and after hydroforming, observed by optical microscopy. In Fig. 9 (a), the low-steel microstructure image in its as-received state reveals the strain-free equiaxed ferrite grains with dispersed islands of coarse pearlite. While, Fig. 9 (b) reveals the presence of longitudinal strained grains after the hydroforming process. Notably, the grains nearly provide uniform elongation, indicating consistent and smoother deformations achieved using the SHF-D process.

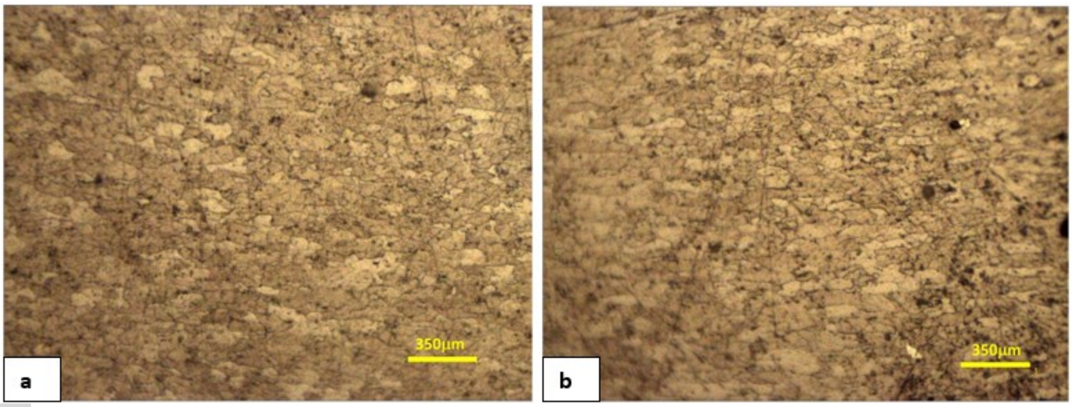

Fig. 9 Optical Microscopy Images of Low Carbon Steel with Magnifications 400 X, (a) as Received, (b) After the Hydroforming Process.

3.2.Process Window

The forming mechanism in the SHF-D process comprises three stages. Firstly, the sheet undergoes bulging until the center of the sheet comes into contact with the die base. This action is followed by drawing the material from the flange, allowing the sheet to conform to the die cavity's base and the walls. Finally, the calibration stage begins, during which the corners of the cup stretch to fill and form the bottom radii of the die cavity. Therefore, to successfully complete these stages and achieve a square cup using hydroforming with a die, an optimal combination of the process parameters that control this forming mechanism is required. Consequently, efforts have been made to identify a process window that ensures the successful formation of the products through hydrostatic formation based on the extensive experimental results under various combinations of the maximum fluid pressure and blank holder force. The obtained square products from all the tested process parameter combinations in the experimental work were classified into four categories: incomplete forming, failed forming (fracture), failed forming (wrinkling), and successful forming, as depicted in Fig. 10. It is worth highlighting that the closing pressure remained constant (250 bar) across all the combinations of the process parameters utilized in the experimental study to prevent oil leakage out of the die set. Moreover, the typical pressure path has been used in which the fluid pressure is gradually increased linearly over a time cycle of 60 seconds, reaching its peak pressure. Furthermore, all experimental tests were conducted under a dry lubricated condition (without lubricant). In the case of the parameter combination falling within region I, characterized by low fluid pressure and BHF values, the applied fluid pressure was inadequate to achieve the complete formation of the part, particularly at the corners. Consequently, the sample only experienced bulging at the center without reaching full depth, and the corners remained unformed. An illustrative example (incomplete forming) can be observed in Fig. 11 (a). It is evident that larger fluid pressures are necessary to enhance the geometrical dimensional accuracy of the part. In region II, the formed cups using combinations of rather moderate fluid pressure and excessive BHF experienced failure at the entry region of the die (failed forming by fracture), as depicted in Fig. 11 (b). This failure can be attributed to the excessive blank holder force, which hindered the smooth flow of the sheet from the flange zone into the die cavity after the initial free bulging stage. The material in the flange region experienced flow resistance due to the excessive BHF, resulting in thinning. Consequently, this thinned sheet was incapable of withstanding further subsequent high deformations caused by bending and unbending, accompanied by stretching due to the fluid pressure as it flowed over the die entry radius region, ultimately leading to fracture. In region III, where a combination of the high-fluid pressure and the high BH force has been applied, the parts failed at one of the bottom corners (failed forming by fracture) due to excessive thinning at the calibration stage (Fig. 11 (c)). When the applied fluid pressure necessary for forming and the BHF were very high, the sheet underwent bulging and drawing into the die cavity. As a result of the substantial stretching during the bulging stage and the metal flow restriction caused by excessive BHF during the drawing stage, the bottom corners of the cup would become significantly thinned. Subsequently, during the calibration stage, these already thinned corners experienced further excessive stretching due to the elevated fluid pressure applied during the corner forming stage, ultimately leading to fracture at these corners. In region IV, characterized by applying high-fluid pressure and low BHF, wrinkles emerged at the cup flange; occurred because the blank holder force was insufficient to suppress the formation of wrinkles during the drawing stage of the sheet (failed forming by wrinkling), as depicted in Fig. 11 (d). Suitable combinations of the fluid pressure required for forming and the blank holder force necessary for holding have resulted in the complete formation of cups (successful forming), as demonstrated in region V. The cups formed in this region exhibited corner formation and achieved the desired depth without experiencing fractures or wrinkling. Although all the cup's dimensions were attained in (region V), it was challenging to achieve a bottom corner radius of the cup conforming with the die's bottom corner. Additionally, noticeable thinning was observed at the bottom corners of these cups, which might approach the critical limit in some successful cases. It can be clearly seen that to achieve the desired level of geometrical accuracy, applying sufficiently high pressure is necessary, while inadequate fluid pressure results in incomplete formation of the cup. On the other hand, an excessive blank holder force leads to failure at the die entry or the bottom corner regions, while an insufficient blank holder force causes wrinkling of the drawn part. Furthermore, it was found that the obtained process window could predict an appropriate forming area and the probability of rupture or wrinkling occurrence under different process parameters. Therefore, the process window illustrated in region V is a valuable guide for selecting the appropriate combination of process parameters to achieve successful drawing without wrinkling and fracture. The successfully formed cups are shown in Fig. 12. The minimum achievable corner radius and the maximum thinning in the cups successfully drawn varied based on the different combinations of the maximum fluid pressure and BHF within region V, which will be further discussed below.

