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Determination of Limit Drawing Ratio of SS 304 Steel using Sheet Hydroforming Process with Female Die

Murat Dilmeç*, & Vehbi Bülüç
Department of Mechanical Engineering, Faculty of Engineering, Necmettin Erbakan University, Konya, 42100, Turkey

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Sheet hydroforming with female die process (SHF-D) is easily applicable without controlling of pressure and blank holder force paths compared to the hydroforming with punch process. Shallow parts can be produced easily with using SHF-D process which is used a lower cost production method in a wide variety of sectors. Limiting drawing ratio (LDR) is indication of formability of sheet metals is determined by using cylindrical punch die. In this study, for the first time, the LDRs of the SS 304 material with different thicknesses was determined experimentally by using the SHF-D instead of sheet hydroforming with punch unlike in the literature. FEA of SHF-D process has been performed. The results showed that relatively shallow sheet metal parts can be easily produced without there is no need to be optimizethe pressure and blank holder force paths by means of SHF-D using obtained LDR. It is important to know the forming limit in the SHF-D, since it can be a more economical production method, especially in the manufacture of shallow and large parts used in the automotive and aerospace industries and obtain more quality products than that from classical deep drawing process. By knowing these ratios, die design and parts manufacturing can be realized less costly. The LDR was experimentally obtained as 1.82 with using the SHF-Dfor the SS 304. The FEA results are in good agreement with experimental results. So, it is useful to analyze the FEA before designing the dies that will be used with the SHF-D.

Keywords: Hydromechanical deep drawing, Limiting drawing ratio, Sheet hydro forming with female die, SS 304 stainless steel

1 Introduction

In order to compete internationally, automobile manufacturers must closely follow new technologies that reduce costs and improve quality. One of the most important of these new technologies is the hydro-forming method, which is not yet widely used. The hydroforming method was developed in late 1940 as an alternative solution to forming and deep drawing of sheets between two dies, in response to the need to produce a small number of deep drawn parts at low cost. The interest of sheet metal product manufacturers to this technology only started to increase after 1990. The high costs of the presses used in the hydro-forming process, the lack of the technology used and the effective use of the system require scientific infrastructure are among the main reasons why this technology is not widely used. This method will become one of the inevitable production methods of industries such as automotive, aviation and food in the next ten years[1].

The hydroforming method is used to form sheet or tubular parts by means of liquid pressure and offers many advantages over conventional die and welded jointing. In the literature, the hydroforming method, also known as fluid forming, flexible die forming, rubber membrane forming, is defined as the forming of sheet metal or tubular metal material in a closed container by means of a fluid medium (water, viscose, polymeric material, etc.) that functions as a male or female die. Due to the incompressible properties of the fluid, the parts are shaped by the pressure effect that occurs during forming[1-3].

Hydro-forming method has many advantages compared to traditional methods such as more obtaining uniform thichness distribution parts can be produced, reaching a greater limiting drawing ratio (LDR), needing a single die, die manufacturing with lower quality materials is possible, and thus the die costs significantly reduced, the effect of the liquid on all sides. Due to the fact that it is possible to produce complex and difficult-to-shape parts in a cost-effective and less step, the parts produced can have better dimensional and geometric accuracy and lower surface roughness, there is no die alignment problem because it is a single die, and it has many advantages such as the fact that it is less, that sheets of different thickness can be formed with a single die[4-10].

In the automotive industry, The need for this technology is increasing day by day due to demands

*Corresponding author (E-mail:muratdilmec@erbakan.edu.tr)

such as weight and fuel saving, high strength, reduction of total number of parts, forming of alloys with low replacement ability[5,11,12]. Because of the efforts to reduce the weight of the automobile and consequently fuel consumption, the automotive industry is in an effort to move towards lightweight constructions rather than entirely heavy constructions. This method has become widely used in automobile parts since thinner sheet can be produced with this method. Because of the efforts to reduce the weight of the automobile and consequently fuel consumption, the automotive industry is in an effort to move towards lightweight constructions rather than entirely heavy constructions. This method has become widely used in automobile parts since thinner sheet can be produced with this method[7,13,14].

In the hydromechanical deep drawing process, various methods have been developed to increase the LDR. Zhang & Danckert[14] summarized these methods in their studies. Shirizly *et al.*[15] and Tirosh *et al.*[16] in their study, due to the decrease in friction force between the sheet and dies thanks to the liquid pressure increased the LDR.

