THE RELATIONSHIP BETWEEN THE MAXIMUM WALL THICKNESS THINNING AND THE RELATIVE HEIGHT OF THE PRODUCT DURING THE FREE DEFORMATION STAGE IN SHEET HYDROSTATIC FORMING OF STAINLESS STEEL SUS304

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Abstract

This article presents the establishment of the relationship between the maximum wall thinning and the relative height of the product during the free deformation stage in sheet hydrostatic forming of stainless steel SUS304. The numerical simulation and experiment are carried out using different input parameters for comparison and evaluation. The finite element method model with Dynaform was used to simulate the deformation process. The process and die parameters selected for the study include forming pressure (P_{th}), die radius (R_d), and blank holder pressure (F_h), while the responses are the maximum wall thinning $\Delta S_{\max}$ (%) and the relative height of the product H_p (%). The relationship between $\Delta S_{\max}$ and H_p also was built by changing the input parameters. This result allows us to determine the relative height of the deformed part with the corresponding maximum wall thinning. The research results provide useful technological recommendations for hydrostatic forming in the free deformation stage.

Keywords: *Hydrostatic forming; SUS304; wall thinning; free deformation stage.*

1. Introduction

Hydrostatic forming is a forming technology that uses a high pressure liquid source that functions as a punch to shape, acting directly on the surface of the sheet or tube to deform the workpiece according to the contour of the die to create detailed shapes. Using the hydrostatic forming process can create parts with complex shapes that are difficult to do with traditional forming technology [1-3]. This advantage makes this technology widely applied to product forming in many important industries such as the aerospace and automotive industries.

Research on hydrostatic forming technology has been developed strongly in recent years. In this technology, several researches focus on the following main

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contents: (1) technology and basic parameters of the hydrostatic forming process, (2) methods of hydrostatic forming, (3) equipment and die development, (4) materials used for hydrostatic forming… [4, 5]. A. Kandil [6] performed an experimental process in which the parameters of hydrostatic stamping included the initial pressure, sheet thickness, sheet material properties, punch geometry, punch load, and drawing ratio on the drawing performance. In this work, the results show that a reasonable set of process parameters allows for obtaining higher limiting drawing ratios than that of the traditional stamping processes. M. T. Nguyen *et al.* [7] conducted a study on the influence of technological parameters of the hydrostatic forming process for the parts of space shape on the thinning of the wall thickness of the part. The results of the study have implications for the fabrication of pressure bearing parts. Deform 2D software is used to simulate the shaping process. Based on the research results, it is possible to determine process parameters such as forming pressure, die radius, and coefficient of friction reasonably to obtain products that meet technical requirements and working conditions. E. Ceretti *et al.* [8] used the finite element method to study the influence of the geometrical features of the pressure chamber on the distance from the punch along with the back pressure and the workpiece holding force on the thinning and wrinkling of the product. The results show the dependence of product quality on the workpiece blocking force and the anisotropy of the studied materials.

Many studies on hydrostatic forming technology have focused on solving problems of technological process and product quality [9-12]. Technological solutions have been introduced to increase the feasibility of the forming process and improve product quality. The reliability of the studies is also confirmed through comparison and verification between theory, numerical simulation and modeling experiment. The relationship between the maximum wall thickness thinning and the relative height of the product is a fairly basic research problem. However, this issue has not been really focused on in the publications. Providing this correlation will make an important contribution to the design of technology as well as control during the forming process of sheet parts.

In this article, the process of hydrostatic forming of the hemisphere part from the original flat sheet SUS304 during the free deformation stage is studied. The numerical simulation and experiment are carried out using different input parameters for comparison and evaluation. The finite element method (FEM) model with Dynaform was used to simulate the deformation process. The process and die parameters selected for the study include forming pressure (P_{th}), die radius (R_d), and blank holder pressure (F_h), while the responses are the maximum wall thickness thinning $\Delta S_{\max}$ (%) and the relative height of the product H_p (%). The relationship between ΔS_{max} and H_p also was built by changing the process parameters. This result allows us to determine the relative height of the deformed part with the corresponding maximum wall thickness thinning. The research results provide useful technological recommendations for hydrostatic forming in the free deformation stage.

