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Process parameters selection in manufacturing of sharp conical parts based on Taguchi design of experiments

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Abstract. Among the sheet metal forming processes, hydrodynamics deep drawing and hydromechanical deep drawing process are two main types of the deep drawing process that can fabricate complicated parts. In the hydroforming process, the blank is formed to the desired shape by applying a considerably high hydraulic pressure. In this article, the selection of the process parameters will be investigated during the manufacturing of a pure copper sharp conical part by finite element analysis and experimental tests. Two finite element models are developed for hydrodynamics deep drawing and hydromechanical deep drawing processes. After verification of the FE model by experimental results, the effect of process parameters includes the applied pressure, friction coefficient, die radius and blank holder force on thinning of the blank are investigated. The thinning ratio of blank is calculated in different zones of the conical part under different working conditions determined according to the Taguchi design of experiment methods. Signal to noise ratio analysis has been carried out and the influence of process parameters on the thinning ratio is determined at different zones of the conical part. The results show that the friction coefficient has an important role in the thinning of the conical nose while at the lateral surface of the cone, the die radius is the most effective parameter on the thinning ratio. The results show that by implementing statistical tools (Taguchi method and signal to noise ratio analysis), it is possible to select the proper process parameters conditions and fabricate defect-free parts. In addition, a non-linear regression equation is developed for prediction of thinning ratio in the hydrodynamics deep drawing and hydromechanical deep drawing processes.

Keywords. Hydrodynamic deep-drawing; hydromechanical deep-drawing; sharp conical part; deep-drawing; sheet metal forming.

1. Introduction

A deep drawing of conical shapes has noticeably more challenges than the deep drawing of cylindrical cups. Manufacturing of conical shapes with conventional forming methods is accompanied with many problems because of the small contact area of the punch tip with the blank at initial steps of forming. This leads to high stresses in this area of the formed conical part and consequently bursting in the sheet. In addition, forming conical cups with conventional deep drawing processes leads to wrinkling on the workpiece walls because the blank is free between the punch and the die. Hence, the conical parts are usually formed by a multi-step deep drawing process [1], the spinning process [2] or explosive forming [3]. The limiting drawing ratio (LDR) is defined as the ratio of the initial blank diameter to the workpiece diameter. The LDR depends on material property, thickness, and geometry. In the multi-step deep drawing of conical components, small limiting drawing ratios (LDR) are available in each step due to high radial tensile stresses. In addition, the ratio of sheet thickness to the initial diameter of the blank has a greater influence on the limiting drawing ratio (LDR) in comparison to the drawing of the cylindrical parts. The limiting drawing ratio (LDR) also depends on the angle of the cone and the ratio of the largest to the smallest diameter of the cone.

Khandeparkar and Liewald [4] studied the manufacturing of complex stepped conical parts by the hydromechanical deep drawing process. The results show that the initially applied pressure has a considerable effect on the drawing ratio and quality of the manufactured parts. High pressures at the beginning of the drawing process are counterproductive. The counter pressure should be selected so that the blank is wrapped around the punch profile with the least bulge formation in the unsupported zone. Hashemi *et al* [5] studied the effects of material properties and initial sheet thickness on the forming and thinning of the conical part by the hydromechanical deep drawing process. The results show that a more uniform thickness distribution will be obtained for thinner sheets. Also, the forming of conical

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parts by hydrodynamic deep drawing process has been studied in a similar article by Hashemi *et al* [6]. The study is carried out on single and bilayer sheets of St14 steel and AA 1050 aluminum alloy materials. The results show that higher drawing ratio and lower geometrical limitations can be obtained for the Aluminum/Steel bilayer blank in comparison with the single-layer aluminum blank. Also, the formability improves when the steel layer is at the outer side. Dong *et al* [7] studied the manufacturing of conical parts (with half cone angle equals to 15°) from AA7075 aluminum alloy at 250 °C temperature and in one step. They used a non-metallic solid granules medium to transfer the pressure to the initial blank. In the preceding researches [4–7] the bottom of the conical part is flat and is not sharp.