Pennington[17] proposed a new method for hydro-forming. In this proposed method, the female die is completely removed and replaced by liquid pressure, thereby increasing the LDR due to the reduction of friction between the sheet and the female die. Hydrodynamical deep drawing is the method by which the fluid is allowed to flow out of the female die and sheet at high speed due to the rapid change of liquid pressure with the progression of the stamp, and it is stated that there is no need to control the liquid pressure in this method. Hsu & Hsieh[18] have successfully performed this process and increased the LDR.

Yang *et al.*[19] proposed the hydromechanical deep drawing process using radial fluid pressure. In this proposed process, the researchers increased the LDR of SS 304 material to as high as 3.3. This process was carried out by modification of the die used in the hydromechanical deep drawing process. At a high pressure, the liquid is allowed to escape from a die cavity opened between the blank holder and the female die. At the same time, the sheet material is pushed inward in the radial direction.

Lang *et al.*[13] have taken measures against wrinkling and tearing damage during the hydromechanical deep drawing process supported by radial fluid pressure. The researchers determined optimum values for the gap and process parameters between the blank holder and the female die. At the end of the study, they increased the limit deep drawing ratio of AA 6016-T4 material which has approximately 1.8 limiting drawing ratio to 2.46 in classical deep drawing.

Zhang *et al.*[12] and Palumbo *et al.*[20] proposed new methods in the hydro-forming process. In these methods, they used a die which moved from the middle of the female die to the high pressure liquid, supporting the deformed regions of the sheet metal during forming. They concluded that the thinning percentages of the sheet metal part were lower in this method and therefore higher LDRs could be obtained.

Gather *et al.*[21] conducted basic research on the effect of hydro mechanical deep drawing process parameters and their interactions with each other. The researchers determined the process parameters to optimize the thinning and geometric accuracy of the sheet. In addition to the process parameters, they have also taken into account the important geometric parameters that have a significant impact on the forming process, and have shown that taking into account these parameters is extremely important for the efficient use of the process. The researchers stated that in real applications, the effect of the template forming parameters on the strain distribution should be investigated.

Wu *et al.*[22] in their work, finite element analysis with the forming of step geometries with hydromechanical deep drawing process examined the upper and lower limits, that is, the process window. Simulation results for forming geometries with step geometry in the hydro mechanical deep drawing process have shown that it is very useful to determine the beginning of the upper and lower forming boundaries of the sheet wrinkles and tears.

Khandeparkar & Liewald[23] used the hydro mechanical deep drawing method in the production of containers with complex graded geometry. Firstly, they made the finite element analysis of the process. They formed positive and negative surfaces with complex geometry on the base of two types of stampa, cylindrical and conical, and the ability of the complex surfaces to be plastered from the stamp to the surface of the plate was investigated to obtain high deep drawing rates. As a result of the study, it has been proved that the process can be applied in step geometries. In this study, advantages such as reduction of deep drawing steps and better part quality have been successfully demonstrated.

Palumbo *et al.*[20] conducted experimental and numerical analyzes of the production of a protuberance square piece connected to a cylindrical region by a male die hydro-forming process. The researchers state that the hydro-forming process is widely accepted in the industry for the production of complex geometry parts. Specifically, they state that complex shaped parts can be produced in a single step more easily in the sheet hydro-forming process and therefore it is necessary to carry out deeper researches on the production of complex shaped parts by sheet hydro-forming process.

The parameters affecting the process in the hydromechanical deep drawing process depend on tool geometries, lubrication conditions, pressure, blank holder force (BHF), pre-bulging process and material properties[24,25]. In the hydromechanical deep drawing process, due to the significant effect of pressure and BHF on the process, there have been many studies on determining effective process parameters and effect levels. In order to achieve a successful forming process in hydromechanical deep drawing process, optimum values of process parameters were determined[22,25-28]. However, it is understood that in the hydromechanical deep drawing process, it is necessary to take into account the process parameters as well as the important geometric parameters that significantly affect the forming process.

Qin & Balendra[29] stated that in the hydromechanical deep drawing process, the forming of parts with concave geometries requires more detailed conditions than those with convex features. In this study, researchers carried out finite element simulations of hydromechanical deep drawing process of sheet metal parts with concave and convex geometry. They concluded that the fluid pressure and BHF curves to be applied must be adjusted to match the component shapes to be shaped in order to prevent the onset of forming defects and to obtain high quality products.

