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A MATHEMATICAL MODEL FOR THINNING RATE PREDICTION OF SHEET DOUBLE HYDRO-FORMING

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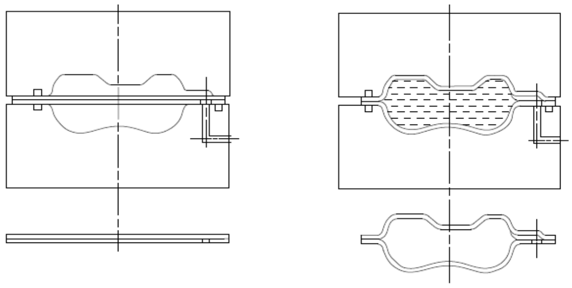
Double sheet blank hydro-forming (DSBH) is a technology for forming hollow parts with complex shapes. The pair of workpieces is deformed and shaped by the high-pressure liquid inside. The material is thinned after hydraulic forming, which significantly affects the quality of the product, especially the fields with high requirements, such as the automotive and aerospace industry. The goal of optimizing input process parameters to ensure that the level of thinning into a product is within the allowable limit is posed by this study. This study considered blank holder force, forming fluid pressure, and relative thickness as candidate factors for optimization using Response Surface Method (RSM). The spherical parts were formed by the DSBH method of welding blank pairs of DC04 carbon steel material based on theoretical analysis, experiment solution, and experiment to verify the results. Experiments were performed with different combinations of parameters using the Box-Behnken design. This paper presented a mathematical model that helps determine material thinning rate according to these three process parameters in the hydro-forming of spherical parts from welded sheet metal pairs. The research results can be applied to control the input parameters in the DSBH to achieve the wall thickness of the spherical part as desired by the manufacturer.

Keywords: double sheet blank, thinning rate, hydro-forming, indexing

1 INTRODUCTION

Hydro-forming is an advanced manufacturing method for producing hollow parts, including sheet, tube and shell (sheet, tube, & shell) components [1,2]. Usually, a dedicated pressurization system is used to create several thousand bars forming pressure, which is used to form hollow parts. During DSBH, the pair of sheet metal blanks are simultaneously shaped under the effect of hydraulic pressure inside the die cavity (Figure 1). The process of DSBH was detailed in references [1,3,4].



Double sheet blank Formed component

Fig. 1. Double sheet blank hydro-forming [3].

DSBH technology combines the advantages of sheet and tube hydrostatic forming technology. It overcomes the disadvantages of tube hydro-forming, which is the ability to shape hollow parts with a sudden change of axis cross-section and limitations in shaping hollow parts with multi-directional changes in space [5,6]. The DSBH process has grown enormously in recent years, especially in vehicle manufacturing [1,4,7]. DHBS technology with outstanding features such as being able to manufacture hollow parts with complex shapes after one stamping step, and at the same time can integrate other operations such as punching, welding joints... so this technology attracts many manufacturers [4] to [6]. Structural strength and stiffness are improved, and tooling costs are reduced because several parts can be fused into one formed part. When removed from the die, parts manufactured by traditional forming methods often undergo back-elasticity and residual stress. This effect is much smaller in hydroformed parts [8] to [10]. The studies mainly focused on the process parameters, geometrical parameters of workpieces and tools, and materials. In sheet hydro-forming, the product is strongly thinned at the hollow bottom because in the early stages of forming, the workpiece deforms freely under hydrostatic pressure and partly due to the blank holder force for sealing anti-wrinkle products. In sheet hydro-forming, the product is strongly thinned at the hollow bottom because, at the beginning of the forming process, the workpiece deforms freely under the action of hydrostatic pressure. And due to the force of contact friction, the blank holder force creates resistance to prevent the workpiece from pulling into the cavity of the die. (Figure 1). Therefore, the distribution of material thickness at each position on the product is different. Yuuki Yanase et al. investigated the internal pressure profile, and the variable blocking force trajectory (VBHF) was determined using sequential approximation optimization to reduce the area of the blank not being pulled into the die cavity by comparing the profile of the blank and the die cavity [11]. E. Karabegovic and J. Poljak proposed a mathematical equation representing the relationship between the working fluid pressure and the deformation of a pair of sheets welded, the blank material used are steel and aluminum [12]. Bharatkumar Modi & D. Ravi Kumar found that when using a variable blank holder force, the deformation ability of the workpiece is better than the method using a constant blank holder force [13]. Kitayama, Satoshi et al. proposed a sequential approximation optimization model to save blank material in sheet metal forming by optimizing the input blank geometry and using the method of varying the blank holder force by different regions [14]. Rainer Krux, Werner Homberg et al. Studied the surface structure of the die and the hydro-forming system combined with the multi-point blank holder method to optimize the flow of workpiece material into the die cavity, applied to parts with symmetrical and asymmetrical geometries [15]. Bharatkumar Modi & D. Ravi Kumar used the Taguchi method and regression model to build the relationship function between the maximum pressure and the variable blank holder force to predict the minimum wall thickness and bottom corner radius when hydro-forming square cups from AA5182. material [16]. The research results of the above authors have shown that the input parameters such as the workpiece blocking force, the liquid pressure, the geometrical shape of the workpiece, and the die influence the quality of the formed product. However, there have not been many research works on DSBH published. Therefore, there is a need for more in-depth research on DSBH and the establishment of reliable mathematical models, allowing for easier planning and forecasting of DSBH in the manufacturing industries. In this study, the Box-Behnken design - Response Surface Method (RSM) is used to design an empirical matrix. On that basis, conduct experiments to study the influence of input technology parameters in the DSBH process to assess the quality of the forming part. Simultaneously analyze and optimize process parameters to control the material thinning rate at the top of the spherical part (the most dangerous position). Furthermore, the completeness of the generated model was confirmed by an analysis of variance (ANOVA) approach. The object of research was a spherical part that is formed by DSBH technology, and the blank material is DC04. The selection of the spherical part because it is difficult to fabricate by conventional stamping methods. This forming technique is used to manufacture tanks and other hollow parts in the transportation industry. And it is also interesting because it's perhaps the most specific detail regarding the axially symmetrical extension, which is typical for many similar-shaped products.