2. Materials and methods

The process of hydrostatic forming of sheet workpiece is carried out according to the following steps. Firstly, the sheet workpiece is placed on the die and it is clamped between the blank holder and the die by the holder pressure (Fig. 1a). Secondly, the pressurized liquid is injected into the die cavity using a liquid feed device and a pipe. The liquid pressure gradually increases, acting on the surface of the workpiece to deform and inflate freely until it contacts the bottom of the die (Fig. 1b). The liquid continues to increase in pressure, forcing the deformed workpiece to fill the corner positions in the die cavity. Finally, this process ends when the workpiece fills in the cavity and forms the forming product (Fig. 1c).

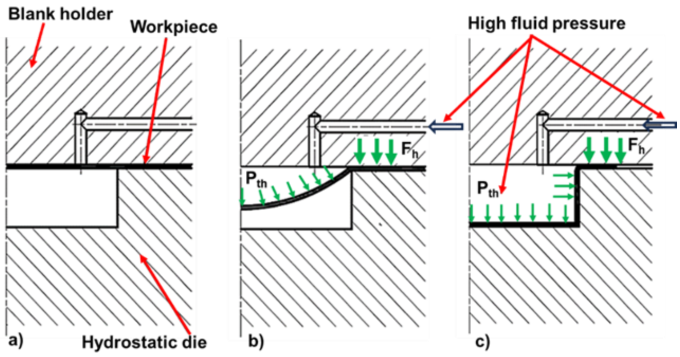

Fig. 1. The process of hydrostatic forming of sheet workpiece.

Numerical simulation is a very effective support tool to study deformation characteristics in the forming process, greatly reducing the cost and time of the experimental process. Simulation results are an important basis for determining the parameters of the experiment. This article uses ETA/Dynaform numerical simulation software to simulate the deformation process of the material during hydrostatic forming in the free deformation stage (Fig. 1b).

Table 1. Chemical composition and mechanical properties of the AA7075 alloy

Chemical composition (in weight percent, %wt)							**Mechanical properties**		
C	Si	Mn	P	S	Ni	Cr	Tensile strength, MPa	Yield stress, MPa	Hardness, HV
0.05	0.65	1.16	0.03	0.025	8.18	18.45	520	205	205

The article simulates the hydrostatic forming process in the free deformation stage. The original workpieces are SUS304 stainless steel according to JIG G4303-91, with a diameter of 110 mm and a thickness of 1 mm. Chemical composition and mechanical properties are shown in Tab. 1. The geometry model including the workpiece, die, and blank holder is shown in Fig. 2a. The geometry model is set up as a surface and saved as a file (.IGS). The geometric model is meshed with elements to suit the calculation process using the FEM. The element type and element mesh shape are planar and quadrilateral, respectively.

This is a forming process with a high pressure liquid punch, so pulling the workpiece in from the die surface is very important to reduce the thinning of the wall and create favorable conditions for the workpiece to press close to the die cavity. According to researched documents, it is shown that the friction between the workpiece and the die surface, the workpiece, and the blank holder plays an important role in the hydrostatic forming process [13, 14]. The coefficient of friction is usually in the range μ = 0.08 - 0.25 [8], so the coefficient of friction between the workpiece and the die surface as well as between the workpiece and the blank holder is selected as 0.125. The die is stationary during forming. The workpiece is pulled into the cavity of the die under the action of forming pressure. The process ends when the workpiece fills the inside of the die.

