Optimization of process parameters for hydromechancal deep drawing of square conical parts based on Taguchi and ANOVA methods

Lai Dang Giang*, Tran Duc Hoan, Le Trong Tan

Le Quy Don Technical University, 236 Hoang Quoc Viet, Nghia Do, Hanoi, Vietnam.
*Corresponding author: danggiang248@lqdtu.edu.vn

Received 3 Jan. 2026; Revised 9 Mar. 2026; Accepted 15 Jun. 2026; Published 25 Jun. 2026.
DOI: https://doi.org/10.54939/1859-1043.j.mst.112.2026.176-183

ABSTRACT

In this study, the effects of process parameters on the forming height of square conical parts in hydromechanical deep drawing were investigated using the Taguchi experimental design combined with analysis of variance (ANOVA). SUS 304 stainless steel was selected as the blank material, and experiments were carried out on a hydromechanical deep drawing system equipped with square conical punch and die sets. Three main process parameters were considered, including the relative blank thickness (s/D), blank holding force (q_{BHF}), and initial forming fluid pressure (P_0). A Taguchi L9 orthogonal array was employed to evaluate the influence of these parameters on the product height based on the "larger-the-better" quality characteristic. The results indicate that the blank holding force has the most significant effect on the forming height, followed by the initial fluid pressure and the relative blank thickness. The optimal combination of process parameters was determined as $s/D = 0.0067$, $q_{BHF} = 6$ MPa, and $P_0 = 25$ MPa. The confirmation experiment under the optimal condition achieved a forming height of 45 mm, with a deviation of 2.97% from the predicted value, demonstrating good agreement between prediction and experiment. The findings of this study provide useful guidance for process parameter optimization in the hydromechanical deep drawing of square conical components

Keywords: Hydromechanical deep drawing; Taguchi method; ANOVA; Forming height; SUS 304 stainless steel.

1. INTRODUCTION

Hydromechanical deep drawing (HMDD) is an advanced sheet metal forming technology in which hydraulic fluid pressure is combined with mechanical punch force to enhance formability and stabilize the deformation process. Classical studies have demonstrated that this method can significantly increase the drawing ratio, suppress wrinkling, and reduce material fracture compared with conventional deep drawing, particularly for components with complex geometries [1-3]. Recent review studies have highlighted the rapid development of hydroforming and hydromechanical forming technologies, especially for lightweight and complex-shaped components in automotive and aerospace applications [4].

In fundamental investigations, Yossifon [5] highlighted the critical role of hydraulic pressure in improving the maximum drawing ratio and expanding forming limits. Subsequent studies have focused on numerical simulations and deformation mechanism analyses to clarify the effects of process parameters—such as fluid pressure, blank holding force, and material properties—on product quality in hydromechanical deep drawing processes [6]. For non-axisymmetric components, especially square box-shaped and geometrically complex parts, non-uniform strain distribution makes the forming process difficult to control. Unlike cylindrical components, square conical parts are non-axisymmetric, resulting in non-uniform strain distribution during forming. Stress concentration tends to occur at corner regions, while material flow differs between flat walls and corner zones. Compared with square cups, the conical geometry introduces a continuously changing wall angle, leading to a more complex deformation path and thickness distribution [7]. Numerous researchers have reported that blank holding force and hydraulic pressure play decisive roles in controlling material flow and ensuring shape stability during forming [8-11].

Lang and co-workers extensively investigated the effects of uniform pressure application and pre-bulging phenomena, demonstrating significant improvements in forming quality of box shaped and complex components produced by HMDD [12-14].

Recent review studies indicate that hydromechanical deep drawing remains an actively researched topic, particularly in response to the increasing demand for lightweight, thin-walled, and complex-shaped components in automotive, aerospace, and household appliance industries. However, compared with cylindrical or square box components, the number of published studies focusing on square conical parts remains relatively limited. For conical parts, Jalil [1] analyzed the hydromechanical deep drawing of cone cups assisted by radial pressure and revealed a strong dependence of forming height on pressure conditions and blank holding force. However, comprehensive studies on the combined effects of relative blank thickness, blank holding force, and initial fluid pressure on the forming height of square conical parts remain limited.