2 MATERIAL AND TECHNIQUES

2.1 Studied material

The chosen material is DC04 steel with surveyed sheet blank thickness t0 of 0.8 mm, 1.0 mm, and 1.2 mm. The mechanical properties of the materials are given in Table 1. To form a spherical part with a diameter (of 50, it is necessary to have an initial blank diameter of D0 = 73 mm [17] and be welded as shown in Figure 2.

Table 1. Room temperature mechanical properties of sheet blank [18].

Alloy	Yield strength (MPa)	Ultimate Tensile Strength (MPa)	Elongation (%)	Density (kg/m^3)
DC04	210 - 220	314 - 412	40	7850

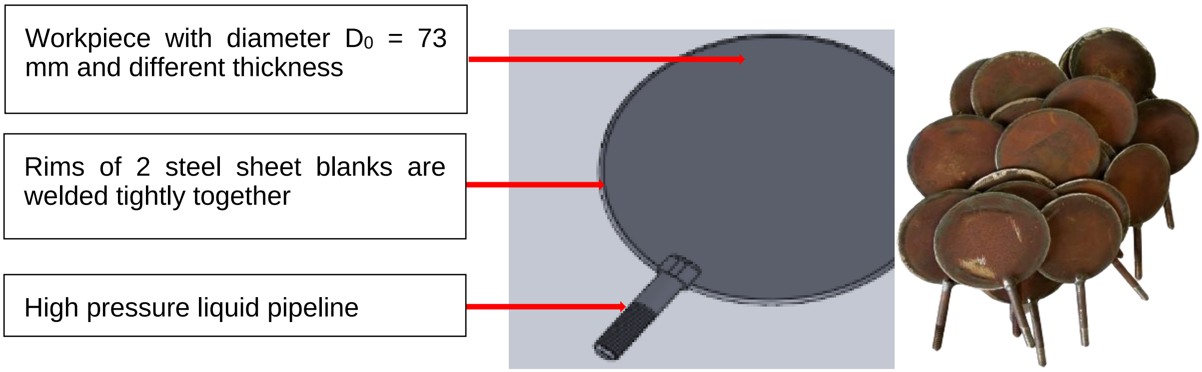


Fig. 2. Experimental workpieces.

2.2 Process parameters

In the study of DSBH to fabricate spherical parts of DC04 material, critical process parameters are internal fluid pressure Pi, blank holder force Fb, and relative thickness tr, whose values must be investigated and determined. The forming fluid pressure exerts yield deformation (Pi)y calculated by Equation (1) [19], and the maximum of forming fluid pressure (Pi)u can be calculated by Equation (2) [19]. These two pressure values were determined as good initial predictors for trial and error work.

$$(P_i)_y = \sigma_y * \frac{2t_0}{\left(r_{min} - \frac{t_0}{2}\right)} \quad (1)$$

$$(P_i)_u = \sigma_u * \frac{2t_0}{\left(r_{min} - \frac{t_0}{2}\right)} \quad (2)$$

Where: σ_y = Yield Strength, MPa; σ_u = Ultimate Tensile Strength, MPa; t_0 = Initial blank thickness, mm; r_{min} = Minimum inner radius of forming product, mm.

The blank holder force directly affects the forming process and the quality of the product. The blank holder force changes the stress-strain state diagram at the rim. In DSBH technology, the blank holder force, in addition to anti-wrinkle purposes, must also ensure the sealing of the die and resist hydrostatic pressure acting on two halves of the die. In order to have preliminary parameters for the survey process, the blank holder force can be determined according to Equation (3) [20].

$$F_b = \alpha . P_i . A \quad (3)$$

Where: α – coefficient (α = 1.1 ÷ 1.3); A – Projection area of die cavity surface, mm^2.

The study investigated the thinning rate at five measuring positions, numbered from 1 to 5 on the cross-section of the spherical part (Figure 3).

The thinning rate ε_i is calculated by Equation (4).

$$\varepsilon_i = \frac{t_0 - t_i}{t_0} . 100\ (\%) \quad (4)$$

Where t_i – product wall thickness at each measuring position, mm.

For the steel DC04 blank, the allowable thinning rate is estimated at 40 % [18].

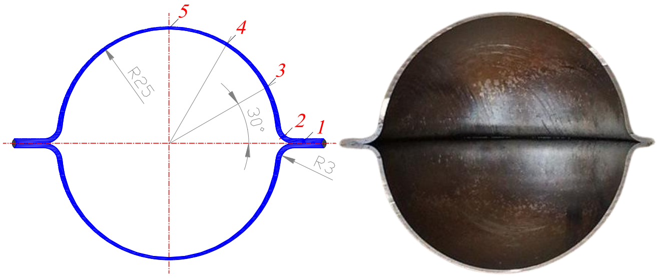


Fig. 3. Sphere part and five measuring positions.

Because a welding technique initially sealed the steel sheet blanks together, when conducting experiments, the coefficient of friction between two surfaces of the steel sheet in contact with each other is determined μ = 0 and between the workpiece surface and die taken μ = 0.15 (lubricated with hydraulic oil VG 46 - Hydraulic Oil VG 46).

