www.dergipark.gov.tr
ISSN:2148-3736
El-Cezerî Journal of Science and Engineering
Vol: 10, No: 3, 2023 (475-491)
DOI: 10.31202/ecjse.1232536

ECJSE

Research Paper

Investigation of Sheet Thickness and Punch Force in Die Surface Angled Hydro-mechanical Deep Drawing Method

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Received: 11.01.2023 **Accepted:** 17.08.2023

Abstract: In this study, the effect of die surface angled hydro-mechanical deep drawing method on sheet metal cup wall thickness and punch force was investigated as experimental and numerical analysis. In the works, 0.9 mm thick DIN EN 10130-1999 sheet metal material was used. The effect of variables on the test results was investigated by using die surface/blank holder angle, punch nose radius, die shoulder radius, chamber pressure and blank holder force as experimental parameters. Numerical analysis experiments were carried out using ANSYS 15.0 package program. Besides, experiments were performed according to the Taguchi experiment plan and L_{18} orthogonal array. The obtained data were analysed statistically by ANOVA analysis of variance in MINITAB 17.0 package program, and the effect of each parameter on the results was determined as a percentage. As a result, it was determined that the thinning was approximately 15% at most and the thickening was 10%.

Keywords: Die surface angled hydro-mechanical deep drawing, Taguchi, FEM, Cup wall thickness, Punch force

1. Introduction

The profession of die-forming provides time, quality, measurement accuracy, material savings, and identity, and also minimizes labour costs in the production of parts. There are many die-forming methods in the production process of sheet metal parts. Deep drawing method is a method widely used in industry due to its efficiency. The most significant convenience provided by the method is to produce seamless and weldless three-dimensional metal cups from two-dimensional sheet metal parts. This method is widely used in many product manufacturing, especially in the automotive industry. Deep drawing die methods are divided into three groups as conventional, hydro-mechanical and die surface angled deep drawing.

It cannot be possible to create deeper parts with a single process with traditional deep drawing methods. Besides, in this method, it is possible to have some negativities such as the absence of homogeneous sheet metal thickness distributions, not being able to perform deep drawing in materials with complex geometries, not to form micro cups and not to shape thin sheet metal materials. These problems encountered in deep drawing processes are reduced by with new molding methods developed. Savas and Seckin [1] stated that in the die surface angled deep drawing method, the ratio of limit drawing increased by 24% and the thinning of the cup walls decreased by 11%. Ozek and Bal [2] examined the effects of radius and angle on the ratio of limit drawing by giving different radius to the die and the punch and different angle values to the die in deep drawing cylindrical containers. In the study, DKP 37 sheet material with a thickness of 1 mm was used, and they stated that the ratio of limit drawing increased depending on the increasing die shoulder / punch nose radius and die

How to cite this article :
H. Ballıkaya, V. Savaş, Ç. Özay, "Investigation of Sheet Thickness and Punch Force in Die Surface Angled Hydro-mechanical Deep Drawing Method," *El-Cezerî Journal of Science and Engineering*, Vol. 10, No. 1, 2023, pp. 475-491.
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surface angle values. Ozek and Tasdemir [3] experimentally investigated the effects of die surface angle, temperature and blank holder force parameters on cup wall thickness, punch force and spring back on the warm deep drawing of AA 5754-O alloy. As a result, they stated that the temperature at which the experimental parameters were most effective on the test results was at OS (room temperature) and 100 °C, and the cup wall thickness distributions became more homogeneous with the increase of the temperature. It is not possible to ignore the advantages of both hydro-mechanical deep drawing methods and die surface angled deep drawing within themselves. However, better results are obtained with the die surface angle hydro-mechanical deep drawing method, which is the combination of these two methods. Many problems can be overcome with the die surface angled hydro-mechanical deep drawing method, which takes its place among the sheet forming methods for the first time. The die surface angled hydro-mechanical deep drawing method, which emerged as a result of combining these two methods to meet almost all of the needs and has attracted attention recently, has been an important research subject. The most important advantage of this method is that it has been possible to achieve high limit drawing rates, such as lower chamber pressure [4]. The die surface angle hydro-mechanical deep drawing method can be explained as a combination of both hydro-mechanical deep drawing methods and die surface angled. This method consists of an angled matrix / blank holder, a punch and a lower oil reservoir used to provide the liquid pressure to be formed. In order to realize the die surface angle hydro-mechanical deep drawing, the first step is to fill the lower oil chamber with oil. In the next step, the sheet material in the form of flakes is placed on the die. A force is exerted on the sheet material with the blank holder. With the press bench, the punch that gives the feature of movement applies force to the sheet material and allows the material to flow into the die. The liquid in the lower oil chamber starts to apply a force in the opposite direction to the punch movement. With the pressure control valve in the lower chamber, the liquid pressure formed is kept constant at a certain level. The fluid pressure created here reduces the friction between the sheet material and the die, while increasing the friction force between the punch and the sheet material [4]. Sheet material is obtained without tearing during deformation and by creating homogeneous thickness distributions [5]. Qin and Balendra [6] worked on hydro-mechanical deep drawing with a concave punch. As a result, they stated that the fractures that occur in the concave formation of the sheet material and the thinning in the thickness of the sheet material may occur when the chamber pressure is insufficient or too high. Singh and Kumar [7] in hydro-mechanical deep drawing; they stated that it offers several advantages over traditional deep drawing in properties such as uniform stress distribution, better surface quality and improved dimensional accuracy and high drawability. They stated that the process parameters, such as the highest chamber pressure and the initial chamber pressure, and the oil gap have a strong influence on the process. In this study, they investigated the effects of the highest chamber pressure and initial chamber pressure on the surface and thickness distribution in hydro-mechanical deep drawing. They stated that the thickness distributions on the cup walls were more homogeneous. They explained that the process at low chamber pressure shifts to traditional deep drawing, while at high chamber pressures the radius region will shift to the wall region. Zhang et al. [8] numerically and experimentally investigated mild steel containers in hydro-mechanical deep drawing. They evaluated the shape variations and thickness distributions. They investigated the effects of pre-pressure and anisotropy on final product quality. They explained that the anisotropy of the sheet material has a strong effect on the cup shape change and cup wall thickness change. Lang et al. [9] explained that the use of aluminum alloys is common in the aerospace industries and automotive and hydroforming is the most effective methods used to increase the drawing rate in deep drawing and cold forming. As a result of the experiments, they stated that the maximum draw ratio was $\beta = 2.46$. They also explained that the chamber pressure will significantly affect the drawing rate. Liu et al. [10] investigated the hydro-mechanical deep drawing process of 1 mm thick 2A12 aluminum sheet material with values of chamber pressure Pb=5 MPa and Pb=30 MPa. They stated that the wrinkles that occur on the curved surface parts cannot be prevented only by the chamber pressure. Low levels of chamber pressure may be suitable for wrinkles at a certain value, but they noted that abrupt breaks occur at high chamber pressure levels. They explained that removing the wrinkles on the curved surfaces can be eliminated by increasing the area of the layer adhering to the punch surface of the sheet material where the pre-pressure is applied. Zhang et al. [11] conducted experimental and numerical analysis of aluminum and mild steel sheet materials by hydro-mechanical deep drawing method. They stated that sheet material thinning generally occurs in the punch radius, while 25% thinning occurs in numerical analysis results and 26% in the measured test results. Chen et al. [12] investigated the production of a complex shaped engine oil sump with thin wall, large dimensions and asymmetric feature in hydro-mechanical deep drawing method by numerical and experimental methods. As a result, they stated that the existing part will not be manufactured by traditional deep drawing method They investigated the effect of process parameters such as initial blank dimension, die shoulder radius and loading path in numerical analysis experiments. They stated that the hydro-mechanical deep drawing method is more appropriate when the ratio of limit drawing obtained in traditional and hydro-mechanical deep drawing methods are compared and the limit shrinkage ratios are increased from 2.34 to 2.77. Bagherzadeh et al. [13] investigated the chilling ability as experimental and numerical analysis by forming a laminated layer with aluminum and steel sheet material in the hydro-mechanical deep drawing method. They modelled the non-uniform reservoir oil pressure distribution using the 3D finite element analysis method. They also stated that sheet thickness thinning is less in sheet materials exposed to lower tensile force on larger surfaces. Abbadeni et al. [14] Analyzed conventional and hydro-mechanical deep drawing processes using two-dimensional finite element analysis using AA5086 aluminum material with 1.12 mm thickness. They used ABAQUS package program for numerical analysis. They investigated the stresses and sheet thickness changes that occur during metal forming. They stated that there was a large plastic deformation in the punch radius and under the container. Plastic deformation distribution results indicated that there are differences between hydro-mechanical deep drawing and conventional deep drawing due to friction. They explained that low friction is the most important feature of hydro-mechanical deep drawing. As a result, they stated that the hydro-mechanical deep drawing process is a more effective method on the sheet metal forming process. Singh et al. [15] they applied support data regression (SVR), a new data mining technique, for thickness estimation along the cup wall in hydro-mechanical deep drawing. After using their experimental results for training and testing the estimates of thickness stresses in hydro-mechanical deep drawing, they applied the model to new data. They compared the SVR estimation results with artificial neural network (ANN), finite element (FE) simulation and experimental observations. They stated that the results obtained with SVR gave accurate results especially in the wall regions of the drawn cup.