In addition, the Taguchi experimental design method combined with analysis of variance (ANOVA) has been proven to be an effective tool for optimizing sheet metal forming processes, allowing the evaluation of parameter significance with a reduced number of experiments. However, the application of this approach to the optimization of forming height in the hydromechanical deep drawing of square conical components remains very limited.

Based on the above considerations, this study aims to investigate the effects of relative blank thickness, blank holding force, and initial forming fluid pressure on the forming height of square conical parts in hydromechanical deep drawing using the Taguchi experimental method combined with ANOVA. The results are expected to clarify the roles of key process parameters and provide a scientific basis for optimizing hydromechanical deep drawing processes for square conical components.

2. PROBLEM

2.1. Material and geometrical model

The study was conducted on a square conical part designed to be compatible with the hydromechanical deep drawing equipment available in the laboratory. The geometry and dimensions of the part were selected to evaluate the forming capability and deformation behavior during the hydromechanical deep drawing process. The detailed geometry of the investigated part is shown in Figure 1.

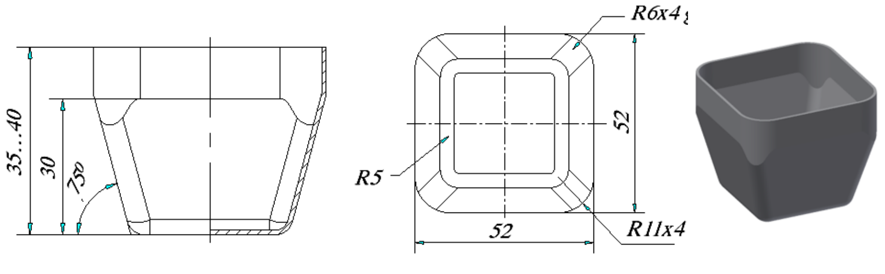


Figure 1. *The detailed geometry of the investigated part.*

SUS 304 stainless steel was selected as the blank material due to its wide industrial application, good corrosion resistance, and high ductility. The chemical composition and mechanical properties of the material were obtained from standard technical data and are summarized in Table 1. These material characteristics provide the basis for analyzing the forming behavior during the experiments.

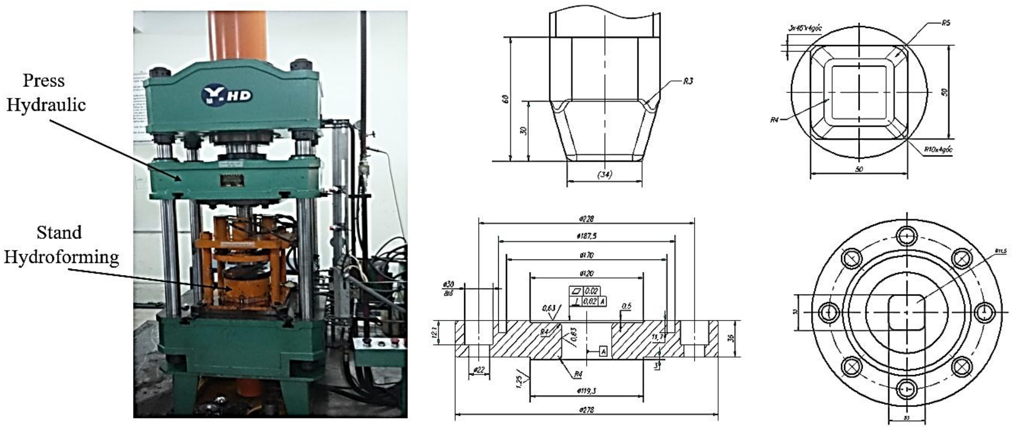
Table 1. *The chemical composition and mechanical properties of the material*

Chemical composition (%)				**Mechanical properties**				
C	Mn	Cr	Ni	σ_b (N/mm2)	$\sigma_{0.2}$ (N/mm2)	δ (%)	ψ (%)	HB
< 0,12	1 - 2	17 - 19	8 - 9,5	520	205	40	25	187

2.2. Tooling and experimental setup

The hydromechanical deep drawing experiments were carried out on a YH32-100 hydraulic press with a nominal capacity of 100 tons in Figure 2a, combined with a dedicated hydromechanical forming setup. The experimental system mainly consists of a punch, die, hydraulic pressure supply system, and a blank holding mechanism.