2.3 Research Methods

Determining the proper process parameters by conducting a series of experiments is expensive and time-consuming. Therefore, it is necessary to have suitable methods to assess the influence of essential parameters on the accuracy and quality of the part. With precision and ease of application in research, Response Surface Method (RSM) is one of the most effective and widely used statistical and mathematical tools for optimizing system performance in engineering [21,22].

In this paper, the combination of the Box-Behnken parametric design method and the Response Surface Method (RSM) was used to improve the quality of the product formed by the DBSH process. An experimental plant was proposed according to the Box-Behnken design. The experimental input elements of this design which was a face-centred format to give different combinations and levels of each test execution. During this experiment, the design of the face-centred format was carried out and the parameters affecting material thinning were analyzed and optimized. RSM can be considered an appropriate approach to analyzing and optimizing this forming technique. This forming process increases the efficiency and superiority of the product [22] to [24].

Hollow parts formed by DBSH need to meet the high requirements of the industrial fields. The product's wall thickness is a significant value related to the product's mechanical properties. Therefore, this combination was chosen to determine the influence of input factors, including liquid pressure in the vessel, blank holder force, and relative thickness on the output, the material thinning rate at the top of the sphere – measured position 5. This measured position is the most dangerous of part because it is easy to crack, tear, and burst during the forming process.

The depth hs of the upper and lower die halves is 25 mm (Figure 4). The three input parameters were blank holder force Fb varying from 80 kN to 148 kN, calibration fluid pressure Pc changing from 350 bar to 386 bar, and relative thickness of blank tr = 1.10 %, 1.37 %, and 1.64%. A quadratic orthogonal design was used to determine the spherical part wall thickness distribution and established a function representing the relationship between the maximum thinning rate □max (5) at the top of the part with input parameters. Table 2 provides the physical and coded values of the input variables for experimental design.

$$\square max\ (5) = f\ (Fb, Pc, tr) \qquad (5)$$

Table 2. Physical and coded values of the input variables.

Input variables/parameters/units			**Coded values**		
			-1	**0**	**+1**
Physical values	Blank holder force (kN)	$x_1 - F_b$	80	114	148
	Calibration liquid pressure (bar)	$x_2 - P_c$	350	368	386
	Relative thickness of blank (%)	$x_3 - t_r$	1.10	1.37	1.64

a) Lower die half b) Upper die half

Fig. 4. Fabrication of two halves of the spherical part dies.

2.4 Design of experiments

A Box-Behnken orthogonal design was created by Statgraphics software that aimed to study the influence of 3 factors over 30 runs. This experimental design was run in 2 blocks, with the order of the experiments completely randomized. These will protect against the effects of hidden variables. The design elements of input parameters and their measures are listed in Table 3.

Table 3. Box-Behnken design matrix with collected data [25].

No	**Coded values**				**Actual Values**			**Output**
	x_1	x_2	x_3	**Block**	**Blank holder force F_b (kN)**	**Calibration pressure P_c (bar)**	**Relative thickness of blank t_r (%)**	$\varepsilon_{max\ (5)\ -\ i}$
1	1	1	0	1	148	386	1.37	$\varepsilon_{max\ (5)\ -\ 1}$
2	-1	-1	0	1	80	350	1.37	$\varepsilon_{max\ (5)\ -\ 2}$
3	0	-1	1	1	114	350	1.64	$\varepsilon_{max\ (5)\ -\ 3}$
4	0	1	1	1	114	386	1.64	$\varepsilon_{max\ (5)\ -\ 4}$
5	0	1	-1	1	114	386	1.10	$\varepsilon_{max\ (5)\ -\ 5}$
6	0	-1	-1	1	114	350	1.10	$\varepsilon_{max\ (5)\ -\ 6}$
7	0	0	0	1	114	368	1.37	$\varepsilon_{max\ (5)\ -\ 7}$
8	1	0	-1	1	148	368	1.10	$\varepsilon_{max\ (5)\ -\ 8}$
9	1	-1	0	1	148	350	1.37	$\varepsilon_{max\ (5)\ -\ 9}$

No	Coded values				Actual Values			Output
	x_1	x_2	x_3	Block	Blank holder force F_b (kN)	Calibration pressure P_c (bar)	Relative thickness of blank t_r (%)	$\varepsilon_{max\ (5)\ -\ i}$
10	-1	0	1	1	80	368	1.64	$\varepsilon_{max\ (5)\ -\ 10}$
11	-1	1	0	1	80	386	1.37	$\varepsilon_{max\ (5)\ -\ 11}$
12	0	0	0	1	114	368	1.37	$\varepsilon_{max\ (5)\ -\ 12}$
13	-1	0	-1	1	80	368	1.10	$\varepsilon_{max\ (5)\ -\ 13}$
14	-1	0	0	1	114	368	1.37	$\varepsilon_{max\ (5)\ -\ 14}$
15	1	0	1	1	148	368	1.64	$\varepsilon_{max\ (5)\ -\ 15}$
16	1	1	0	2	148	386	1.37	$\varepsilon_{max\ (5)\ -\ 16}$
17	-1	-1	0	2	80	350	1.37	$\varepsilon_{max\ (5)\ -\ 17}$
18	0	-1	1	2	114	350	1.64	$\varepsilon_{max\ (5)\ -\ 18}$
19	0	1	1	2	114	386	1.64	$\varepsilon_{max\ (5)\ -\ 19}$
20	1	1	-1	2	114	386	1.10	$\varepsilon_{max\ (5)\ -\ 20}$
21	-1	-1	-1	2	114	350	1.10	$\varepsilon_{max\ (5)\ -\ 21}$
22	-1	0	0	2	114	368	1.37	$\varepsilon_{max\ (5)\ -\ 22}$
23	1	0	-1	2	148	368	1.10	$\varepsilon_{max\ (5)\ -\ 23}$
24	1	-1	0	2	148	350	1.37	$\varepsilon_{max\ (5)\ -\ 24}$
25	-1	0	1	2	80	368	1.64	$\varepsilon_{max\ (5)\ -\ 25}$
26	-1	1	0	2	80	386	1.37	$\varepsilon_{max\ (5)\ -\ 26}$
27	0	0	0	2	114	368	1.37	$\varepsilon_{max\ (5)\ -\ 27}$
28	-1	0	-1	2	80	368	1.10	$\varepsilon_{max\ (5)\ -\ 28}$
29	-1	0	0	2	114	368	1.37	$\varepsilon_{max\ (5)\ -\ 29}$
30	1	0	1	2	148	368	1.64	$\varepsilon_{max\ (5)\ -\ 30}$