The hydroforming process generates a growing interest in the automotive, aerospace and gas industries. The hydroforming technology has several advantages over the conventional sheet metal forming processes, such as improving the sheet formability, better surface quality, higher dimensional accuracy, less spring-back and the possibility of forming complicated shapes [8–12]. In recent years, many innovative methods of hydroforming have been proposed such as hydromechanical deep drawing and hydrodynamic deep drawing. In the hydromechanical deep drawing process, the punch deforms the blank to its final shape by moving against a fluid under controlled pressure. The blank is held between the blank holder and the die. A pressure chamber is attached to the lower die in which the fluid is injected so that the blank contacts the punch prior to drawing and causes a bulge up the blank which is called pre -bulging. In hydrodynamic deep drawing, a punch with the desired shape forces the blank into the die cavity with pressurized liquid and however the blank is formed around the punch. The frictional force between the blank and the punch allows using higher pressures and consequently stress concentration is reduced on the blank at the punch tip area and the formability will be improved. During the last decade, a few numbers of researches have been conducted in the forming of conical parts by hydroforming techniques. Kawka *et al* [13] studied the finite element simulation of wrinkling in deep drawing of conical cups. Their results proved that the element type and the number of meshes are very effective on numerical results even for minor changes. Thiruvarudchelvan and Tan [14] proposed a new method for forming conical cups in the conventional deep drawing by an annular urethane pad. In their method, the urethane pad prevents the contact of the punch tip and blank surface and delays the rupture of the blank in the forming process. Lang *et al* [15] investigated the effect of calibration step on the amount of forming for conical cups in sheet hydroforming process. Their results proved that suitable calibration can prevent the fracture and reduce the wrinkling. Gorji *et al* [16] studied the hydrodynamic deep drawing of conical– cylindrical cups. They investigated various pressure paths and studied the effect of those paths on thickness distribution and drawing ratio of the hydroformed specimens. Wang *et al* [17] investigated the effect of the hydrodynamic deep drawing process parameters in the fabrication of a conical box with double concave features. By developing an analytical solution and verified experimental measurements, the thinning and formability of the part were explored. Yaghoubi *et al* [18, 19] studied the manufacturing of conical parts by hydrodynamic deep drawing method. The pressure path was predicted by training a neural network according to the data of the finite element model and uniform thickness can be obtained by optimizing the pressure path.

As it was seen in the literature review, there is not a comprehensive report on hydromechanical and hydrodynamic deep drawing process of conically shaped parts with the investigation of the effects of process parameters on thickness distribution of hydroformed specimens. In this article, the effect of process parameters includes applied pressure, friction coefficient, die radius and blank holder force on thinning of blank will be investigated. A finite element model is developed for process investigation. After verification of the FE model by experimental results, the thinning of blank was investigated in different zones of the conical part. A plan for implementing the experiments have been extracted according to the Taguchi method. A signal to noise ratio analysis had been done and the influence of process parameters on the thinning is determined at different zones of the conical part.

2. Material and methods

In this section, firstly the process specifications will be introduced, then the developed finite element model will be presented. At last, the design of experiments (DOE) will be explained.

2.1 *Problem definition and material properties*

A conical part with 60° half angle selected for fabrication by deep drawing. Figure 1 shows the schematic diagram of the part and dimensions of deep drawing die and the experimental test set-up for the hydrodynamic deep drawing process. The initial blank is a circle with 70 mm diameter and 2 mm thickness from pure copper Cu 99.9%. Table 1 shows the material properties of the initial blank which was obtained from the tensile test by the authors and the sheet supplier. The initial yield strength of the sample is 123 MPa. Table 2 shows the dimensions of punch, die, blank holder and the initial blank.

2.2 *Finite element modeling*

A finite element model has been developed for a detail investigation of the drawing process. Abaqus finite element