Palumbo *et al.*[30] focused on the problems associated with the production of complex shapes using the sheet metal hydroforming process. They performed tests for the die cavity with different shapes in the sheet hydro-forming with female dieprocess. For the production of cylindrical, square and compound shaped parts, the simulations of the female die sheet hydro-forming process were performed and they confirmed the results of the analysis with experimental data. They took the minimum thinning of the sheet as a criterion for success in solving the basic problems related to the formation of compound shapes. They have created a simple die design to easily create various configurations. Thus, dies with a wide variety of composite geometries and sizes could be formed. They made useful inferences about the process from the comparison between dies containing square and compound shaped cavities. They concluded that if the die cavity is a square die, the possible fracture zone is formed at the corner radius due to bending-reverse bending, and in the case of the cylindrical die cavity, the cylindrical part has a positive effect because of the smooth pull in all directions.

Önder & Tekkaya[31] focused on the determination of the optimum forming process and process parameters for various geometric shapes such as circular, elliptic, rectangular and square in the sheet hydro-forming with female die process. They compared the numerical results of simulations of hydromechanical deep drawing and conventional deep-drawing processes, as well as the female die-sheet hydroforming process. For each section, the depth, the ratio of characteristic dimensions and the corner radius were systematically changed. Throughout the study, St14 and DC04 steels were used as the sample material for numerical analysis and experimental verification. They used the results such as thickness distributions and radius formation to evaluate the success of the forming process. The analyzes show that, depending on part geometry and dimensional properties, the hydro-forming process may be preferable to produce more suitable products. The researchers argue that this data may be useful for selecting an appropriate manufacturing process for a given part geometry and for determining the boundaries of each sheet forming process.

Shallow parts with complex geometry can be produced using the sheet hydro-forming with female dieprocess. In the process, the use of unsuitable process parameters can lead to excessive thinning or wrinkling of the sheet metal and leakage from the pressurized environment. Thus, the targeted forming limits cannot be reached. These problems can be reduced by optimizing process parameters. As can be seen from these studies, studies on the development of hydromechanical deep drawing process are continuing.

Palumbo *et al.*[30] emphasized the need for experimental research to determine the reproducibility of geometric parameters in the sheet hydro-forming with female die process. In addition, there are no studies on the sheet hydro-forming with female die process and the LDR is determined by this process. It would be more appropriate to produce parts with relatively shallow depth by the sheet hydro-forming with female dieprocess instead of the hydromechanical deep drawing process, which is more laborious and complex to apply. Therefore, in order to determine the forming boundary of sheet materials by the sheet hydro-forming with female dieprocess, it will be beneficial to determine the boundary drawing ratio in the sheet hydro-forming with female dieprocess.

2 Materials and Methods

In this study, the Limiting Drawing Ratio(LDR) for the SS 304 stainless steel sheet using sheet hydroforming with female die was determined experimentally.

2.1 Die design

In order to determine the LDR with the female die, a die with a diameter of 50 mm, whose height can be adjusted by sheet washers with 1 mm thickness, was designed and manufactured. Fig. 1 shows the schematic representation of the dies in which the sheet hydro-forming with female die process is performed.

2.2 Obtaining the yield curves for SS 304 sheet material

The mechanical behavior of SS 304 stainless steel material was determined and yield curves were obtained by making tensile tests to introduce the material to simulation programs. SS 304 plates with a thickness of 1 mm are cut to conform to ASTM E 8M-04 standard. In order to determine the effect of anisotropy, three repetitive tests were performed in the rolling direction, 45° and 90° angles of the rolling direction.

Tensile tests were performed in Shimadzu brand drawing device with a capacity of 100 kN in the laboratory of the University in three successive repetitions and real stress-strain diagrams were obtained. Before the tensile test was applied to the samples, the gauge lengths were marked as approximately 50 mm and measured with an accuracy of ± 0.003 mm by the video extensometer on the tensile device. The samples were attached to the jaws from the grips and pulled at a speed of 25 mm/min. The applied load was measured by the load cell and the elongation in the measurement length was measured with the video extensometer and the values were transferred to the computer. By evaluating the data, engineering and real stress-strain diagrams were drawn. The actual yield curve of the material will be used in the simulations of the hydroforming process.