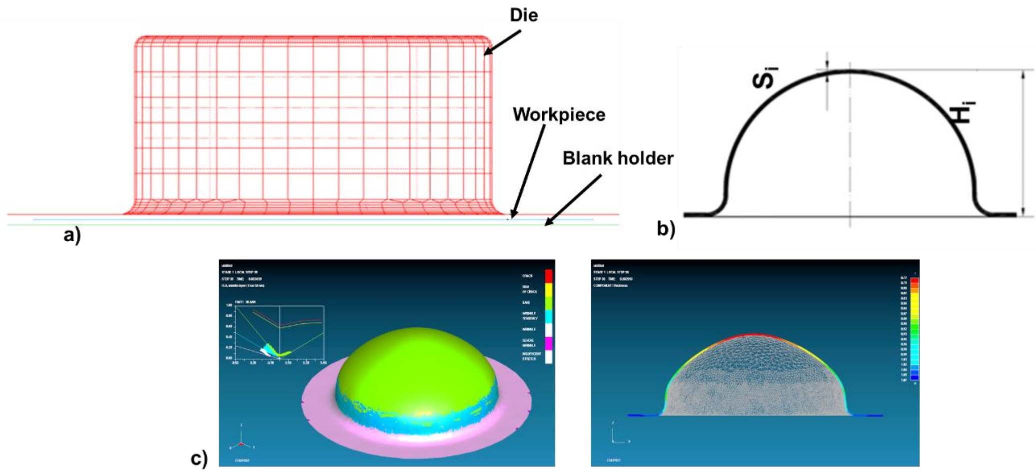

Fig. 2. The geometric model of die and meshed workpiece (a), diagram for determining S_i and H_i values (b), and wall thickness distribution of the semi product (c).

Process parameters were set up including forming pressure (P_{th}) and blank holder pressure (F_h) and die radius (R_d) [6-10]. The values of the process parameters are summarized in Tab. 2. The combination of values of the 3 selected process and die parameters has 27 cases. For example, case one has P_{th} of 20 MPa, F_h of 3 MPa, and

R_d = 3 mm which is denoted as 1 - R3P20F3. According to published studies, in the sheet forming process under the effect of hydraulics or compressed air, the top position of the semi product is most thinned in the free deformation stage [7, 11]. Conducting simulations in each case on ETA/Dynaform software, we can observe the distribution of the wall thickness of the semi-product and the height of the top of the hemisphere during the deformation process (Fig. 2c). The wall thickness values are measured by a JENA universal microscope. The simulated results are exploited as the maximum wall thickness thinning and the relative height of the semi product in the free deformation stage corresponding to different sets of process parameters. On that basis, the relationship between these quantities can be built, thereby evaluating the deformation ability of the workpiece and making recommendations related to the quality of the forming product [15-17].

Table 2. Levels and their values of the process parameters

Symbol	Process parameters	Low level	Middle level	High level
P_{th}	Forming pressure (MPa)	20	25	30
F_h	Blank holder pressure (MPa)	3	6	9
R_d	Die radius (mm)	3	5	7

The maximum wall thickness thinning and the relative height are calculated by using (1) and (2), respectively (Fig. 2c).

$$\Delta S_{\max} = \frac{S_o - S_i}{S_o} \cdot 100\% \tag{1}$$

$$H_p = \frac{H_i}{d} \cdot 100\% \tag{2}$$

where S_o is initial workpiece thickness (mm), S_i is the thickness of the top of the hemisphere at the time i (mm), H_i is the height of the semi product reached at the time i (mm) (Fig. 2c), and d is the inner diameter of the die (mm).

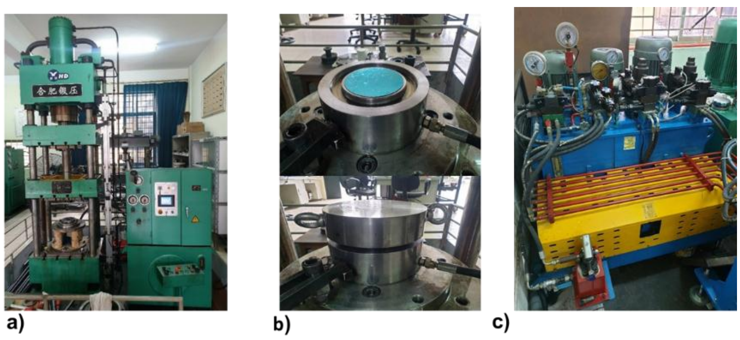

Fig. 3. The double action hydraulic press YH-28 (a), forming dies (b), and high pressure fluid generator (c).