The punch and die were manufactured from C45 steel and heat-treated to achieve a hardness of approximately 40 HRC to ensure sufficient strength and durability during the forming process. The tool geometry was specifically designed for the square conical part, enabling accurate investigation of the effects of process parameters on the forming behavior. The experimental setup and tooling system are illustrated in Figure 2b.



a) b)

Figure 2. Experimental setup and tooling system.

2.3. Process parameters and experimental design

The initial blank size was determined using the volume constancy method, with a blank diameter of D = 120 mm. In this study, three key process parameters were selected to investigate their influence on the final forming height, including:

- Relative blank thickness (s/D);
- Blank holding force (q_{BHF});
- Initial forming fluid pressure (P_0).

The blank thickness was set at three levels of 0.8 mm, 1.0 mm, and 1.2 mm, corresponding to relative thickness ratios s/D of 0.0067, 0.0083, and 0.01, respectively. The blank holding force q_{BHF} was preliminarily determined based on theoretical considerations and experimental experience, with three levels of 4.5 MPa, 6 MPa, and 7.5 MPa. The initial forming fluid pressure P_0 was also selected at three levels of 25 MPa, 30 MPa, and 35 MPa.

Table 2. Process parameters and their levels.

Process parameters	Symbol	Level		
		1	2	3
s/D	A	0.0067	0.0083	0.01
q_{BHF}, MPa	B	4.5	6	7.5
P_0, MPa	C	25	30	35

To reduce the number of experiments while maintaining reliable results, the Taguchi method was employed for experimental design. A Taguchi L9 orthogonal array was constructed to evaluate the individual and combined effects of the process parameters on the forming height. The selected parameter levels and the experimental matrix are presented in Tables 2 and 3.

Table 3. Orthogonal array (L9) of Taguchi method.

Exp. No	Process parameters					
	A	B	C	s/D	q_{BHF}	P_0
1	1	1	1	0.0067	4.5	25
2	1	2	2	0.0067	6.0	30
3	1	3	3	0.0067	7.5	35
4	2	1	2	0.0083	4.5	30
5	2	2	3	0.0083	6.0	35
6	2	3	1	0.0083	7.5	25
7	3	1	3	0.01	4.5	35
8	3	2	1	0.01	6.0	25
9	3	3	2	0.01	7.5	30

2.4. Objective function and evaluation method

The objective function in this study is the height of the formed part after hydromechanical deep drawing. The forming height is considered a direct indicator of the forming capability and was evaluated based on the “larger-the-better” criterion.

According to the Taguchi method, the signal-to-noise (S/N) ratio for the “larger-the-better” characteristic was calculated using the following equation:

$$S/N = -10\log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \quad (1)$$

Where y_i is the measured height of the formed part and nnn is the number of repetitions. The S/N ratio analysis combined with analysis of variance (ANOVA) was used to evaluate the contribution of each process parameter and to determine the optimal parameter combination for the hydromechanical deep drawing process.

3. RESULTS AND DISCUSSION

3.1. Experimental results

Hydromechanical deep drawing experiments were carried out according to the Taguchi L9 orthogonal array with variations in three process parameters: relative blank thickness (s/D), blank holding force (q_{BHF}), and initial forming fluid pressure (P_0). The formed square conical parts obtained from the experiments are shown in Figure 3.

***Figure 3.** The formed square conical parts obtained from the experiments.*

The measured forming heights of the products are summarized in Table 4. The results reveal that the forming height varies significantly with changes in process parameters, ranging from 16 mm to 38 mm for the Taguchi experimental runs. This indicates that the selected process parameters have a pronounced influence on the forming capability of square conical parts.

Table 4. *Taguchi L9 orthogonal array and experimental results.*

Exp. No	**Process parameters**			**Results**
	A	**B**	**C**	**h**
1	1	1	1	28
2	1	2	2	33
3	1	3	3	36
4	2	1	2	23
5	2	2	3	27
6	2	3	1	33
7	3	1	3	16
8	3	2	1	38
9	3	3	2	25

Visual inspection of the formed parts shows that certain parameter combinations lead to stable shapes with relatively uniform side walls, whereas other combinations result in reduced height or non-uniform deformation. These observations provide a solid experimental basis for further Taguchi and ANOVA analyses

3.2. Signal-to-noise (S/N) ratio analysis

Based on the “larger-the-better” criterion, the signal-to-noise (S/N) ratios were calculated to evaluate the effects of process parameters on the forming height. The average S/N ratios corresponding to each parameter level are presented in Table 5.