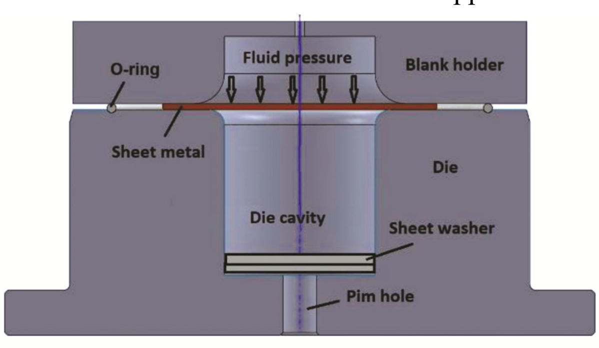

Fig. 1 — The die used on performing sheet hydroforming process with female die.

2.3 Performing experiments to obtain the limit drawing ratio with using female die

Primarily, SS 304 sheet metal plates were cut into circles by means of sheet cutting machine and work pieces of initial diameter were obtained for forming. It is important to cut the sheet circularly without error. In order to reduce friction, both surfaces were first lubricated with paraffin and then polyethylene film was used to fit the diameter of the work piece. LDR is defined as the ratio of inital sheet metal diameter to die diameter which can be successfully drawn into the die. For this reason, in order to determine the diameter to determine the LDR, 80 mm to 110 mm in the range of 2 mm intervals of different initial diameter sheets were cut and test samples were created.

Fluid pressure and BHF are two main process parameters in the sheet hydro-forming process. With the applied pressure, BHF has a direct effect on the forming of the work piece. Particularly, BHF's pressure-compatible movement is important in the successful conclusion of the process. The low BHF has a negative impact on the sealing and causes creases. The high BHF causes the workpiece not to flow completely into the die cavity, resulting in tears (Fig. 2).

In order to detect LDR, samples of initial diameters gradually decreasing were formed and the diameter of the initial sheet sample which can be formed successfully was determined and the LDR was calculated.

The rules applied in the sheet hydro-forming with female die tests are as follows:

- Place the prepared work piece on the blank holder so that it is fully centered.
- The BHF and pressure to be applied are entered into the system.
- The process is started to perform the forming process.

2.4 Modelling sheet hydroforming with female die using finite element analysis

Finite element analysis of the sheet die hydro-forming process with female die was performed. The results of the analysis were compared with the thickness distribution in the obtained test samples. Components of the sheet hydro-forming with female die process, consists of blank holder, sheet material and bottom die. Using the solid model designed in 3D software, a geometric model was created and FEA modelling steps were followed in Dynaform finite element software. Since the sheet material thickness is 1 mm, it was modeled as a shell. SS 304 material was selected as the material (Fig. 3). In the 3D model, the sheet material is positioned in the middle of the blank holder and the lower die. Figure 4 shows the components of the sheet hydro-forming with female die process with surface models.

In the sheet hydro-forming with female die process, firstly, the BHF is applied for the controlled drawing of sheet metal into the die. Then, high pressure liquid is applied on the sheet material. During pressing with the blank holder, the lower die remains stationary and a BHF of 18000 N is applied on the sheet material. The applied BHF was applied sufficiently so that the sheet part did not fracture or wrinkling (Fig. 5).

When a constant force of 18000 N is applied to the blank holder, there is no wrinkling in the flange area and no early damage to the part. After the BHF is applied, high pressure liquid is applied to the surface of the sheet material. According to the results of both experiments and analysis, it was determined that the part was fully formed at 110 MPa and this pressure value was applied as constant in the analyzes (Fig. 6).

In order to define the pressure value, click the tab that says Pressure P = 0 in the Hydro mech section of the process menu and the Hydro mech menu will be opened.

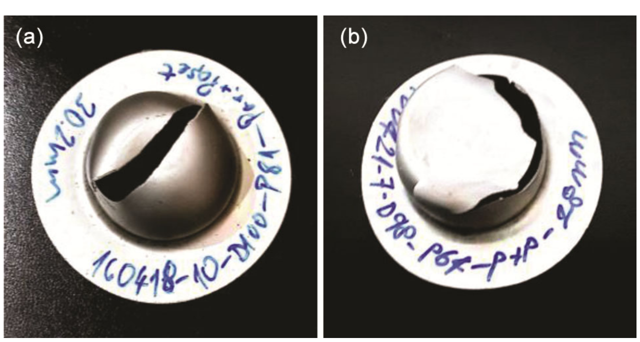

Fig. 2 — Failed parts where rupture occurs before completion of forming, a) Thickness 1 mm, work piece diameter 100 mm, punch diameter 50 mm, drawing height 30, 2 mm, and b) Thickness 1 mm, work piece diameter 98 mm, punch diameter 50 mm, drawing height 28 mm.