The experimental process was carried out on hydraulic press YH-28 with a maximum nominal force of 100 tons, the displacement speed of the main slide from 15 - 70 mm/s. This hydraulic press is a double action hydraulic press. The hydraulic cylinders are controlled by PLC. The digital display allows adjustment and setting of values such as stroke and boundary pressure (Fig. 3a). The hydrostatic forming die is made from SKD 11 material according to standard JIS G 4404. Finishing the working dimensions to an accuracy of grade 7, the surface roughness at the working faces of level 7 is equivalent to Ra 1.25 µm. The working planes are parallel to each other and perpendicular to the center of the part (Fig. 3b). The forming pressure is generated using high pressure liquid generating equipment which must produce a liquid pressure sufficiently large to carry out the forming process (Fig. 3c).

3. Results and discussions

3.1. Effect of process and die parameters on the maximum wall thickness thinning

Simulation with the case radius of the die is 3 mm (R_d = 3 mm). Meanwhile, the forming pressure is 20 MPa, 25 MPa, and 30 MPa and the blank holder pressure is 3 MPa, 6 MPa, and 9 MPa. The graph of the relationship between the maximum wall thickness thinning over time is shown in Fig. 4a.

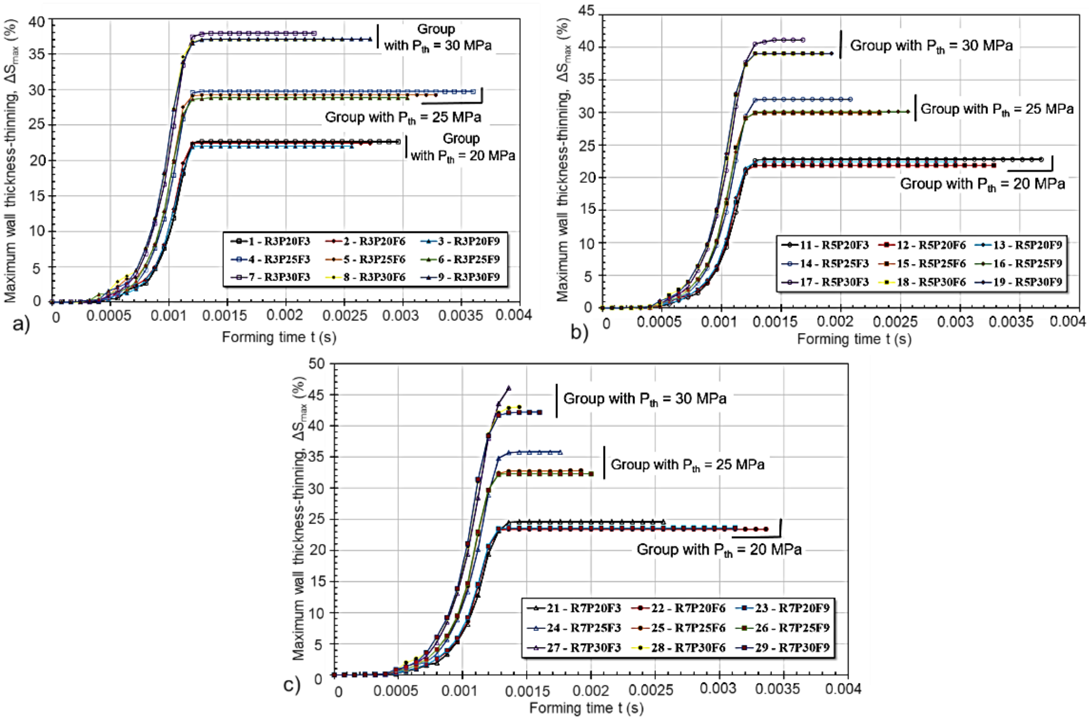

Fig. 4. Change of ΔS_{max} (%) over time with R_d = 3 mm (a), R_d = 5 mm (b), and R_d = 7 mm (c).