Die surface angled hydro-mechanical deep drawing method is a method that is effective on the results depending on many parameters. For this reason, the number of experiments to be carried out is pretty high. Also, it is a long-term method regarding time and expensive in terms of cost. As can be applied to many engineering fields, the Taguchi experimental design method can easily be applied to this method as well. In addition to the high quality of the products; Taguchi experiment design technique provides the opportunity to get better results with much less trial in quality improvement. Tolerance design is applied to select the appropriate performance characteristic and convert the results to the S/N ratio [16, 17]. There are three different quality variants in tolerance design. These are; Smaller is better; Larger is better; and, Nominal is best [18–21].

The punch force value is desired to be the smallest and therefore, the “Smaller is better”; is preferred. The distribution of cup wall thickness should be constant in the deep drawing process. In other words, nominal values should be preferred throughout section [22]. Smaller is better; and, Nominal is best; quality variables are calculated using equation 1-2-3-4.

“Smaller is better”

$$S/N = -10(\log(\sum \frac{1}{\bar{y}^2})/n)) \quad (1)$$

"Nominal is best"

$$\bar{y} = \sum_{i=1}^{n} y_i / n \tag{2}$$

$$s^2 = \sum_{i=1}^{n} (y_i - \bar{y})^2 / n - 1 \tag{3}$$

$$S/N = 10 \log(\bar{y}^2 / s^2) \tag{4}$$

In equations 1, 2 and 3, y_i is the measured thickness value, n is the number of measurements, $\bar{y}$ is the mean value and s is the standard deviation [22].

Raju et al. [22] investigated the effect of die radius, punch radius and pressure plate strength parameters on thickness change in deep drawing method of AA 6061 sheet material. As a result of the experimental studies, they stated that the effect of the die radius on the cup wall thickness was 66.49%, the effect of the punch radius was 9.23% and the effect of the pressure plate was 29.16%. They used Taguchi experimental design method for the experimental studies. Sharma and Rout [23] numerically investigated the hydro-mechanical molding method according to the L_9 orthogonal array using the Taguchi experimental design method on 1 mm thick sheet material. In this study, they investigated the effects of friction, anisotropy ratio and stress hardening between punch and sheet material surfaces for different deformation shapes. They developed the LsDyna-Explicit Dynamics simulation for the finite element model. They stated that the minimum thickness variation, limit shrinkage ratio, higher anisotropy ratio can be obtained with effective lubrication for deep drawing process in the containers obtained as the final product. Reddy et al. [24] investigated the effects of deep drawing process parameters for AA6111 aluminum alloy using analysis of variance and Taguchi experimental design method using L_9 orthogonal array. They stated the optimum process parameters and their main effects on the thickness distribution of the sheet material in different areas. They investigated three important process parameters, punch radius, die radius and press plate strength. They evaluated these parameters as % on the thickness distribution of the sheet material. They stated that the effect of the pressure plate strength was 56.98%, the effect of the punch radius was 32.12%, and the effect of the die radius was 12.90%. Hassan et al. [25] conducted research on formability of thin sheets or metal foils using the traditional deep drawing and friction method. They carried out experiments according to the L_9 orthogonal array using the Taguchi experimental design method. They evaluated the experimental results with ANOVA analysis of variance and FE method. In the experiments, they used Al050-0 and 0.5 mm thick sheet material. They determined the ratio of limit drawing as β=3.3.

This study investigated the effects of the die surface/blank holder angle, punch nose radius, die shoulder radius, chamber pressure and blank holder force which are the parameters of the die surface angled hydro-mechanical deep drawing method on cup wall thickness and punch strength by using the DIN EN 10130-1999 sheet metal material. A new die model was developed for experimental studies, and the experimental and numerical validity of this developed model was shown in the previous study [4]. In addition, the results obtained by performing the numerical analysis of the study were compared with the experimental results. The optimum levels of the parameters were determined and the effect rates of these parameters were determined in % by ANOVA analysis.

2. Experimental Methods

2.1. Materials

In this study, 0.9 mm thick DIN EN 10130-1999 sheet metal material with low carbon content and high forming capability, which is used in many areas of industry, especially in the automotive and white goods sector, was used. In order to determine the mechanical properties of the material, samples were taken at angles of 0°, 45° and 90°, according to the rolling direction, and a tensile test was applied at a speed of 5mm / min in a SHIMADZU brand test device. The data obtained after the tensile test is shown in Table 1.

Table 1. Mechanical properties of DIN EN 10130-1999 sheet metal material

Direction of rotation (°)	Yield strength (N/mm^2)	Tensile strength (N/mm^2)
0	185.45	310.78
45	203.30	333.55
90	189.46	303.65

The chemical properties of the material used in the experimental studies are given in Table 2.