2.5 Measuring the thickness distribution of the parts

In order to verify the finite element analysis, the thickness distributions of the successfully formed work pieces were measured by an ultrasonic measuring device. The thicknesses of the samples having three different pressure curves in 1 mm thick material were measured every 2 mm along the curved length starting from the center towards the flange edge. When applying the get to the instrument pen during this measurement, the value of the screen is recorded by touching the pen in a position

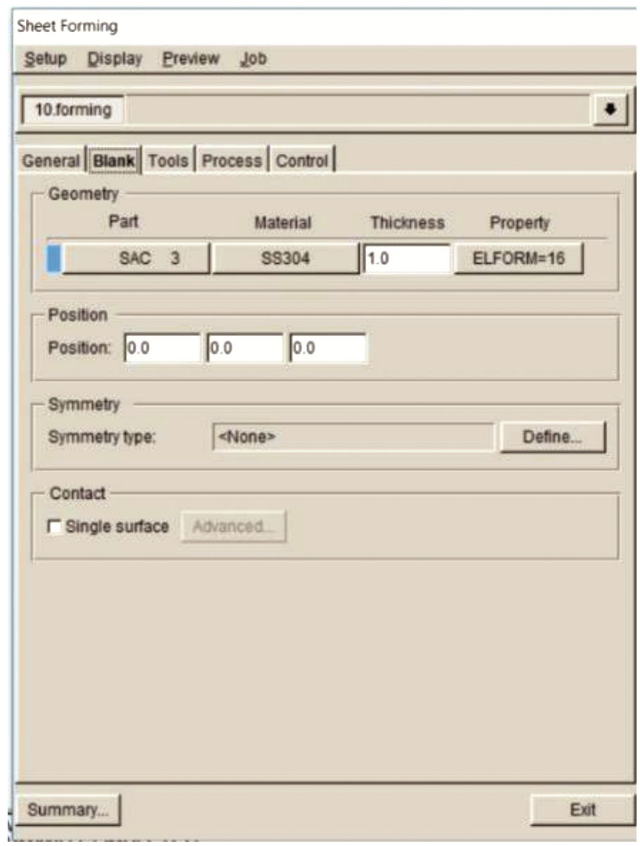

Fig. 3 — Defining the sheet material.

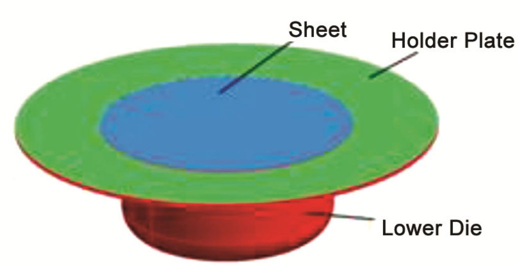

Fig. 4 — Components of sheet hydroforming process with female die.