According to Fig. 4a, it can be seen that the graphs have changed in 3 different stages: In the first stage (range from 0 - 0.0005 seconds), the slopes of the graph lines and the time axis are very small, equivalent to a small increase in the maximum wall thickness thinning. Moreover, at this stage, the graph lines are almost coincident, showing that in this time period, the effect of process parameters is not much. In the second stage (range from 0.0005 - 0.0012 seconds), the slope between the graph lines and the time axis is very large, proving that in this period, the maximum wall thickness thinning increases very quickly. At the same time, during this period, the graph lines began to separate clearly and divided into 3 groups according to 3 different forming pressure levels, showing that the effect of the process parameters started to be larger, especially in the forming pressure. During the third stage (approximately 0.0012 seconds and later), the graphs parallel to the time axis show that the maximum wall thickness thinning remains the same value and does not change anymore. And the graphs were divided into 3 distinct groups, with the larger the forming liquid pressure, the greater the degree of thinning at the top of the hemisphere reached the correspondingly larger value.

Similarly, building the relationship graphs of the maximum wall thickness thinning over time when the radius of the die is R_d = 5 mm and R_d = 7 mm shown in Fig. 4b and Fig. 4c also realizes the same rule. Thus, in the free deformation stage, the larger the value of the forming pressure, the larger the value of the maximum wall thickness thinning at the top of the hemisphere is achieved.

Continuing to observe the 3 graphs in Fig. 4, it was found that in the same group with the same forming pressure P_{th} = 20 MPa, the value that the maximum wall thickness thinning received tends to be different change and the change was not significant. When the radius of the die is 3 mm, 5 mm, and 7 mm, the maximum wall thickness thinning obtained is about 22.6%, 22.8%, and 24.6%, respectively. But the forming pressure is 25 MPa, this trend is more obvious. When the radius of the die is 3 mm, 5 mm, and 7 mm, the maximum wall thickness thinning obtained is about 29.7%, 32%, and 35.8%, respectively. The forming pressure is 30 MPa, and the maximum wall thickness thinning was different. When the radius of the die is 3 mm, 5 mm, and 7 mm, the maximum wall thickness thinning obtained is about 37.9%, 32%, and 35.8%, respectively.

3.2. Effect of process and die parameters on the relative height of the product

The graph of the relationship between the relative height of the product over time with R_d = 3 mm is shown in Fig. 5a. From Fig. 5a, it can be seen that the graph lines are changing in 3 different stages: In the first stage (range from 0 - 0.0004 seconds), the slopes of the graph lines and the time axis are very small, which equates to a small increase in height during this stage. Moreover, the graph lines are almost coincident, showing that during this stage the effect of process and die parameters on the relative height of the product is not much. In the second stage (range from 0.0004 - 0.0012 seconds), the slope between the graph lines and the time axis is very large, proving that the relative height increases very quickly during this stage. At the same time, the graph lines began to separate clearly and divided into 3 groups according to 3 different forming pressure levels. This result confirms the larger effect of the parameters, especially the forming pressure. In the third stage (approximately 0.0012 seconds or later), the slopes of the graph lines and the time axis are much smaller than that of the second stage, indicating a slow increase in relative height. And the graph lines have separated into 3 distinct groups. As the forming pressure increases, the relative height increases.