3 EXPERIMENTAL PROCESS

Based on studies on the device system and requirements for process parameters in hydro-forming, an experimental system consisting of 4 modules was built (Figure 5). Specifically, it included a hydraulic press, an experimental die set, a pressure intensifier, and one computer-connected process parameter measurement set [18, 26, 27]. Figure 6 shows a schematic diagram of the experimental system. The die is installed on the hydraulic press, connected to the high-pressure liquid feeder and the input parameter measuring device. The pair of welded sheet blanks are clamped between the upper and lower die halves. The blank holder force is generated by the piston of the hydraulic press. The pressure intensifier provides the hydraulic pressure in the die cavity, then the blanks are plastically deformed to form an expansion area and finally contact the die cavity profile. When there is a change in pressure inside the die, the pressure in the blank holder cylinder the forming height will be recorded by the measurement system and displayed on the computer. The experimental process ends when the investigated parameters are determined as designed. To evaluate the influence of blank holder force on the hydro-forming process, the blank holder force is adjusted by changing the pressure in the blank holder cylinder (the cylinder of hydraulic press). The values of blank holder force are determined based on the area of the die cavity surface, which is determined by Equation (3) and by the trial and error method.

The metal forming process fails when one of the following conditions occurs:

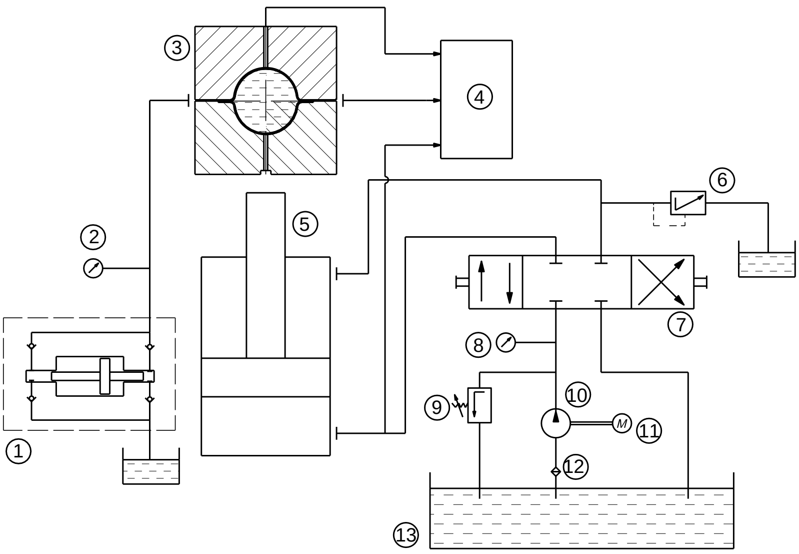
1. The large blank holder force during the forming process causes increased friction to hinder pulling metal from the blank rim into the die cavity. When the forming fluid pressure increases, the top area of the part under the effect of tensile stress in two directions will cause the workpiece to be strongly thinned and destroyed when the height of 25 mm has not been reached. Then the liquid pressure will be drastically reduced, and the product will not form further.

2. The small blank holder force during the forming process, when forming liquid pressure increases larger than blank holder force, which leads to two die halves being pushed apart, causing instability of blank holder force at the rim of the sheet blank. The forming process will end when the strong and tight welding connection between the two

sheet blanks is destroyed, causing leakage and loss of pressure. And then, the blank holder force is not enough to seal when the forming pressure increases, so P_i at the time of leakage is not large enough for part forming deformation to reach the height of 25 mm.

An experimental system was built allowing us to investigate the influence of input parameters such as blank holder force, forming liquid pressure, relative thickness on the thinning rate at the top position of the sphere (a most dangerous place) to obtain the aim for successful product formation.

Fig. 5. Experimental system.



1 Pressure intensifier
2 Hydraulic oil pressure gauge
3 Hydrostatic stamping die
4 Measurement system
5 Hydraulic press cylinder
6 Safety valve
7 Distribution valve
8 Hydraulic pressure gauge
9 Overflow valve
10 Hydraulic pump
11 Electric motor
12 Oil filter
13 Oil tank

Fig. 6. The principle diagram of the experimental system.

4 RESULTS AND DISCUSSIONS

4.1 Results

The blank holder force Fb was constant in the experiments, and the high-pressure liquid was injected into the die with increasing pressure to the calibration pressure value Pc as planned in Table 3. The measurement system using DASYLab software (DASYLab version 11.0) will display the values of blank holder force, forming liquid pressure, the height of the formed product (Figure 7). The pressure intensifier injects liquid into the die with the same steps, but they differ only in the calibration pressure generation stage. Therefore, these calibration pressure values have been collected and summarized in Table 3.