Table 2. Chemical analysis of DIN EN 10130-1999 sheet metal material

C	P	S	Cr	Mn	Mo
0.044	0.108	0.0085	0.0116	0.241	0.0116
Ni	**Cu**	**Nb**	**Ti**	**Sn**	**Fe**
0.0261	0.00452	0.00241	0.00027	0.0864	99.46

2.2. Experimental Method and Procedure

The working mechanism of the die surface angled hydro-mechanical deep drawing die which is specially designed and manufactured is shown in Fig. 1. The literature was made use of to determine the measurement of the die geometry, especially the die gap measure, that is a single-sided die gap difference between the die and the punch. Equation 5 was used for the single-sided die gap [26].

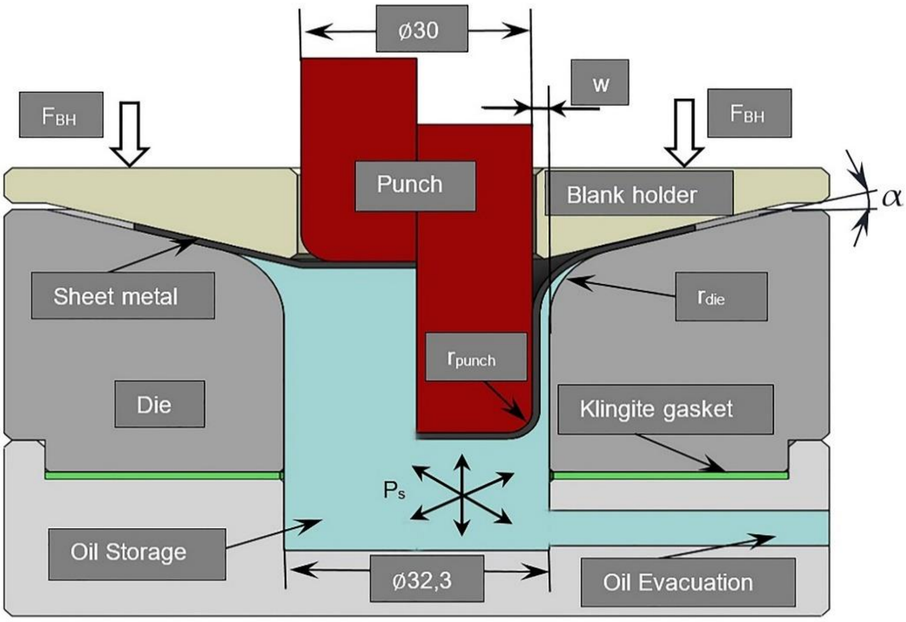

Figure 1. Schematic illustration of die surface angled hydromechanical deep drawing process

$$w = s + k\sqrt{10s} \tag{5}$$

w: Drawing clearance (mm)
s: Sheet thickness (mm)
where k is the coefficient of the material (0.07 for steel) [26]. In the experimentals, a 0.9-mm thick sheet metal material was used. The single-sided die gap is 1.15 mm.

In this study, die surface/blank holder angles, punch nose radius, die shoulder radius, chamber pressure and blank holder force were used as experimental parameters of the die surface angled hydro-mechanical deep drawing method. Experiment parameters and the levels of these parameters are given in Table 3.

Table 3. Experiment parameters and levels

Symbol	Experimental Levels	Value 1	Value 2	Value 3	Value 4	Value 5	Value 6
A	Die surface angle (°)	0°	2.5°	5°	10°	12.5°	15°
B	Die shoulder radius (mm)	6	8	10	-	-	-
C	Punch nose radius (mm)	6	8	10	-	-	-
D	Chamber pressure (MPa)	6	8	10	-	-	-
E	Blank Holder Force (N)	1946.95	5882.78	9507.64	-	-	-

Experimental studies were carried out on a C type press machine operating with a hydraulic system with a loading capacity of 60 tons. The die surface angled hydro-mechanical deep drawing experiment set is shown in Fig. 2.

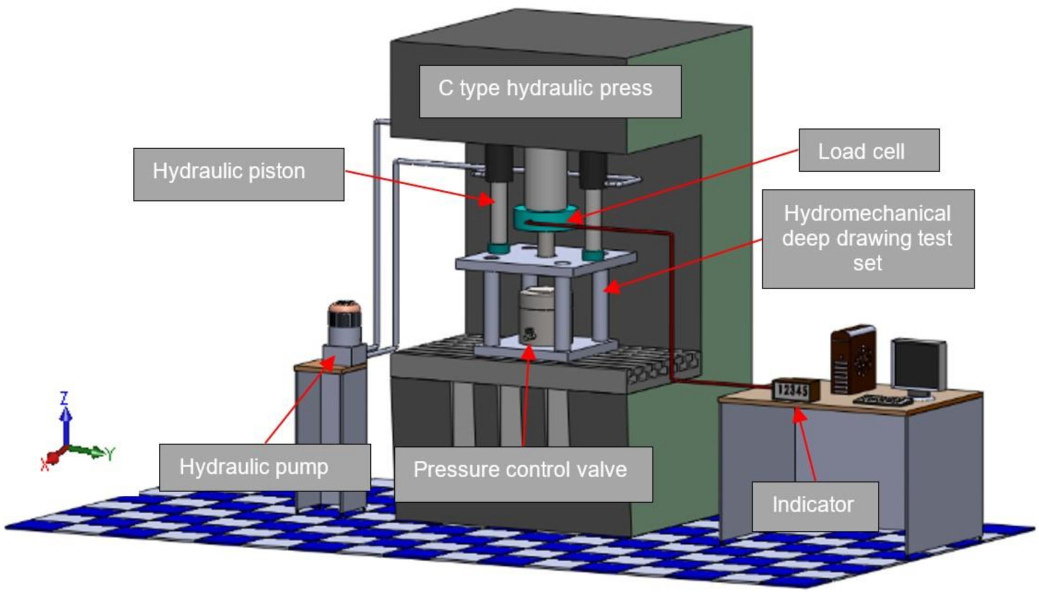

Figure 2. Experimental equipment of die surface angled hydromechanical deep drawing process

The movement speed of the punch was fixed at 4 mm/s [27]. The speed control valve of the machine was used to position the punch movement in a stable speed. By moving the punch by the press machine toward the -z direction, the sheet metal material was enabled to flow into the die. For the blank holder force, a force was applied by a separate hydraulic system operating independently of the machine. Equation 6-11 was made use of to determine the blank holder force [26].

$$r_m = 0{,}035 + \big(50 + (D - d)\big).\sqrt{s} \tag{6}$$

$$d_e = d + 2w + 2.r_m \tag{7}$$

$$A_{BH} = \frac{\pi}{4}\left[D^2 - {d_e}^2\right] \tag{8}$$

$$\beta_{actual} = \frac{D}{d} \tag{9}$$

$$p = \left[(\beta_{actual} - 1)^2 + \frac{d}{200.s}\right].\frac{R_m}{400} \tag{10}$$

$$F_{BHF} = A_{BH}.p \tag{11}$$

w : Drawing clearance (mm)
D : Diameter of the blank (mm)
d : Punch diameter (mm)
s : Sheet thickness (mm)
rm : Die edge curvature radius (mm)
de : Effective diameter of the blank holder (mm)
ABH : Blank holder area (mm^2)
βactual : Actual draw ratio
Rm : Tensile strength (N/mm^2)
p : Blank holder pressure (N/mm^2)

During the experimental studies, a CAS LS-20T load cell was used to measure the force acting on the punch. CAS 1500A indicator was used to save and transfer the results obtained from the load cell to the computer. The data were saved to the computer using the RS232 connection with the DNC computer program at 10^{-1} seconds interval.