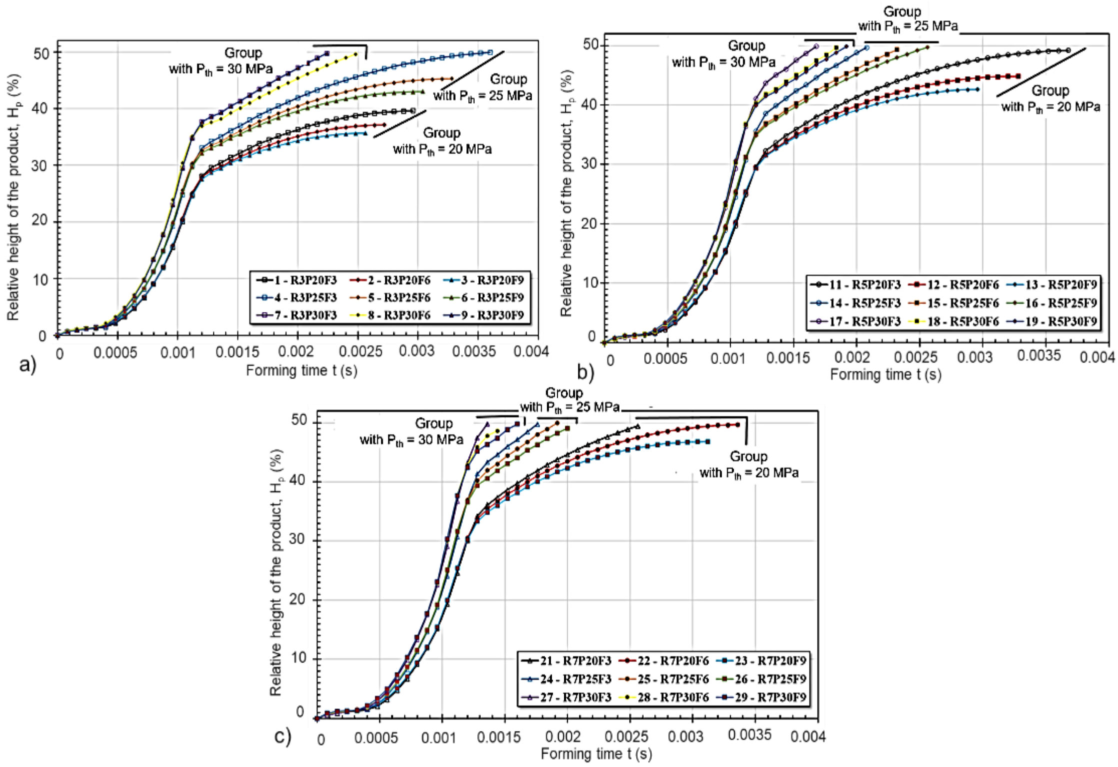

Fig. 5. Change of H_p (%) over time with R_d = 3 mm (a), R_d = 5 mm (b), R_d = 7 mm (c).

Similarly, constructing the graphs of the relationship between the relative height of of the product over time when the radius of the die is R_d = 5 mm and R_d = 7 mm shown in Fig. 5b and Fig. 5c also realizes a similar law. During the free deformation stage, as the forming pressure increases, the relative height of the product increases.

3.3. The relationship between the maximum wall thickness thinning and the relative height of the product

From the simulation results, the article builds the relationship graphs between the maximum wall thickness thinning and the relative height of the product with different process and die parameters. The graph of this relationship with R_d = 3 mm is shown in Fig. 6a. Based on Fig. 6a, in an early stage of deformation, the relative height of the product increases, and the maximum wall thickness thinning increases rapidly. Then, as the relative height continued to increase, the maximum wall thickness thinning at the top of the hemisphere remained at a constant value.

Based on the simulation results in Fig. 6a, useful process recommendations can be made. For example, with a forming pressure of P_{th} = 20 MPa, the part that achieves a relative height of about H_P = 28.7% must accept the maximum wall thickness thinning of about $\Delta S_{\max}$ = 22 - 22.6%. With a forming pressure of P_{th} = 25 MPa, the part that achieves a relative height of about H_P = 33% must accept the maximum wall thickness thinning of about $\Delta S_{\max}$ = 28.7 - 29.7%. With a forming pressure of P_{th} = 30 MPa, the part that achieves a relative height of about H_P = 38.9% must accept the maximum wall thickness thinning of about $\Delta S_{\max}$ = 37.1 - 37.9%.