Conduct trial-and-error experiments to determine the blank holder force, and the results show that, with the values of blank holder force less than 49.42 kN (corresponding to the pressure of blank holder force cylinder less than 13 bar) and larger than 155.85 kN (corresponding to the pressure of blank holder force cylinder larger than 41 bar) for a failed forming process (Figure 7).

With the blank holder force value range varying from 79.83 kN to 148.25 kN (corresponding to blank holder cylinder pressure changing from 21 bar to 39 bar), the part was formed successfully without wrinkle or crack. The forming process in this range of blank holder force values shows that, when increasing the internal fluid pressure to deform the workpiece to the height of 25 mm (equal to the radius of the spherical part R = 25 mm), it is still necessary to continue to increase the pressure to form the profile of the part. When forming pressure reaches the calibration value, the sheet blank is completely deformed according to the profile of the die cavity. Figure 8 shows the result of the spherical part that is successfully formed.

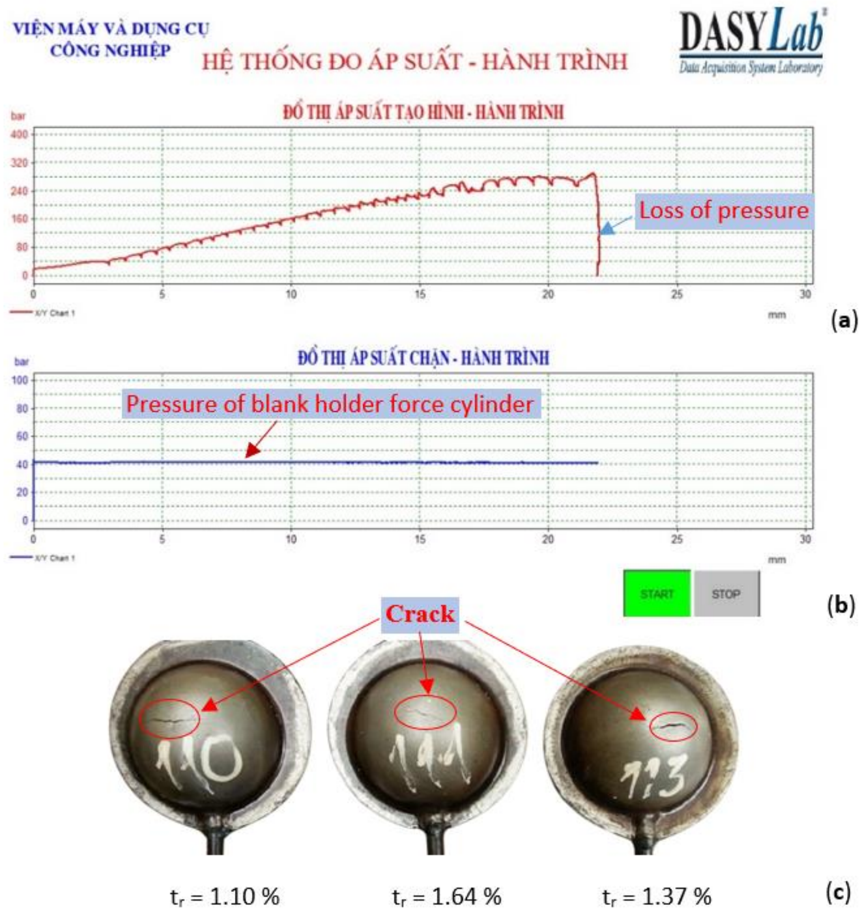


Fig. 7. Measurement graph including (a) forming fluid pressure; (b) pressure of blank holder force cylinder; (c) defective formed part.

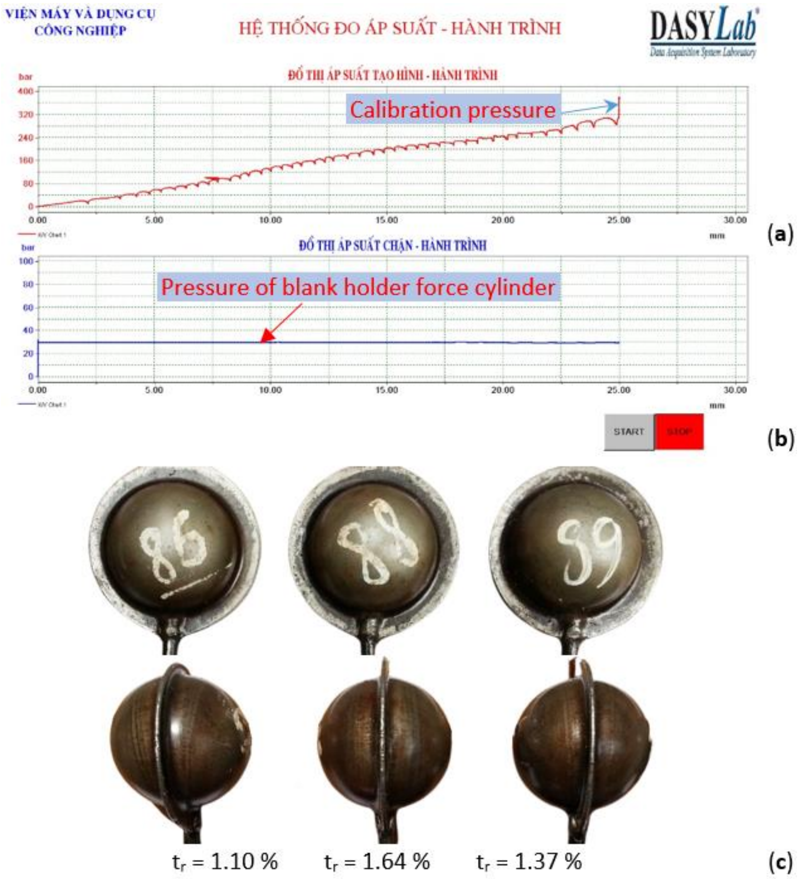


Fig. 8. Measurement graph including forming pressure (a) and blank holder force (b); successfully formed parts (c).