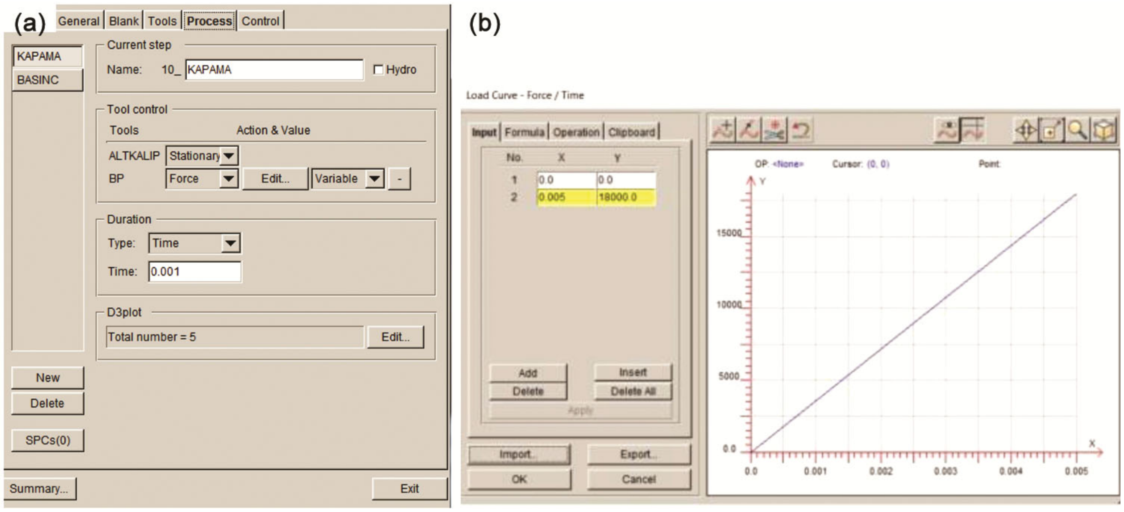

Fig. 5— a) Defining the closing process, and b) Defining the time-BHF curve.

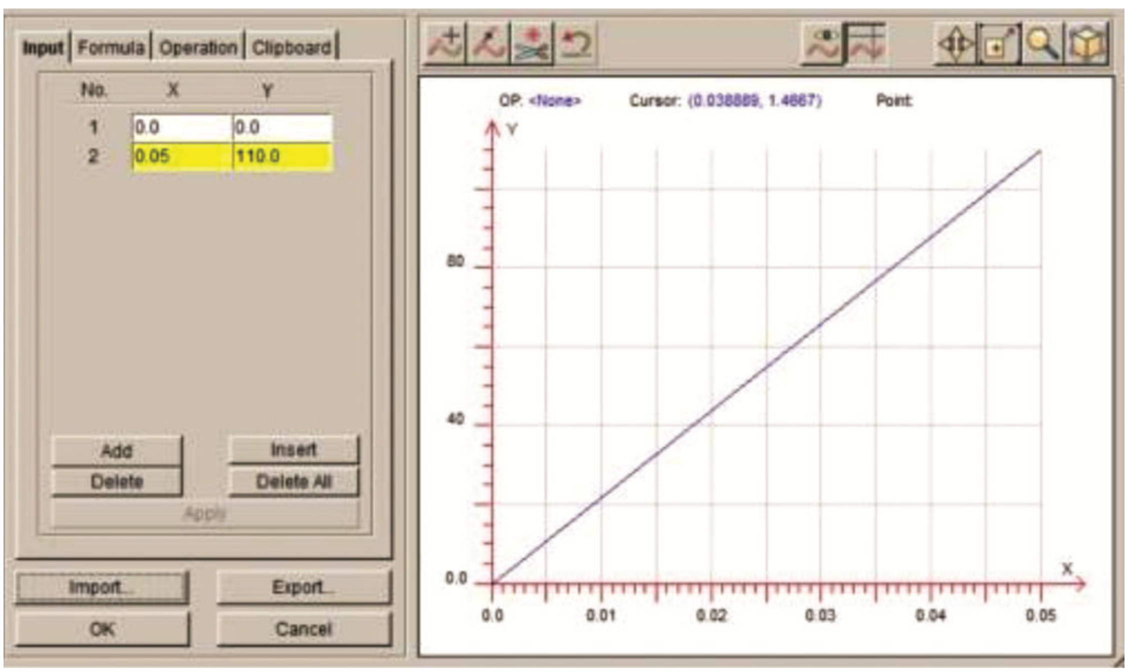

Fig. 6 — Defining the time-fluid pressure curve.

Fig. 7 — Section view of successfully formed specimens

perpendicular to the surface of the sample at each measurement point (Fig. 7).

3 Results and Discussion

3.1Mechanical properties of SS 304 material

The true and engineering yield curves for SS 304 stainless steel in 0 °, 45 ° and 90 ° directions according to the rolling direction are obtained. All yield curves were obtained very close to each other. To see the effect of planar anisotropy, flow curves was taken from all directions and compared with each other (Fig .8). The yield curves in different rolling directions were not very different from each other. For this reason, no need to determine the anisotropy coefficients required for the anisotropic model was determined in the analysis and it was decided to use the yield curve in the rolling direction of the material in the material modelling.

3.2 Limit drawing ratio obtained from female die process

The LDR found for the successfully formed work pieces (Fig. 9) of 1.0 mm thick SS 304 material used during the experiments is shown below (Table 1). For comparison, the LDR for materials with a thickness of 0.18 mm is also determined.