Table 5. *Signal-to-noise ratio analysis.*

Level	**Average S/N for forming height**		
	A	**B**	**C**
1	30.15	26.75	30.38
2	28.74	30.27	28.52
3	27.88	29.82	27.95
Mean (m)	28.92	28.92	28.92
Delta (max-min)	2.27	3.44	2.36
Contribution,%	28.1	42.68	29.22

For the relative blank thickness (s/D), the highest S/N ratio is observed at level A1 (s/D = 0.0067), and the S/N ratio decreases as the blank thickness increases. This trend indicates that thinner blanks tend to achieve greater forming heights in the hydromechanical deep drawing process (Figure 4).

Regarding the blank holding force (q_{BHF}), the S/N ratio increases from level B1 to B2 and reaches a maximum at level B2 (q_{BHF} = 6 MPa), followed by a slight decrease at level B3. This behavior suggests the existence of an optimal blank holding force. Insufficient blank holding force leads to unstable material flow, while excessive force increases friction and restricts material movement, thereby reducing the forming height.

For the initial forming fluid pressure (P_0), the maximum S/N ratio is obtained at level C1 (P_0 = 25 MPa), and the S/N ratio decreases with increasing pressure. This indicates that excessively high initial fluid pressure may hinder axial material flow and reduce the achievable forming height.

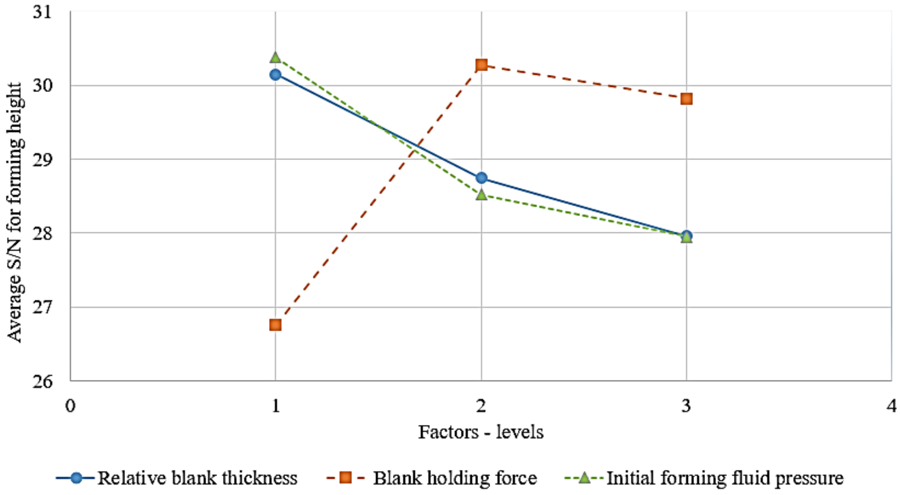


Figure 4. *S/N ratio response diagram.*

3.3. Analysis of variance (ANOVA)

To quantify the contribution of each process parameter to the forming height, analysis of variance based on the S/N ratios was performed. The results are summarized in Table 5.

The ANOVA results indicate that the blank holding force (q_{BHF}) is the most influential parameter, contributing 42.68% to the total variation in forming height. This is followed by the initial forming fluid pressure (P_o) with a contribution of 29.22%, and the relative blank thickness (s/D) with a contribution of 28.1%. These results highlight the dominant role of boundary conditions in the hydromechanical deep drawing process.

The blank holding force governs blank stability, friction conditions, and material flow into the deformation zone. The initial fluid pressure assists the forming process but may reduce axial deformation when excessively high. The relative blank thickness directly affects the deformation resistance and stretchability of the blank.

3.4. Optimal parameter combination and confirmation experiment

Based on the principle of selecting the parameter levels with the highest average S/N ratios, the optimal parameter combination was identified as A1–B2–C1, corresponding to s/D = 0.0067, q_{BHF} = 6 MPa, and P_o = 25 MPa.