In order to provide the die chamber pressure in the die surface angled hydro-mechanical deep drawing method, the hydraulic oil (Hydro Oil Aw 46) with a kinematic viscosity of 46 mm/s^2 at 40 °C was used as a forming fluid in accordance with ISO 11158 standards. For the control of the internal pressure of the die, a FESTO brand pressure control valve with a maximum working capacity of 12 MPa was used. The pressure control valve was calibrated together with manometer and the hydraulic pump. Calibration process was carried out for each changing chamber pressure.

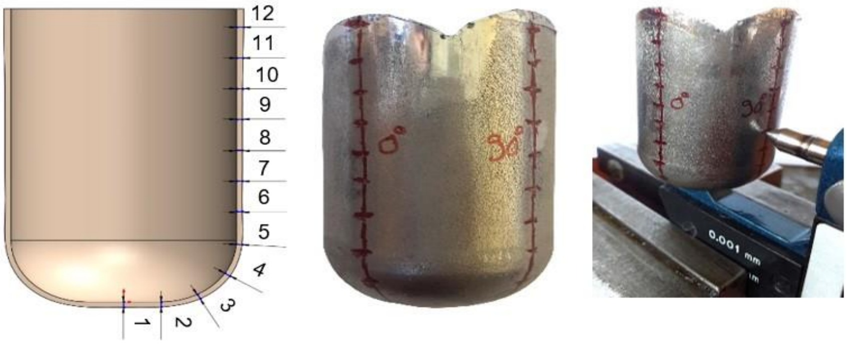

Figure 3. Measuring positions of the drawing cups

In order for the experimental studies to be carried out, the studies were repeated up to the maximum diameter value that can be drawn for each experiment by applying the experiment plan of Table 4. The diameter measure, which was just previous the damaged diameter from the samples subjected to the drawing process determined the ratio of limit drawing of that experiment. The maximum drawing diameter experiments were repeated three times to verify the ratio of limit drawing. The experiment specimens were cut on wire electrical discharge machining. Thickness measurement at 12 points with 5 mm intervals starting from the centre of the cut work piece to rolling direction was made as shown in Fig. 3 [7]. Thickness measurements were measured with a QLR Digit brand micrometer with an accuracy of 10-4 mm. In order to determine the wall thickness, the measurement was taken for the level of the highest limit drawing ratio of each parameter.

2.3. Finite Element Modelling of Hydroforming

The finite element method was carried out in the ANSYS Workbench 15.0 package program. The equipment in numerical analysis studies, namely die, punch, blank holder, die sub-chamber, were designed both as 3D and in the same dimensions with die-punch radius measurements, die surface angle measurements, drawing gap measurement, initial blank dimension measurement used in experimental studies. In order to obtain the results of sheet metal thickness changes in numerical analysis, the sheet metal material was shaped as a surface and the sheet metal thickness value was defined in the package program. The die equipment was developed using the Explicit Dynamics-Design Modeler menu and recorded as xxx.agdp file extension [23].

The properties of the sheet metal material were determined from the Engineering Data menu in the package program. While the tensile and yield strengths required for the sheet material to be used in finite element method were determined according to the result of tensile test. The elasticity modulus (E), bulk modulus, material density (g), Poisson's ratio (ν) and shear modulus were obtained from the package program. The sheet metal material feature was determined as non-linear, and other die equipments were as rigid.

During the formation of mesh structures, a "Face sizing" was defined, as a mesh interval of 1 mm for the punch nose radius and die shoulder radius zones and, as a mesh interval of 3 mm for the workpiece surface. The contact option between sheet metal material and die and blank holder was defined as friction. In the Explicit Dynamics analysis method, were defined displacement to the punch, force for the blank holder force, fixed support to fixation the matrix and pressure for the chamber pressure applied to the sheet material. These definitions and mesh structures given for numerical analysis experiments are shown in Fig. 4.

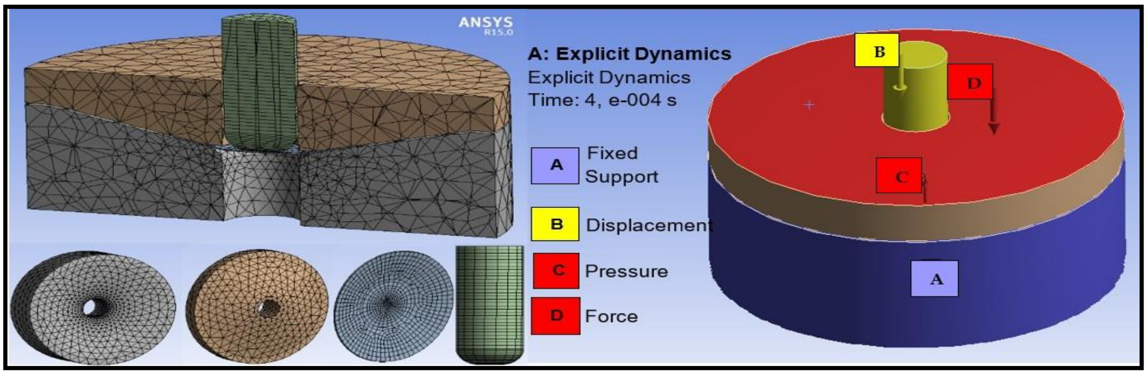

Figure 4. Numerical analysis mesh structure and process definitions [4]

3. Results and Discussion

In this study, in the die surface angled hydro-mechanical deep drawing method, the effects of die surface angle, punch nose radius, die shoulder radius, die chamber pressure, and blank holder force parameters on cup wall thickness and punch force were investigated by using Taguchi experimental design method. Experimental design, cup wall thickness and punch force results are given in Table 4.