In the table, the pressure applied during the experiments (MPa), the BHF (kN), the initial diameter of the workpiece (mm), die diameter (mm) and drawing height (mm) with LDR (Table 1).

3.3 Results of finite element analysis

The thickness distribution obtained on the part at the end of the finite element analysis is given in Fig. 10.

As seen from the figure, the maximum thinning is occured at the bottom of the cup. The thickness distributions determined by the process modelling in Dynaform finite element software are as shown in Fig. 11.

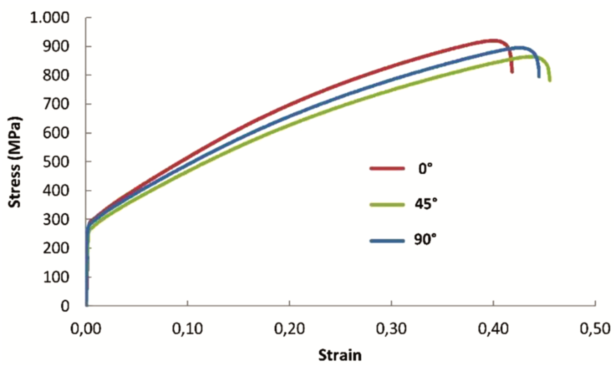

Fig. 8 — Change of true stress-strain curves according to rolling direction.

Fig. 9 — Sample 1, Sample 2 and Sample 3 (SS 304, thickness 1.0mm).

3.4 Thickness distributions of the specimens

The pressure-time graphs of the successfully formed parts are given in Fig. 12 and the thickness distribution graphs are given in Fig. 13, compared to FEA.

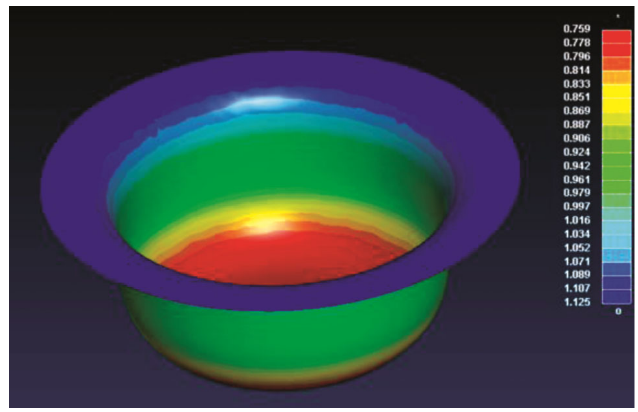

Fig. 10 — Thickness distribution in the sample after analysis.

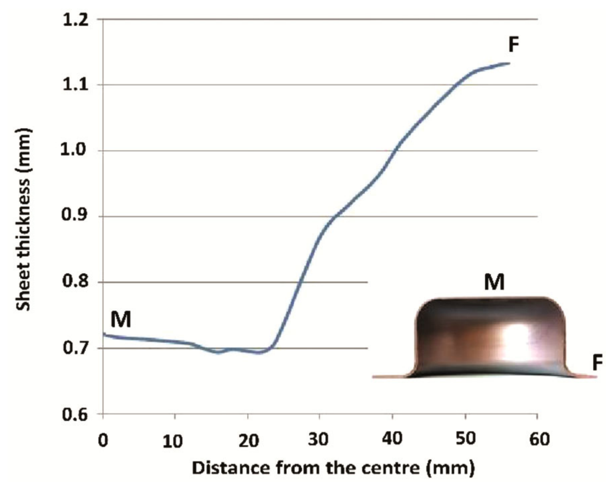

Fig. 11 — Thickness distribution of sheet metal obtained from FEA.

Table 1 — Limiting Drawing Ratio value obtained from female die for SS 304 material

Sheet Thickness (mm)	Applied Pressure (MPa)	Blank Holder Force (kN)	Diameter Workpiece (mm)	Die Diameter (mm)	Drawing Height (mm)	Limit Drawing Ratio with Female Die
1	112.1	469.8	91	50	26	1.82
	115.8	500.1				
	114.3	560.8				
	107.0	472.1				
	104.4	433.4				
0.18	19.7	122.4	91	50	27	1.82
	19.7	122.1				
	19.7	127.4				
	19.7	136.3				
	19.8	147.1				

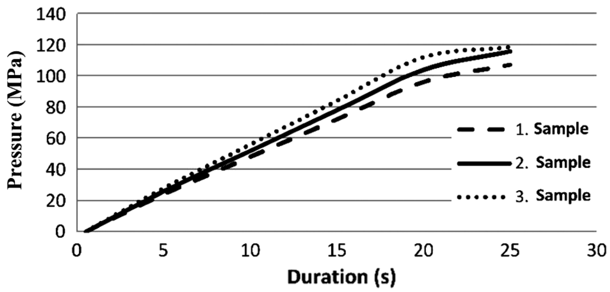

Fig. 12 — Chance of pressure as a function of time for sheet thickness 1.0 mm (Experimental results).