At that point, the optimal product height is determined as follows:

$$\begin{aligned}(S/N)_{opt} &= (S/N)_{\max A} + (S/N)_{\max B} + (S/N)_{\max C} - 2*mean\\ &= 30.15 + 30.2 + 30.3 - 2*28.92\\ &= 32.80 \qquad (2)\\ \Rightarrow h_{opt} &= 10^{\frac{(S/N)_{opt}}{20}} = 10^{\frac{32.8}{20}} = 43.7\ mm\end{aligned}$$

A confirmation experiment was conducted under the optimal condition to validate the optimization results. The formed part exhibited a stable geometry with uniform side walls and no visible defects such as wrinkling or fracture. The maximum forming height achieved was 45 mm, which is significantly higher than that obtained in the Taguchi experimental runs (Figure 5). The deviation between the predicted and experimental values was calculated as **2.97%**, indicating good agreement between the model prediction and the experimental result. This confirms the reliability and effectiveness of the proposed optimization method for hydromechanical deep drawing of square conical parts.

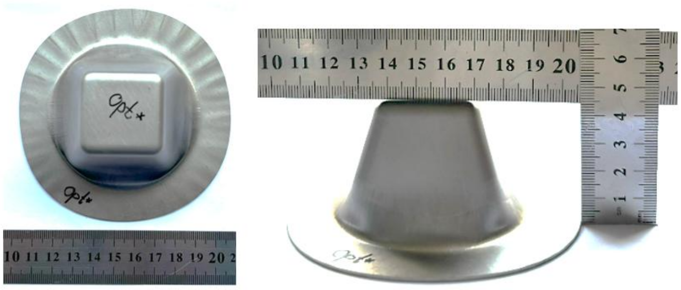


Figure 5. *Product at optimal technological conditions.*

This confirms the effectiveness of the Taguchi–ANOVA approach in optimizing process parameters for the hydromechanical deep drawing of square conical parts.

4. CONCLUSIONS

In this study, the effects of process parameters on the forming height of square conical parts in hydromechanical deep drawing were investigated using the Taguchi experimental design combined with analysis of variance. Based on the obtained results, the following conclusions can be drawn:

- The investigated process parameters, including relative blank thickness (s/D), blank holding force (q_{BHF}), and initial forming fluid pressure (P_o), have a significant influence on the forming height of square conical parts.

- ANOVA results indicate that the blank holding force is the most influential parameter, contributing 42.68% to the variation in forming height, followed by the initial forming fluid pressure (29.22%) and the relative blank thickness (28.1%).

- The optimal process parameter combination for maximizing the forming height was identified as s/D = 0.0067, q_{BHF} = 6 MPa, and P_o = 25 MPa, corresponding to the A1–B2–C1 setting in the Taguchi design.

- Confirmation experiments conducted under the optimal condition produced a stable square conical part with uniform side walls and without defects such as wrinkling or fracture. The maximum forming height achieved was 45 mm, which is significantly higher than those obtained in the Taguchi experimental runs. The small deviation of 2.97% confirms the strong predictive capability of the Taguchi–ANOVA approach for optimizing hydromechanical deep drawing parameters.

The results demonstrate the effectiveness of the Taguchi–ANOVA approach for process parameter optimization in hydromechanical deep drawing and provide valuable guidance for industrial application and further research on square conical part forming.

REFERENCES

[1]. A. Jalil *et al.*, "*Process analysis of hydrodynamic deep drawing of cone cups assisted by radial pressure*". Journal of Engineering Manufacture 231, Issue 10, (2015). Doi:10.1177/0954405415612325.

[2]. B. Meng *et al.*, "*Influence of cavity pressure on hydrodynamic deep drawing of aluminum alloy rectangular box with wide flange*". International Journal of Mechanical Sciences, vol 77, (2013). Doi: 10.1016/j.ijmecsci.2013.10.012.

[3]. B. Modi *et al.*, "*Development of a hydroforming setup for deep drawing of square cups with variable blank holding force technique*". The International Journal of Advanced Manufacturing Technology, vol 66, (2013). Doi: 10.1007/s00170-012-4397-4.

[4]. B. Colin *et al., "A state of the art review of hydroforming technology: Its applications, research areas, history, and future in manufacturing"*. International Journal of Material Forming, (2019). Doi:10.1007/s12289-019-01507-1.