Table 4. Punch force and cup wall thickness obtained in L_{18} Taguchi experimental design

E.N	A	B	C	D	E	Punch force (N)	S/N	Thickness values measured at different positions												Avarage	Standard deviation	S/N
								1	2	3	4	5	6	7	8	9	10	11	12			
1	0	6	6	6	1964.95	35708.4	-910.554	0.85	0.839	0.779	0.846	0.882	0.854	0.86	0.888	0.93	-	-	-	0.858	0.041058	24.4085
2	0	8	8	8	5882.78	37552.68	-914.928	0.867	0.841	0.847	0.846	0.819	0.825	0.846	0.858	0.984	-	-	-	0.859	0.049056	24.8683
3	0	10	10	10	9507.64	39730.5	-919.825	0.857	0.829	0.814	0.821	0.834	0.826	0.843	0.867	0.915	0.992	-	-	0.859	0.055001	23.8806
4	2.5	6	6	8	5882.78	39308.67	-918.898	0.863	0.823	0.802	0.854	0.817	0.842	0.86	0.9	0.988	-	-	-	0.861	0.055819	23.7644
5	2.5	8	8	10	9507.64	38455.2	-916.991	0.863	0.835	0.826	0.849	0.837	0.864	0.897	0.931	0.994	-	-	-	0.877	0.054907	24.0707
6	2.5	10	10	6	1964.95	43056.09	-926.807	0.847	0.809	0.805	0.81	0.8	0.813	0.835	0.849	0.9	0.957	-	-	0.842	0.050328	24.4751
7	5	8	6	6	9507.64	39848.22	-920.082	0.862	0.86	0.817	0.854	0.832	0.85	0.877	0.927	0.862	-	-	-	0.859	0.032844	28.3597
8	5	10	8	8	1964.95	42212.43	-925.088	0.875	0.831	0.819	0.844	0.814	0.827	0.843	0.875	0.951	0.982	-	-	0.866	0.057266	23.5933
9	5	6	10	10	5882.78	46980.09	-934.383	0.879	0.824	0.817	0.785	0.782	0.794	0.799	0.792	0.813	0.879	0.953	-	0.828	0.053329	23.8299
10	10	10	6	10	5882.78	40976.37	-922.507	0.876	0.841	0.814	0.851	0.87	0.886	0.93	0.997	-	-	-	-	0.883	0.057297	23.7577
11	10	6	8	6	9507.64	41967.18	-924.582	0.875	0.848	0.827	0.853	0.818	0.84	0.864	0.905	0.994	-	-	-	0.869	0.053484	24.2193
12	10	8	10	8	1964.95	45959.85	-932.476	0.827	0.8	0.805	0.8	0.783	0.796	0.809	0.812	0.848	0.91	0.957	-	0.831	0.054213	23.7156
13	12.5	8	6	10	1964.95	41035.23	-922.631	0.867	0.832	0.818	0.865	0.839	0.869	0.887	0.926	0.993	-	-	-	0.877	0.053868	24.2366
14	12.5	10	8	6	5882.78	43389.63	-927.477	0.875	0.842	0.826	0.839	0.82	0.836	0.823	0.816	0.854	0.947	-	-	0.847	0.039078	26.7272
15	12.5	6	10	8	9507.64	47097.81	-93.46	0.866	0.828	0.814	0.81	0.763	0.769	0.791	0.792	0.794	0.795	0.884	0.95	0.820	0.054607	23.5375
16	15	10	6	8	9507.64	41368.77	-923.335	0.866	0.842	0.83	0.852	0.831	0.85	0.876	0.91	0.985	-	-	-	0.871	0.049358	24.9364
17	15	6	8	10	1964.95	42820.65	-926.331	0.876	0.844	0.842	0.853	0.817	0.848	0.869	0.91	0.979	-	-	-	0.870	0.048157	25.1460
18	15	8	10	6	5882.78	47823.75	-935.929	0.846	0.809	0.804	0.828	0.792	0.808	0.799	0.798	0.839	0.91	0.968	-	0.836	0.055097	23.6263

According to the experimental results given in Table 4, S/N ratios were calculated in MINITAB 17.0 package program. The S/N ratios determined for the punch force were calculated according to, the lowest the best, performance characteristic [28]. In deep drawing processes of sheets, it is desirable that sheet metal thickness distributions should be as constant as possible. Therefore, for the thickness distribution S/N ratios, the nominal is the best, performance characteristic was chosen [22].

The data obtained as a result of the experimental studies were evaluated according to the ANOVA statistical analysis method. In Table 5, the effects of the parameters on the change in cup wall thickness were evaluated in percentages. The most significant parameter affecting the cup wall thickness change was the punch nose radius parameter with a rate of 62.858%. Furthermore, the other parameters presented effects as follows: die surface angle 21.076%, chamber pressure 9.244%, blank holder force 3.593% and, die shoulder radius 2.198%.

Table 5. Result of ANOVA for Cup wall thickness

Symbol	Parameters	DF	SS	Variance	F ratio	(%)
A	Die surface angle (°)	5	0.016495	0.003299	70.6235	21.076
B	Die shoulder radius (mm)	2	0.0017893	0.000894	19.1525	2.198
C	Punch nose radius (mm)	2	0.048593	0.0242965	520.1228	62.858
D	Chamber pressure (MPa)	2	0.007226	0.003613	77.3505	9.244
E	Blank holder force (N)	2	0.002865	0.001432	30.6749	3.593
	Error	4	0.000186	0.00005		1.029
	Total		0.077157			100

Detection of wall thickness change in all deep drawing processes is a significant result in terms of product strength and quality. The least thickness change indicates that success has been achieved in the product obtained. The thinning of the sheet metal thickness that occurred in the die surface angled hydro-mechanical deep drawing method was negligible. When Table 4 is examined, it is seen that there was a negligible wall thickness change (0.1 mm) at the bottom of the vessel. The reason for this is that there is a liquid pressure affecting the sheet metal material during the deep drawing method. Besides, small deformations occur in the blank zones in contact with the punch, therefore there is less thinning in the blank part around the punch corner [7]. The 5th and 6th points coinciding the punch nose radius zone of the cup (Fig. 3) are the zones where the thinning is the most due to the greatest stress occurring [7, 14, 29]. The allowable thinning ratio for cup wall thickness change in the hydro-mechanical deep drawing method is between 20% and 25% [7, 30, 31]. In experimental studies, 0.9 mm thick sheet metal material was used and measurements were taken from the samples obtained from all test results. Among the measured values, the thinnest sheet metal thickness value was determined as 0.763 mm. There was only a 15% thinning in the cup wall thickness. At the upper points of the container, a higher material thickness value is measured than the thickness of the sheet metal used [11]. In the study, the maximum value of the sheet metal thickness was measured as 0.997 mm and the thickening was determined to be 10%. This situation is shown graphically in Figures 5a-e.