Because the detail is spherical symmetric about the center, only the thickness measurement survey is carried out on a quarter of the experimental part. The positions were measured as shown in Figure 3. These were measured on a Future Tech FM700 (Figure 9) and Figure 10.

Figure 9. Measurement of material thickness on the Future Tech FM700.

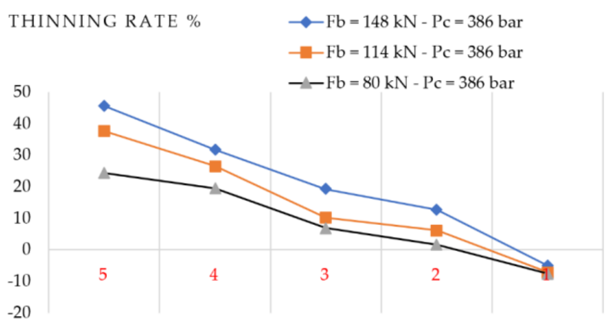


Fig. 10. The material thinning rate at five measured positions for the relative thickness of workpiece tr = 1.37 %.

From Equation 4 and Figure 10, it is shown that the part is thinned at points 2 to 5 and thickened at point 1. This result is consistent with the plastic deformation speed and material feed during the hydro-forming process.

Table 4. The material thinning rate in experimental order in the design matrix.

No (block 1)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
$\varepsilon_{max\ (5)-i}$	45.5	21.5	19.7	20.2	34.6	31.9	31.2	49.6	41.4	15.8	27.4	31.7	31.5	30.9	21.9
No (block 2)	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**
$\varepsilon_{max\ (5)-i}$	44.8	22.2	18.8	20.5	35.5	32.3	31.3	48.8	41.8	16.2	25.9	29.9	30.9	29.7	22.4

4.2 Identify the Considerable Factors

Table 5. Analysis of variance for thinning rate [25].

Source	**Sum of Squares**	**Df**	**Mean Square**	**F-Ratio**	**P-Value**
A:Blank holder force	973.44	1	973.44	190.65	0.0000
B: Forming liquid pressure	38.44	1	38.44	7.53	0.0116
C:Relative thickness	1218.01	1	1218.01	238.55	0.0000
AA	66.2585	1	66.2585	12.98	0.0015
AC	70.2113	1	70.2113	13.75	0.0012
CC	127.228	1	127.228	24.92	0.0000
Total error	117.435	23	5.10587		
Total (corr.)	2625.2	29			
R-squared = 95.5266 % R-squared (adjusted for d.f.) = 94.3597 % Standard Error of Est. = 0.622298			Mean absolute error = 1.60949 Durbin-Watson statistic = 2.2589 (P = 0.7476) Lag 1 residual autocorrelation = -0.201381		

The ANOVA table (table 5) shows the change in material thinning rate into separate pieces for each effect of input parameters. And also show the statistical significance of each effect by comparing the mean square with an estimate of the experimental error. The most critical value in the table is the P-value. Six results, including A (Blank holder force), B (Forming liquid pressure), C (Relative thickness), AA, AC, CC have P-values less than 0.05; they are all non-zero and significant at 95.0% confidence. Therefore, the model is determined to be meaningful for the research objective - the material thinning ratio.

4.3 Model development

The coefficients and their estimated values of the regression model for measuring the thinning rate of a measured point at the top of the spherical part are all significant terms shown in Table 6. Equation (6) represents the relationship of this thin variable ratio with the input parameters. The response surface for the model was built, which is considered reasonable.

Establishment of regression model for thinning rate ε^5_{max} at the top of the sphere (measured position 6) considers blank holder force, forming liquid pressure, relative thickness and its square term, interaction of blank holder force, forming liquid pressure, relative thickness as significant factors as given in Equation (6).

Table 6. Regression coefficients for thinning rate [25].

Coefficient	**Estimate**
Constant	-106.139
A: Blank holder force	0.0824873
B: Forming liquid pressure	0.0861111
C: Relative thickness	160.022
AA	0.00258351
AC	-0.322712
CC	-56.769

$$\varepsilon_{max\ (5)} = -106.139 + 0.0824873*F_b + 0.0861111*P_c + 160.022*t_r + 0.00258351*F_b^2 - 0.322712*F_b*t_r - 56.769*t_r^2 \quad (6)$$

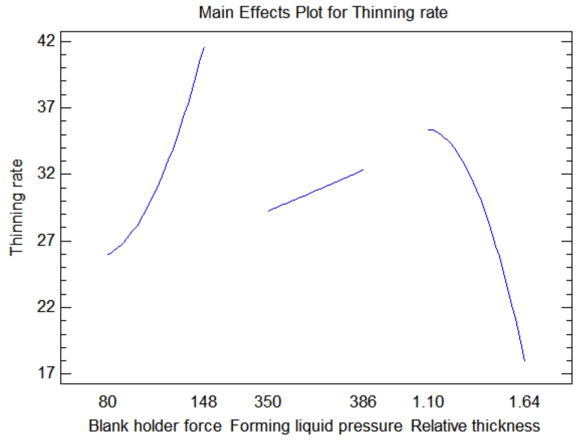


Figure 11. The graph shows the effect of input parameters on thinning rate [25].