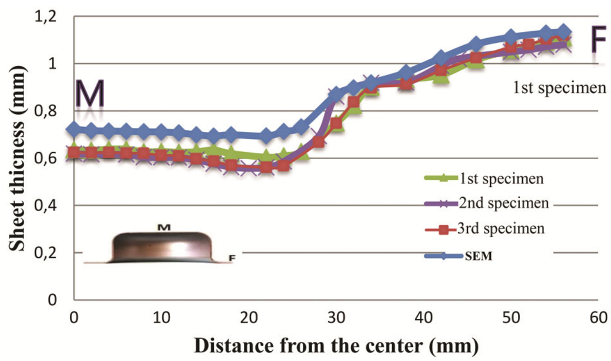

Fig. 13 — Comparison of thickness distributions obtained from experimental and FEA (for sheet thickness 1.0 mm).

As can be seen from the figures, the results obtained from the experiments and the results obtained by the finite element method were found to be very close to each other. This shows us that it is useful to analyze the finite element method before designing the dies that will be used with the sheet hydroforming process with female die.

In the literature, Yang *et al.*[19] obtained LDR of 3.3 for the SS 304 material in the hydromechanical deep drawing process using radial fluid pressure. In this study, by using sheet metal hydroforming with female die method, the LDR was obtained as 1.82. Although a lower LDR is obtained compared to the hydromechanical deep drawing process, the fact that the sheet hydro-forming with female die process is easily applicable and demonstrates that particularly shallow parts can be produced easily, especially without controlling of pressure and blank holder force paths, emphasizes the importance of the process and its use as a cost-effective production method in a wide variety of sectors shows. Furthermore, although close LDRs can be obtained in the conventional deep drawing process, it is important to determine the limiting drawing ratio with using the female die process due to its advantages such as more uniform thickness parts can be produced by the sheet hydro-forming with die process and high dimensional tolerance.

4 Conclusion

In this study, for the first time, the LDRs of the SS 304 material with different thicknesses was determined experimentally by using the sheet hydroforming with female die process (SHF-D). SHF-D process can be easily applicable without pressure and blank holder force control compared to the sheet hydroforming with punch process. The sheet hydro-forming process with female die demonstrates that particularly shallow parts can be produced easily, especially without pressure and blank holder control, emphasizes the importance of the process and its use as a lower cost production method in a wide variety of sectors shows.

The following results were drawn:

- Limiting drawing ratios for SS 304 material with a thickness of 1 mm and 0.18mm were found to be 1.82 using sheet hydro-forming process with female die.
- For SS 304 material, the drawing height was found to be 26mm for 1.0mm thickness and 27mm for 0.18mm thickness.
- When the thickness distributions are examined, it is seen that the data obtained from the finite element analysis and the experimental values are quite compatible with each other.
- It was seen that the data obtained from the experimental studies and the data obtained by finite element analysis were compatible with each other and the same LDR (1.82) was obtained.
- It is important to determine the LDR value with sheet hydroforming with female die process because it can be performed more easily and economically than other conventional deep-drawing method and hydromechanical deep-drawing method. Although close LDRs can be obtained in the conventional deep drawing process, it has been found necessary to determine the female dielimiting drawing ratio due to the advantages of producing more uniform parts by means of the more uniform thicknesses with the sheet hydro-forming method with the female die and because of its advantages such as less stretching and high dimensional tolerance.
- In this study, the application of the blank holder force as variable in order to obtain a greater limiting drawing ratio may provide better results.

- In this study, the sealing is achieved by a ring-shaped step on the surface of the pressure die. Therefore, a step height appropriate to the thickness of the part to be shaped must be selected. LDRs can be determined depending on the step height and the thickness of the part that provides sealing and LDR can be determined for different materials.

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