When Fig. 5a is examined the die surface angle value with the highest thinning in thickness change was determined as α=12.5°. The reason for this is that with the increase of die surface angle, the ratio of limit drawing increased [4]. As seen in Fig. 5b, as the radius of the die decreases, the force of pulling the material into the die will increase. It was observed that the stress increased in the sidewall of the material due to the increasing punch force and therefore, thinning in cup wall thickness was higher [32]. It was seen that the thinnings decreased with the increase in the punch nose radius parameter values expressed in Fig. 5c [28]. However, at the third level of the parameter, even if a slight thinning occurred, it was negligible. In the graphic shown in Fig. 5d, the most effective level in chamber pressure parameter is the second level. The reason for this is that when the pressure is excessive, it will cause more swelling on the sheet metal material, and the sheet metal material will tear. If the chamber pressure is low, the pressure will not have an effect on the deep drawing process [6, 33]. The cases where thinning occurs are situations where there is insufficient or excessive pressure. In the graphic shown in Fig. 5e, the effect of the blank holder force parameter on the cup wall thickness is shown. At low values of this parameter, the process is closer to traditional deep drawing. It is known that depending on the increasing initial sheet metal diameter, the friction zone between the die and blank holder increases, therefore, the zone affected by the friction force increases. As a result of wrinkles on the sides of the cup, the friction between the inner surface of the die and the material increases and this increases the deep drawing force. At the highest level of the parameter, the friction force increases and makes the deep drawing force increase. At the first and third levels of the parameter, thinning occurred in the thickness of the cup wall due to the increasing punch force. When Fig. 5 and Fig. 6 are examined, there was a thinning in sheet metal thickness at the points 5, 6 and 7 where the cup punch nose radius started, moreover, thickening was seen in the upper throat of the deep-drawn cup.

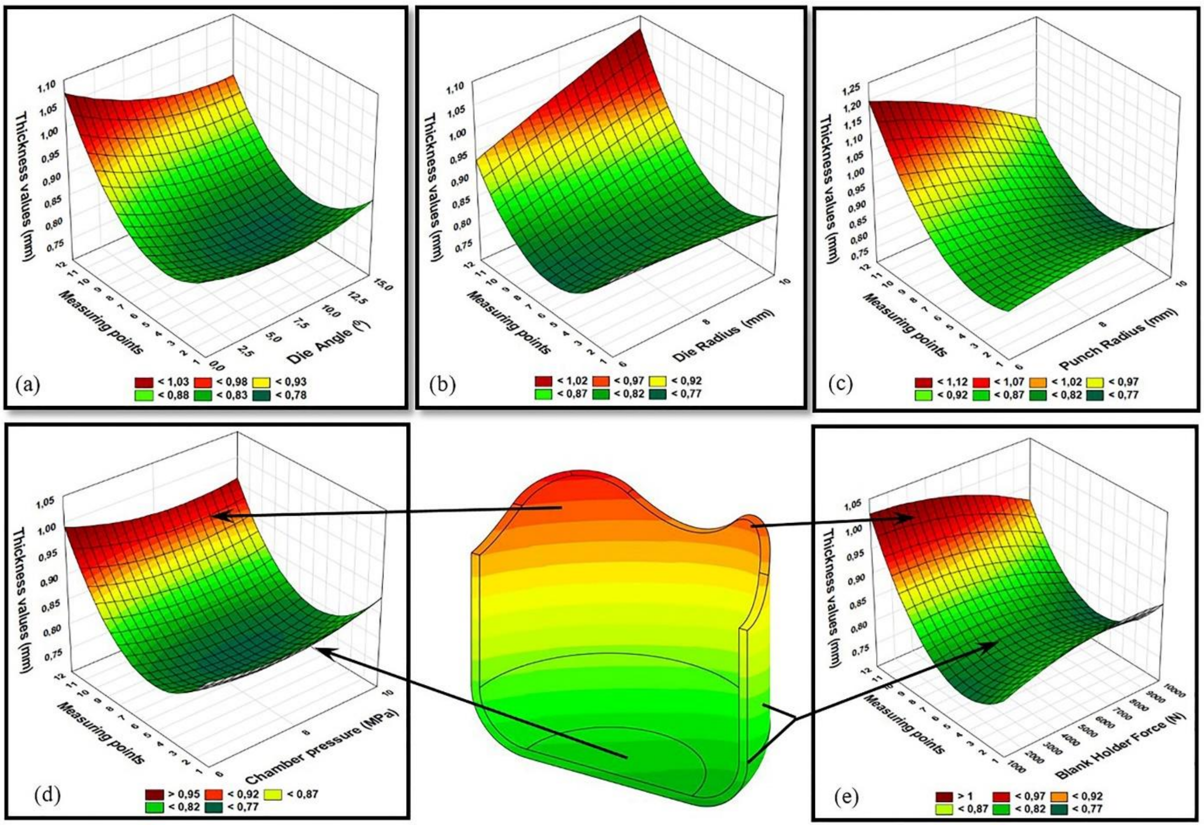

Figure 5. The effect of parameters on Cup wall thickness Change

The cup wall thickness changes obtained as a result of numerical studies are shown in Fig. 6. When Fig. 6 is examined, cup wall thickness values did not show much change between numerical analysis and experimental analysis. Thinning in the punch nose radius zones and thickening towards the upper parts of the cup occurred.

Punch force results are shown in Figures 7a-e. The factors affecting the change of punch force are the friction force between the die and the sheet metal material, the blank holder force and the deformation resistance of the sheet metal material. In the angled dies, it was determined that the blank holder force decreases with the angle increasing up to 5 degrees and is constant after this value [34]. With the increase of the die surface angle, the decrease in the blank holder force decreased the punch force. As a result of the increase of the die surface angle up to 12.5 degrees, the ratio of limit drawing increased, and consequently, the punch force slightly increased due to the resistance of the sheet metal material to deformation (Fig. 7a). In addition, as the die surface angle increased, the contact distance between the die and sheet metal material increased and the punch force increased with the increase of the friction force [2]. When the punch moved into the die, it was seen that there was an increase in the force applied to form the sheet metal material, considering the increase in the stroke length.