Figure 11 shows that blank holder force and relative thickness significantly affect the material thinning rate. The blank holder force is increased from 80 kN to 148 kN causes a sharp increase in thinning rate along a quadratic line. In contrast, an increase in relative thickness from 1.10 % to 1.64 % causes a sharp decrease in thinning rate along a quadratic line. Meanwhile, an increase in forming fluid pressure from 350 bar to 386 bar causes a linear increase with a small slope coefficient of 0.0861111. A proper DSBH process can obtain precise shape and dimension as well as enhance the mechanical properties of the part as designed. The relationship between thinning rate values at the top of the spherical parts and the blank holder force, the forming liquid pressure, and the relative thickness of the blank was determined by mathematical modeling. The influence of each process parameter on the thinning rate is evaluated by Equation (6). Use Statgraphics software to build graphs (Figures 12-14) to show the relationship between these parameters. The chart has shown the maximum and minimum values of the thinning rate at the top of the spherical part. Equation (6) is used to determine thinning rates that are less than the recognized rate of 40%. The thinning rate in the DSBH technique to ensure the strength and rigidity of the structure is within the recommended range of 20% to 40% shown in Figures (12-14).

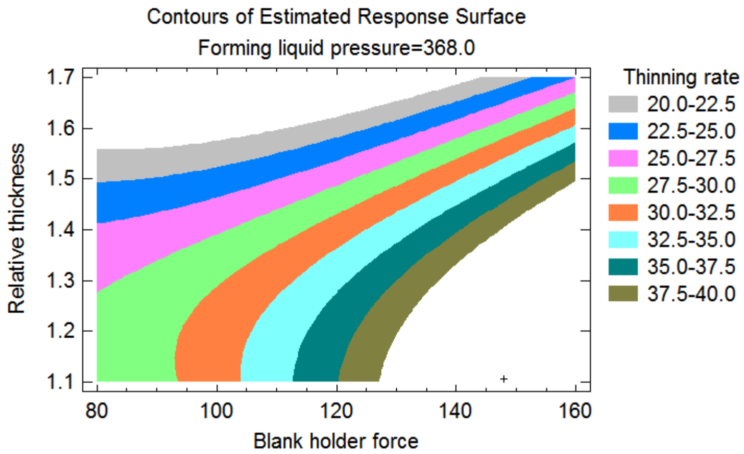


Fig. 12. Dependence of □max (5) on Fb and tr when fixed Pc.

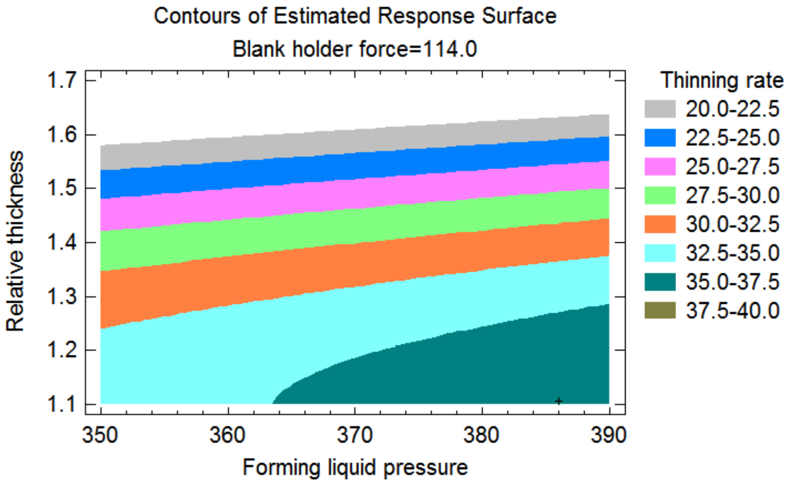


Figure 13. Dependence of □max (5) on Pc and tr when fixed Fb.