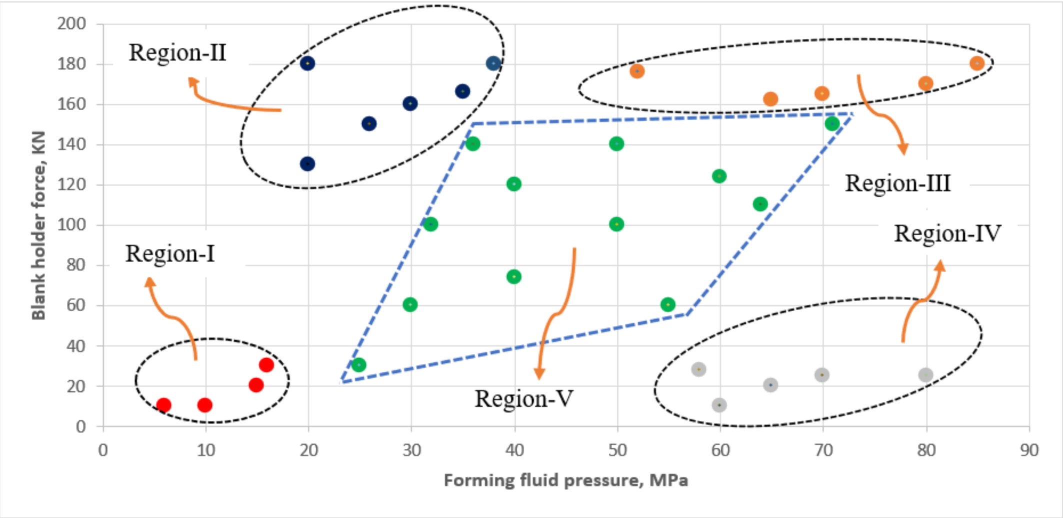

Fig. 10 Process Window (Region V) for Successful Hydroforming of the Cups.

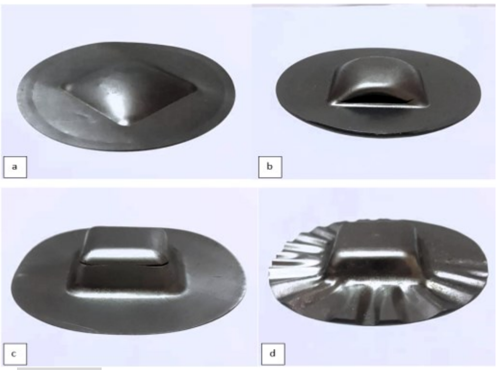

Fig. 11 Square Cups have been Formed Experimentally with Different Combinations of Blank Holder Force and Fluid Pressure: (a) Incomplete Forming, (b) Failure at Die Entry, (c) Failure at the Bottom Corner, and (d) Failure at Flange by Wrinkling.