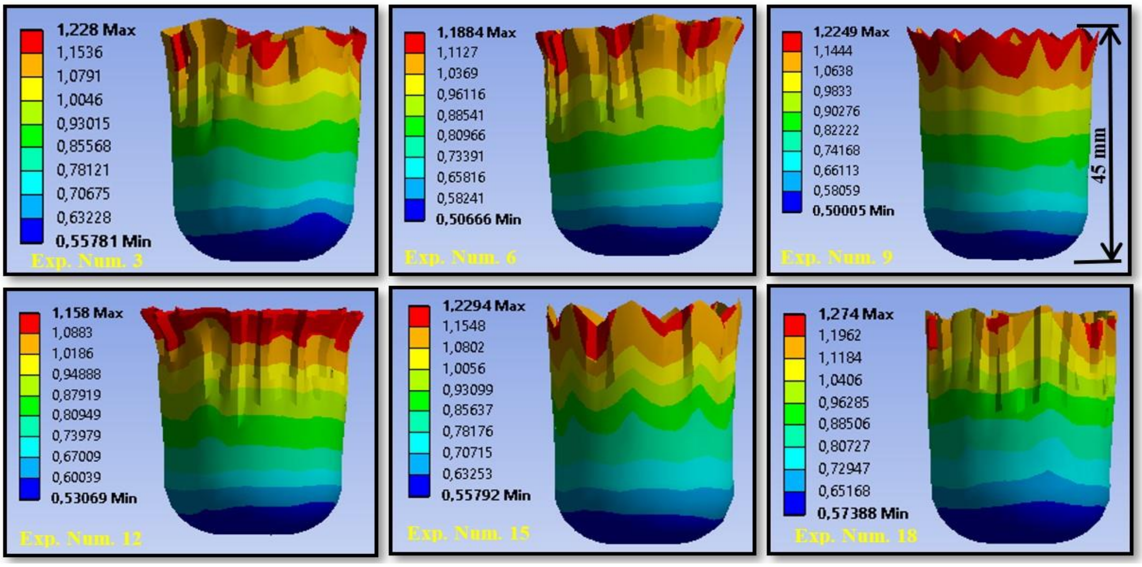

Figure 6. Cup wall thickness change according to numerical analysis results

It is seen that the greatest value in the punch force was at the distance where the punch pushes the sheet metal into the die and tries to form it. The maximum applied punch force decreased towards the end of the deep drawing process. As the sheet metal material moves into the die, the amount of sheet metal remaining between the die and the blank holder decreases. Therefore, the area affected by the friction force that will occur in the intermediate area decreases and the punch force required for forming decreases. Thickening occurs towards the upper parts of the sheet metal material and the sheet metal material exceeds the single-sided die gap. Thus, the sheet metal material shows a relative compression tendency between the punch and the die. As the punch force tends to decrease, after a certain point it again increases slightly and then some decreases are shown in the punch force again [35]. The optimum level of the die shoulder radius parameter was the second level. At the first level, it is more difficult for sheet metal material to flow into the die. For this reason, the punch force has increased in the first level. When the die shoulder radius value exceeds 8 mm, towards the end of the deep drawing process, wrinkles occurred on the upper parts of the sheet metal because the blank holder was not able to make ironing sufficiently and punch force increased due to compression (Fig. 7b). In the punch nose radius parameter, according to the increasing radius value, an increase occurred in the punch end radius zone. Since the force required to form the sheet metal material was applied to a larger area, an increase in the ratio of limit drawing occurred and the applied punch force increased accordingly (Fig.7c) [4]. Since the fluid pressure between the die and sheet metal was insufficient at low chamber pressure values, an increase in friction force occurred and the punch force increased accordingly. In the pressure values of the chamber pressure parameter above 8 MPa, the punch exposed to high-pressure value also increased the punch force applied to shape the sheet metal material (Fig. 7d). There was not enough sealing for the first and second level blank holder force. For this reason, the hydro-mechanical deep drawing process converged to traditional deep drawing. For this reason, the punch force decreased in the third level of the parameter (Fig. 7e).

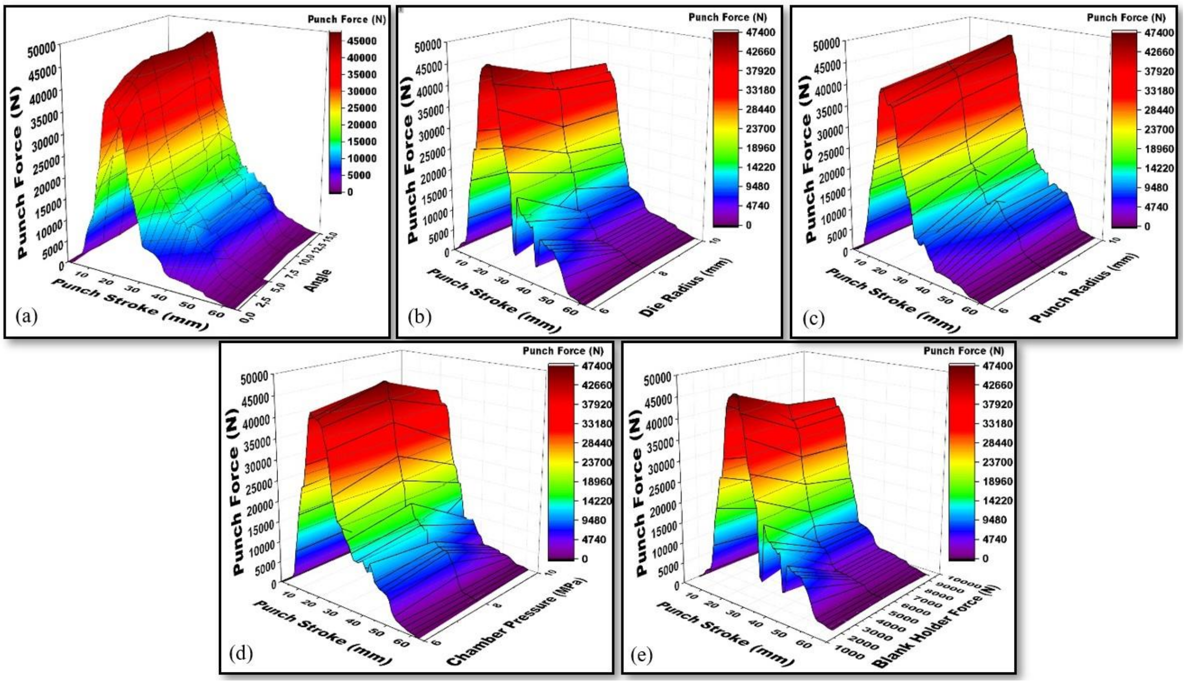

Figure 7. The effect of parameters on punch force change

Changes in punch forces obtained as a result of numerical studies are shown in Fig. 8. When Fig. 8 is examined, punch force values did not show much change between numerical analysis and experimental analysis. In numerical analysis, the stresses created by the punch forces on the cup were calculated by the Equivalent von Mises Stress, and its unit is MPa.

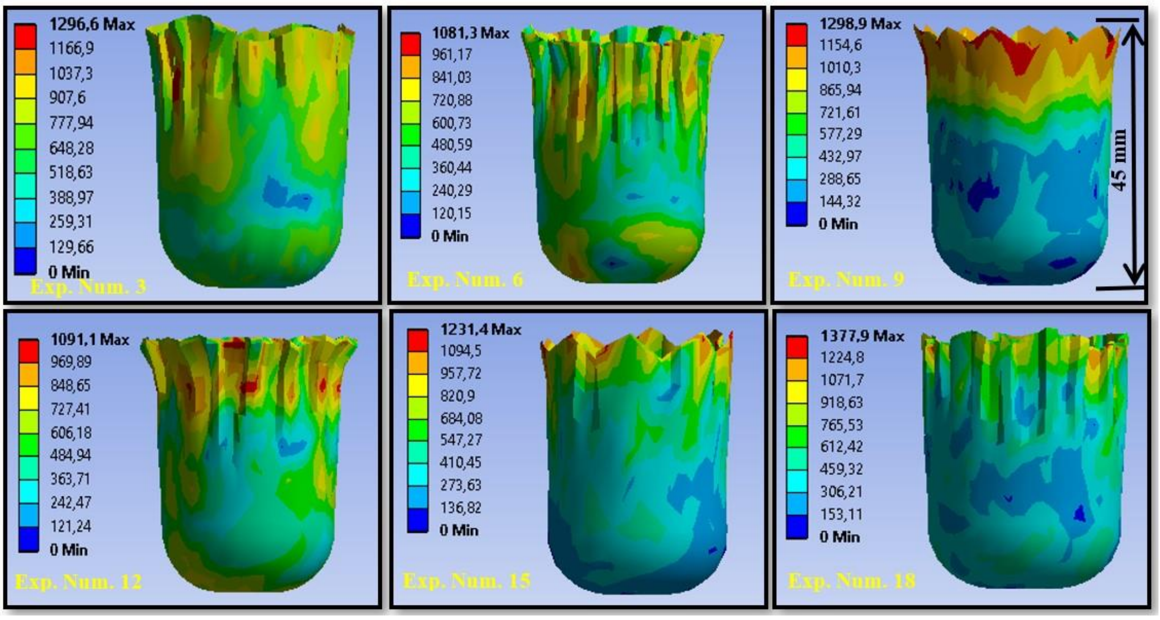

Figure 8. Stresses created by punch forces on the cup according to numerical analysis results