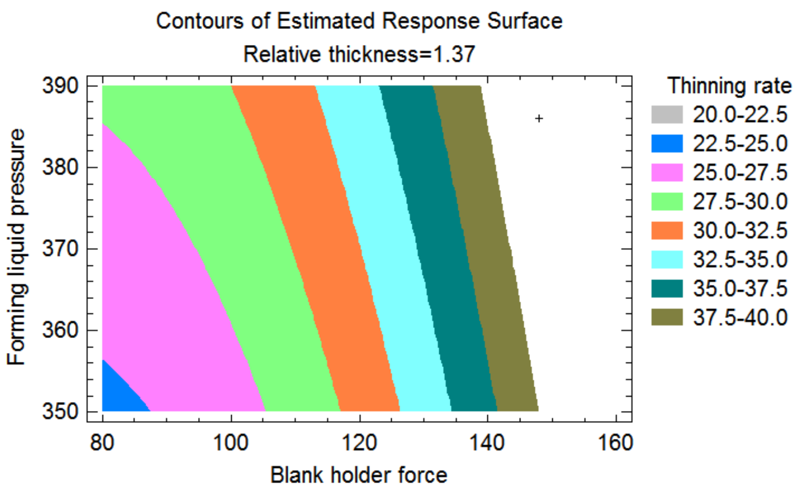
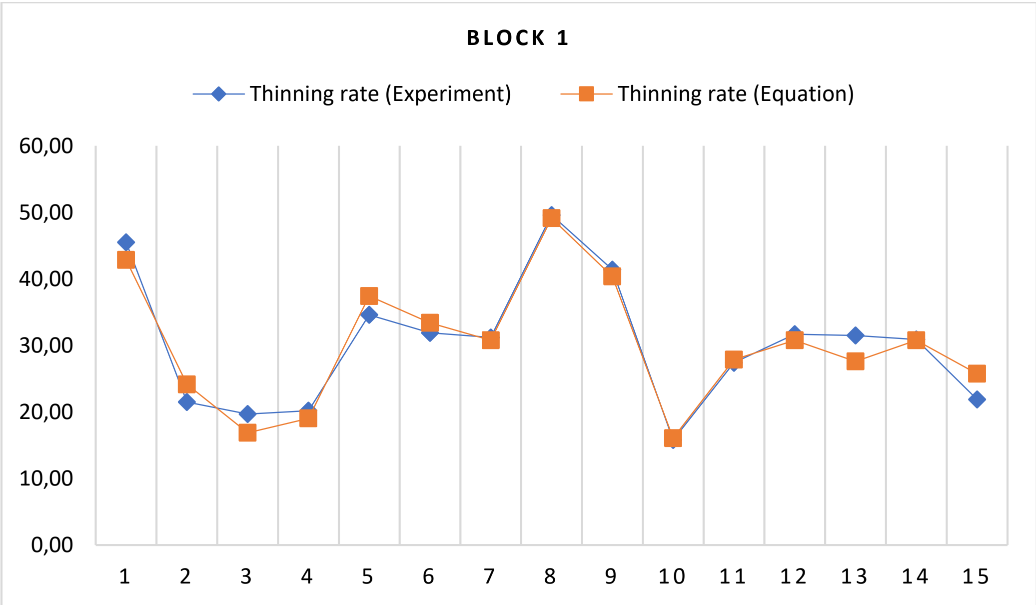
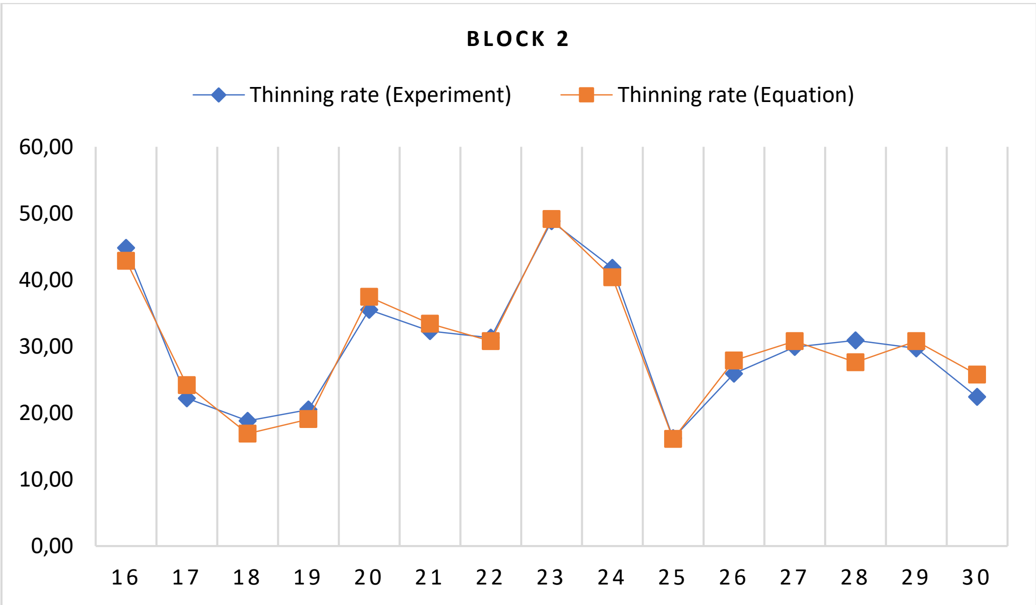


Figure 14. Dependence of □max (5) on Fb and Pc when fixed tr.

4.4 Evaluation of the mathematical model of the thinning rate at the top of the spherical part



a)



b)

Fig. 15. Comparison of modeled and experimental results, including (a) block 1 and (b) block 2.

To evaluate the mathematical model of thin scaling at the top of the sphere, this study compares the results between the built mathematical model and the experiment of the two blocks, as shown in Figure 15. The average error of blocks 1 and 2 is very low at 0.66% and -0.15%, respectively. The error indicates the effect of other unincluded parameters during the investigation, including weld quality uniformity, friction uniformity, and sheet thickness uniformity. The research results have verified the reliability of the mathematical model of the material thinning rate at the top of the spherical part according to the Box-Behnken design and response surface method.

5 CONCLUSIONS

Successful manufacturing of parts using DBSH is mainly dependent on controlling critical process parameters such as blank holder force, changes in hydraulic pressure over time, and relative thicknesses to the material thinning rate of the part. This paper discusses the combined application of Box–Behnken design and RSM to optimize the three input parameters to obtain the shape and thinning rate as the design of the spherical part. The ANOVA method was used to analyze the experimental results with the support of Statgraphics Centurion software. From experimental results and mathematical models, it has been confirmed that the proposed approach is reasonable. The mathematical model of thinning rate at the top of the spherical part has been developed, which is essential in designing a more efficient DSBH process. The mathematical model is built with low average error, so it proves that the model's reliability is high, allowing calculation and control of the parameters and the stability of the forming process. The research results only consider the impact of three input parameters in the double sheet blank hydro-forming process. Many influencing parameters still need to be studied, such as friction, the geometry of the blank corresponding to forming different shapes, rate of increase of fluid pressure, blank holder force by is to master the shaping results with DSBH technology fully.

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