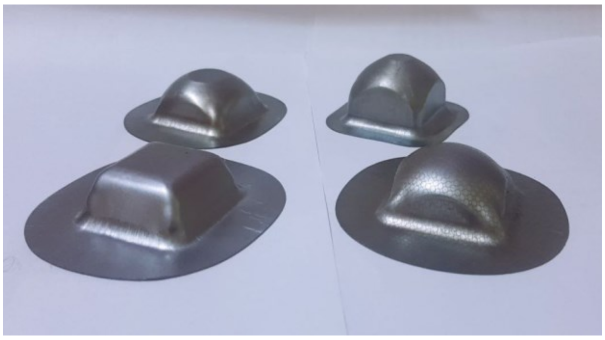

Fig. 12 Some Hydroformed Cups Produced using the Process Window (Region V).

3.3.The Effect of the Fluid Pressure and the Blank Holder Force on the Formability

The results clearly indicated that the maximum fluid pressure and the maximum BHF are the crucial process parameters affecting the formability of the 1006AISI low-carbon steel alloy sheets in hydroforming square cups. Figure 13 illustrates the effect of the maximum fluid pressure and the maximum BHF on the maximum percent thinning, while Fig. 14 demonstrates the effect of these process parameters on the minimum corner radius. In the successfully formed cups, maximum thinning was obtained at one of the four bottom corners, particularly along the diagonal side of the cup, due to the forming mechanism of the SHF-D process, requiring the fluid pressure to start from zero and gradually increase until it reached the maximum value at the end of the forming process. Initially, during the bulging and draw-in stages, the cup's base and sidewalls formed. In the final deformation stage, known as the calibration stage, the highest fluid pressure was applied to the cup corners to shape and fill the bottom corners of the die cavity. As a result, the corners experienced high biaxial stretching, leading to the greatest thinning in these regions. Due to the square shape of the die cavity, which has straight and corner sides, the deformation modes varied along the contour of the die cavity. Specifically, the metal flows more smoothly along the straight sides than the corner sides, causing the metal at the corner sides to undergo more stretching than that at the straight sides, generating the maximum percentage thinning exactly at these sides. The figures clearly demonstrate that an increase in both the maximum fluid pressure and the maximum BHF reduced the bottom corner radius of the cup, thereby improving its geometric accuracy, while the maximum percentage thinning increased. As the peak pressures were increased for forming and holding purposes, as already clarified, more deformation occurred in the cup's bottom corners in the final deformation stage. Hence, strains in these regions also increased, resulting in a smaller radius leading the cup to conform more closely to the die bottom corners. Moreover, due to the biaxial stretching of the sheet material in the corners, which intensifies during the calibration stage, the thinning of the sheet also increased. The maximum percentage of thinning in the cup increased to nearly 23% when a combination of a maximum peak pressure of 71 MPa and a maximum blank holder force of 150KN was employed. At the same time, a minimum corner radius of 9 mm could be achieved without any instances of fracture. It should be noted that these results were obtained from successful cup formations in dry conditions (without lubrication between the die and the sheet) within the process window (region V).