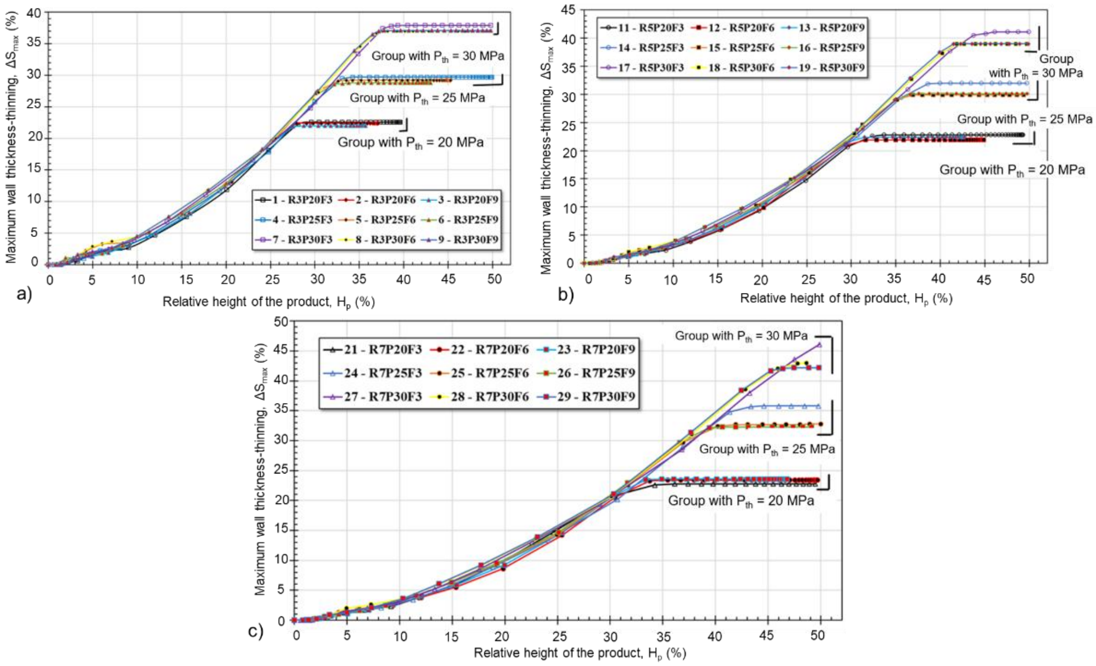

Fig. 6. The relationship between ΔS_{max} and H_P with R_d = 3 mm (a), R_d = 5 mm (b), and R_d = 7 mm (c).

Similarly, we can also build a graph of the relationship between the maximum wall thickness thinning and the relative height of the product with R_d = 5 mm and R_d = 7 mm.

These graphs are shown in Fig. 6b and Fig. 6c. Based on the simulation results in Fig. 6b, process recommendations can also be obtained. For example, with a forming pressure of P_{th} = 20 MPa, the part that achieves a relative height of about H_P = 32.6% must accept the maximum wall thickness thinning of about ΔS_{max} = 21.9 - 22.8%. With a forming pressure of P_{th} = 25 MPa, the part that achieves a relative height of about H_P = 38.6% must accept the maximum wall thickness thinning of about ΔS_{max} = 30.1 - 32%. With a forming pressure of P_{th} = 30 MPa, the part that achieves a relative height of about H_P = 43% must accept the maximum wall thickness thinning of about ΔS_{max} = 39 - 41.1%. As in other cases, when the die radius is 7 mm (Fig. 6c), the relationship between the maximum wall thickness thinning and the relative height of the product is also the basis for selecting and completing the process and die parameters. For example, with a forming pressure of P_{th} = 20 MPa, the part that achieves a relative height of about H_P = 36% must accept the maximum wall thickness thinning of about ΔS_{max} = 22.8 - 23.6%. With a forming pressure of P_{th} = 25 MPa, the part that achieves a relative height of about H_P = 43% must accept the maximum wall thickness thinning of about ΔS_{max} = 32.3 - 35.8%. With a forming pressure of P_{th} = 30 MPa, the part that achieves a relative height of about H_P = 48% must accept the maximum wall thickness thinning of about ΔS_{max} = 42.2 - 46.1%.

3.4. Verification experiment

The experimental process is carried out with process and die parameters including forming pressure of 25 MPa and blank holder pressure of 6 MPa and die radius of 5 mm.

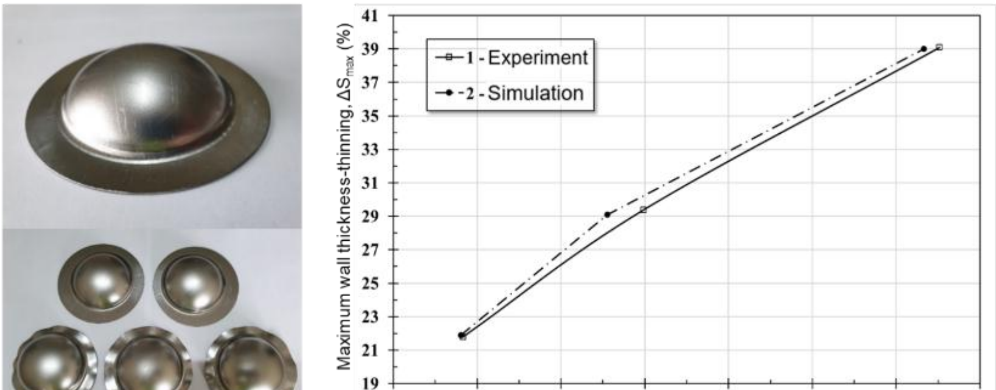

Fig. 7. Products after hydrostatic forming (a) and diagram of the relationship between ΔS_{max} and H_p in simulation and experiment (b).