[5]. S. Yossifon *et al.*, "*The Maximum Drawing Ratio in Hydroforming Processes*", Journal. Eng. Ind. (1990). Doi: 10.1115/1.2899294.
[6]. F. Rahmani *et al., "Numerical and Experimental Study of the Efficient Parameters on Hydromechanical Deep Drawing of Square Parts"* . Journal of Materi Eng and Perform 22, (2013). Doi: 10.1007/s11665-012-0301-5.
[7]. A. Afsoon *et al.*, "*Hydro-mechanical deep drawing of conical components: Wrinkling behavior and process enhancement"*. Journal of Engineering Research. Vol 13, (2025), Doi: 10.1016/j.jer.2024.04.005.
[8]. G. Papadia *et al., "Pre-bulging influence on an inverse drawn shape obtained with Hydromechanical Deep Drawing (HDD)"*. Int J Mater Form 3 (Suppl 1), (2010). Doi:10.1007/s12289-010-0763-7.
[9]. S. H. Zhang,. "*Analsis of the hydromechanical deep drawing of cylindrical cups*". Journal of Materials Processing Technology, (2000). Doi:10.1016/S0924-0136(99)00439-2.
[10].F. F. Damborg *et al.*, *"Hydromechanical deep drawing"*. Scandinavian Journal of Metallurgy 29(2), (2000). Doi:10.1034/j.1600-0692.2000.d01-7.x
[11].J. Tirosh *et al.*, *"On the hydrodynamic deep-drawing process"*. International Journal of Mechanical Sciences, vol 27, (2003). Doi: 10.1016/0020-7403(85)90075-X.
[12].L. Lang *et al.*, *"Investigation into the forming of a complex cup locally constrained by a round die based on an innovative hydromechanical deep drawing method"*. Journal of Materials Processing Technology, (2005). Doi:10.1016/j.jmatprotec.2005.06.030.
[13].L. Lang *et al.*, *"Study on hydromechanical deep drawing with uniform pressure onto the blank"*. International Journal of Machine Tools and Manufacture, (2004). Doi:10.1016/j.ijmachtools.2003.10.028
[14].L. Lang *et al.*, *"Investigation into the effect of pre-bulging during hydromechanical deep drawing with uniform pressure onto the blank*". International Journal of Machine Tools & Manufacture, (2004). Doi: 10.1016/j.ijmachtools.2003.11.004.

TÓM TẮT

Nghiên cứu ảnh hưởng của các thông số công nghệ dập thủy cơ đến chiều cao chi tiết dạng côn vuông bằng phương pháp Taguchi

Trong bài báo này, khảo sát ảnh hưởng của các thông số công nghệ đến chiều cao chi tiết dạng côn vuông trong quá trình dập thủy cơ được bằng phương pháp thực nghiệm Taguchi kết hợp với phân tích phương sai (ANOVA). Ba thông số công nghệ chính được lựa chọn để nghiên cứu bao gồm: chiều dày tương đối của phôi (s/D), áp lực ép biên (q_{BHF}) và áp suất chất lỏng tạo hình ban đầu (P_0). Ma trận thực nghiệm Taguchi L9 được xây dựng nhằm đánh giá ảnh hưởng của các thông số đến chiều cao sản phẩm theo tiêu chí "lớn nhất là tốt nhất". Kết quả phân tích cho thấy áp lực ép biên là yếu tố ảnh hưởng lớn nhất đến chiều cao sản phẩm, tiếp theo là áp suất chất lỏng ban đầu và chiều dày tương đối của phôi. Tổ hợp thông số công nghệ tối ưu được xác định là $s/D = 0.0067$, $q_{BHF} = 6$ MPa và $P_0 = 25$ MPa. Thí nghiệm xác nhận tại chế độ tối ưu cho thấy sản phẩm đạt hình dạng ổn định và chiều cao lớn nhất là 45 mm, sai lệch 2.97% so với kết quả dự đoán xác định từ phương pháp Taguchi. Kết quả nghiên cứu có ý nghĩa thực tiễn trong việc lựa chọn và tối ưu hóa thông số công nghệ cho quá trình dập thủy cơ các chi tiết dạng côn vuông.

Từ khóa: Dập thủy cơ; Taguchi; ANOVA; Chiều cao sản phẩm; Thép SUS 304.