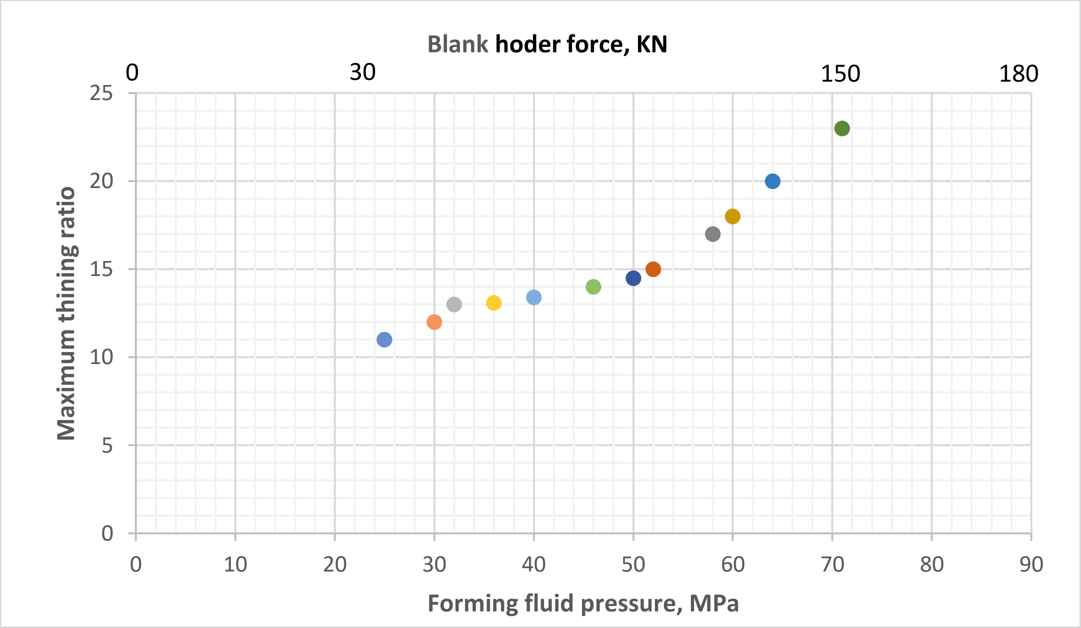

Fig. 13 The Effect of the Maximum Pressure and the Maximum BHF on the Maximum Thinning Ratio in the Successfully Formed Cups.

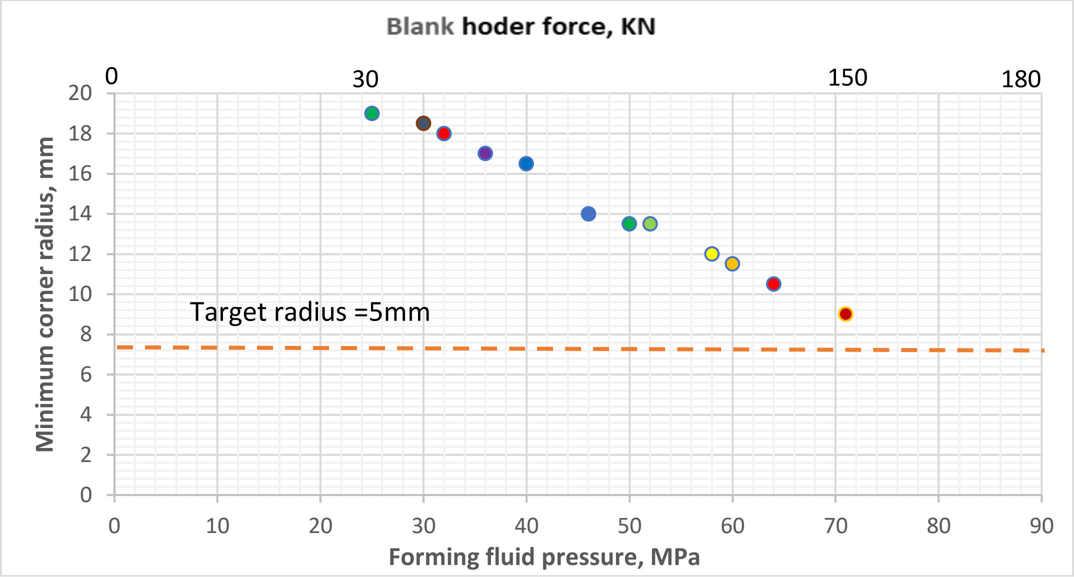

Fig. 14 The Effect of the Maximum Pressure and the Maximum BHF on the Minimum Corner Radius in the Successfully Formed Cups.

4.CONCLUSION

The present research studied the influence of the main parameters on the process feasibility and product formability in the hydrostatic forming of sheet metal. The following conclusions can be drawn based on the results and the discussions presented:

- An experimental setup was developed specifically for hydrostatic forming. It was verified that the setup capability to manufacture square cups with a side length of 40 mm from the 0.5 mm thick 1006AISI steel alloy, with a peak pressure of up to nearly 71MPa (without lubrication).
- A process window with the optimum combinations of the peak blank holder force and the peak pressure was determined to form the cups with the entire die depth without failure at the die entry region, bottom corners, or wrinkling at the cup flange.
- Increasing the peak pressure and the peak blank holder force decreased the achievable minimum corner radius, thereby improving dimensional accuracy. At the same time, this action increased the percentage of thinning.
- The bottom corner radius was reduced with the increase in the peak pressures from 19mm to 9% without any instances of fracture.
- With the high peak pressures for forming and holding, thinning occurred at the cup's bottom corners, where biaxial stretching was the main deformation mode during calibration. More precisely, this region's thinning was 23-24 %, which may approach the critical limit.
- When aiming to achieve small corner radii in sheet hydroforming (better dimensional accuracy), the percentage of thinning should not exceed a certain limit to avoid failure. Therefore, this process window helps select the optimal peak pressures based on the desired corner radius and the maximum allowable thinning for a given component.
- After the hydroforming process, the difference in the microstructure and the change in the grain boundaries resulting from planes sliding due to the deformation and strain hardening was observed.

Accordingly, it is recommended that the research scope be expanded and more experimental data generated to enhance reliability in the future.

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