The experimental product is shown in Fig. 7a. The obtained product has a hemispherical shape similar to the simulation results. The products have uniform shapes, no tearing, and glossy surfaces. Some products have wrinkles at the flash. $\Delta S_{\max}$ and H_p are defined and a relationship is established between them. Experimental and simulation results are displayed and compared in Fig. 7b.

From the graph of Fig. 7b, it can be seen that when the relative height increases, the degree of the maximum wall thickness thinning also increases. $\Delta S_{\max}$ and H_p in the experiment have a value of 35.97% and 29.40%, respectively. $\Delta S_{\max}$ and H_p in simulation have a value of 35.10%, and 29.10%, respectively. Thus, comparing the simulation and experimental results shows that the law of changing the maximum wall thickness thinning and the relative height of the product obtained from the experimental results is similar to the simulation results.

4. Conclusion

In this work, numerical simulation and experimental process were carried out for the free deformation stage in the hydrostatic forming process from SUS304 stainless steel. The law of the effect of parameters on responses is analyzed based on the histograms of the maximum wall thickness thinning and relative height of the product over simulation time.

The relationship diagrams between the maximum wall thickness thinning and the relative height of the product are established from the simulation results. Analysis of the dependence of the maximum wall thickness thinning on the relative height of the product was performed. From there, it is possible to determine the maximum wall thickness thinning in hydrostatic forming of sheet corresponding to each defined relative height.

The experimental process is performed for a specific set of parameters including a forming pressure of 25 MPa and blank holder pressure of 6 MPa and a die radius of 5 mm. Experimental results are compared and evaluated with simulation results. The similarity between simulation and experiment shows the reliability of the research results.

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MỐI QUAN HỆ GIỮA BIẾN MỎNG CHIỀU DÀY THÀNH LỚN NHẤT VÀ CHIỀU CAO TƯƠNG ĐỐI CỦA SẢN PHẨM TRONG GIAI ĐOẠN BIẾN DẠNG TỰ DO KHI TẠO HÌNH THUỶ TĨNH TẤM THÉP KHÔNG GỈ SUS304

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Tóm tắt: Bài báo trình bày sự thiết lập mối quan hệ giữa lượng biến mỏng thành lớn nhất và chiều cao tương đối của sản phẩm trong giai đoạn biến dạng tự do khi dập thuỷ tĩnh tấm thép không gỉ SUS304. Quá trình mô phỏng số và thực nghiệm được thực hiện với các thông số đầu vào khác nhau để so sánh và đánh giá. Mô hình FEM của phần mềm Dynaform được sử dụng để mô phỏng quá trình biến dạng. Các thông số quá trình và khuôn được lựa chọn cho nghiên cứu bao gồm áp suất tạo hình (P_{th}), bán kính cối (R_d) và áp lực ép biên (F_h), trong khi các đáp ứng là lượng biến mỏng thành lớn nhất ΔS_{max} (%) và chiều cao tương đối của sản phẩm H_p (%). Mối quan hệ giữa ΔS_{max} và H_p cũng được xây dựng bằng cách thay đổi các thông số đầu vào. Kết quả này cho phép xác định chiều cao tương đối của sản phẩm sau biến dạng với lượng biến mỏng thành lớn nhất tương ứng. Kết quả nghiên cứu đưa ra những khuyến nghị công nghệ hữu ích cho quá trình tạo hình thủy tĩnh ở giai đoạn biến dạng tự do.

Từ khóa: *Tạo hình thủy tĩnh; SUS304; biến mỏng thành; giai đoạn biến dạng tự do.*

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