Table 6 shows the S/N ratios corresponding to the punch force values obtained by the deep drawing of the sheet metal material with the die surface angled hydro-mechanical deep drawing method. The S/N ratios are determined according to the performance characteristics, " Smaller is better " for punch force values. In this Table 6, optimum levels of deep drawing parameters are shown as (^{a}).

Table 6. Average S/N ratio for punch forces

Symbol	Experimental Levels	Value 1	Value 2	Value 3	Value 4	Value 5	Value 6
A	Die surface angle (°)	-91.510[a]	-92.089	-92.651	-92.652	-92.823	-92.853
B	Die shoulder radius (mm)	-92.489	-92.383[a]	-92.417	-	-	-
C	Punch nose radius (mm)	-91.966[a]	-92.256	-93.066	-	-	-
D	Chamber pressure (MPa)	-92.423	-92.488	-92.377[a]	-	-	-
E	Blank Holder Force (N)	-92.398	-92.568	-92.323[a]	-	-	-

The S/N ratios graph created according to Table 6 is shown in Fig. 9. When the graphic in Fig. 9 is examined, it will be seen that the optimum levels of deep drawing parameters are the levels where the S/N ratio is the highest. It is seen that the largest S/N ratios of the parameters are at A1B2C1D3E3 levels.

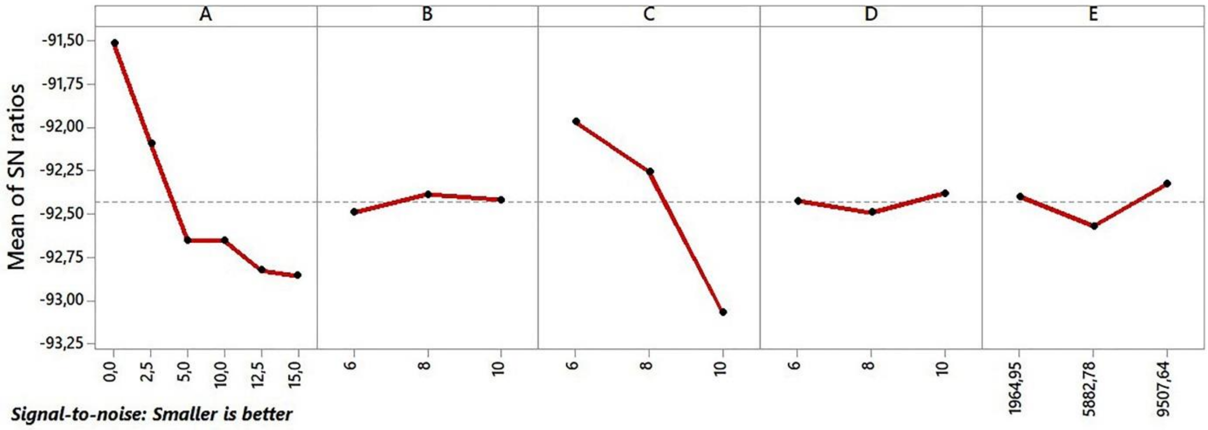

Figure 9. The effect of parameters on S/N ratio

Table 7. Result of ANOVA for Punch force

Symbol	Parameters	DF	SS	Variance	F ratio	(%)
A	Die surface angle (°)	5	4.182504161	0.836500832	619.312737	49.99
B	Die shoulder radius	2	0.03466419	0.017332095	12.8320102	0.382
C	Punch nose radius	2	3.90236396	1.95118198	1444.57937	46.69
D	Chamber pressure	2	0.03728461	0.018642306	13.8020394	0.414
E	Blank holder force (N)	2	0.18946866	0.09473433	70.1376199	2.23
	Error	4	0.00540276	0.001350692		0.274
	Total		8.35168835			100

ANOVA variance analysis of the punch force is given in Table 7. As can be seen in Table 7, all parameters had an effect on the punch force results. However, the most effective parameter was the die surface angle with 49.99%. Furthermore, other parameters affecting as follows: punch radius parameters 46.69%, blank holder force 2.23%, chamber pressure 0.414% and die shoulder radius parameters 0.382%.

4. Conclusions

The In this study, the deep drawing process of 0.9 mm thick DIN EN 10130-1999 sheet metal material was performed using the die surface angled hydro-mechanical deep drawing method. Experiments were carried out using the L_{18} orthogonal array in Taguchi experimental design. The die surface angle, punch nose radius, die shoulder radius, chamber pressure and blank holder force control parameters were used as the process parameters. In the experimental and numerical analysis results, the effects of process parameters on the punch force and sheet metal thickness change results were examined. Besides, the optimum process parameter levels were determined by taking into account the S/N ratios and ANOVA variance analysis results to determine the nominal sheet metal wall thickness and minimum punch force.
In the general evaluation of the study:

- The maximum thinning of the sheet metal thickness value was 15% and, the maximum thickening was 10%.
- With the increase of the die surface angle parameter up to 12.5°, thinning increased in cup wall thickness. However, with the increases after 12.5°, cup wall thickness increased. Between 12.5° and 15° die surface angles, it converged to the nominal value.
- With the increase of the die shoulder radius, the change of the sheet wall thickness converged to the nominal value.
- With the increase of the punch nose radius value up to 8 mm, the sheet thickness approached to the nominal value. However, in cases where the punch nose radius exceeds 8 mm, the nominal value was moved away.
- Chamber pressure approached the nominal value at 8 MPa.
- The optimum level for the blank holder force parameter is FBH= 5882.78 N.
- The punch force increased with the increase of die surface angle.
- The punch force decreased until the die shoulder radius value became 8mm, then with the increases after this value, the punch force increased.
- As the punch nose radius increased, the punch force also increased.
- The punch force increased until the chamber pressure reached 8 MPa, but it decreased when the chamber pressure increased above 8 MPa value.
- While the blank holder force (FBH) was 9507.64 N, the punch force dropped to the minimum value.

Authors' Contributions

HB and VS designed the structure. HB fabricated the die, carried out the experiments work, the theoretical calculations, in collaboration with VS and ÇÖ, and wrote up the article. ÇÖ conducted the statistical studies. Numerical analysis studies were carried out by HB. All three authors have read and approved the article.

Competing Interests

The authors declare that they have no competing interests.

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