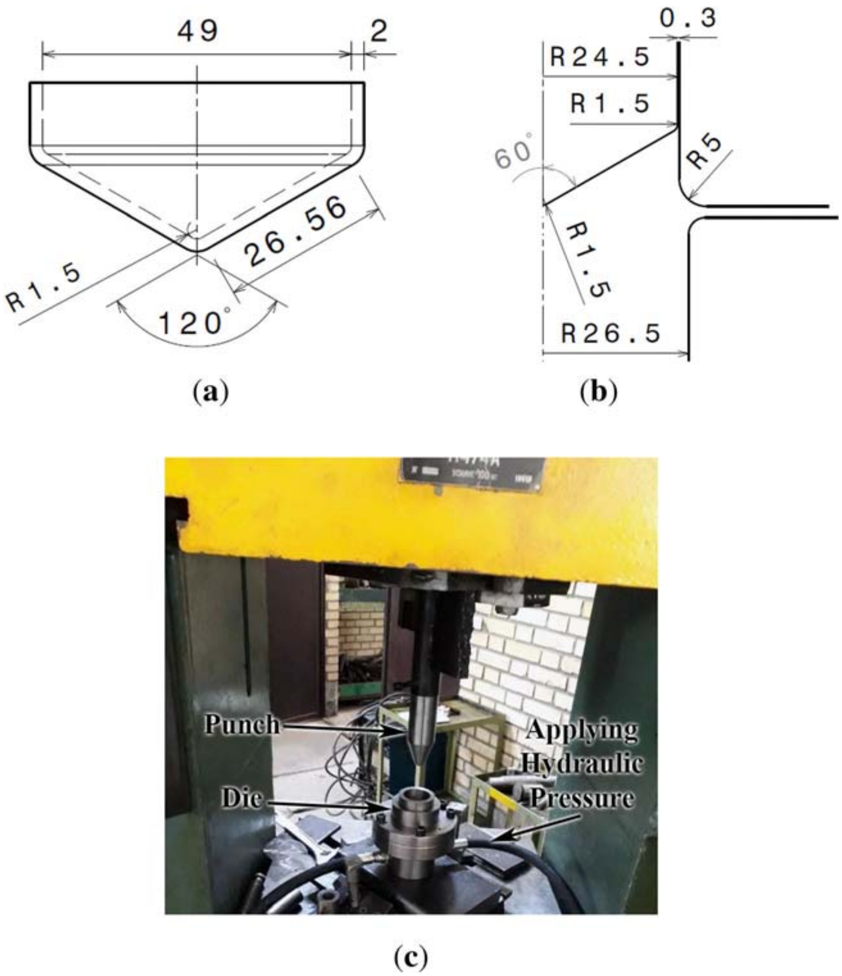

Figure 1. (a) The conical part of study, (b) schematic of the designed die and (c) the die set-up and hydraulic press used in the experimental tests.

Table 1. Material properties of Cu 99.9%.

Properties	Value
Elastic modulus (GPa)	114
Yield strength (MPa)	123
Poisson's ratio	0.32
Strength coefficient K (MPa)	531
Strain hardening exponent n	0.44
Density (kg/m^3)	8940
Normal anisotropy	1

Table 2. The dimensions of the die, punch, blank holder and initial blank.

Die parameters	Value
Punch diameter (mm)	49
Punch nose radius (mm)	1.5
Inside die diameter (mm)	49.6
Clearance (mm)	0.3
Punch half-angle (°)	60
Inside diameter of the blank holder (mm)	50
Blank holder entrance radius (mm)	5
Blank diameter (mm)	70
Blank thickness (mm)	2

code has been used for modeling. The punch, die, holder and blank are modeled based on the details of figure 1. The punch, die and the blank holder is assumed as rigid elements and the blank is deformable with material properties similar to table 1. The analysis has been done by Abaqus Explicit solver with nonlinear geometry deformation. The blank meshed by the CAX4R element type, which is a four-node bilinear axisymmetric quadrilateral element and reduced integration formulation. A mesh sensitivity analysis had been done and the suitable mesh size is selected for the FE model. The friction coefficient is an influencing parameter in the forming processes. The friction coefficient is assumed as 0.05 between the blank and blank holder and also between the blank and die. The value of 0.05 friction coefficient is selected according to hard

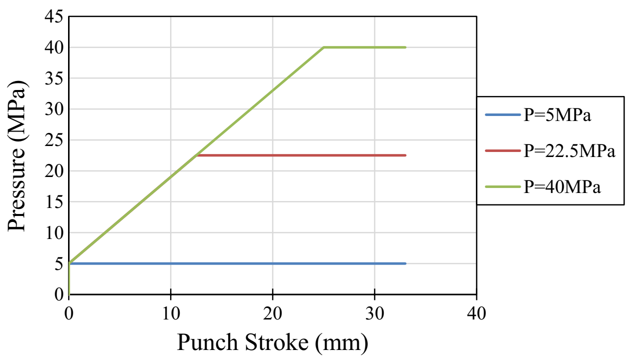

Figure 2. The applied internal pressure in the die set.

contact of the surfaces at room temperature [20]. The friction coefficient between the punch and blank is selected as a parameter of DOE and has three levels of variation (0.08, 0.14 and 0.2). The applied pressure in the die set varies according to the equation (1).

$$P = \begin{cases} P_0 + 1.4 \times S & P < P_{max} \\ P_{max} & P \geq P_{max} \end{cases} \quad (1)$$

where P_0 is initial pressure in the die (5 MPa) and P_{max} is the final pressure (MPa) applied to the die according to the DOE level. S is the punch stroke (mm). The pressure in the die set increases to initial pressure P_0 before moving the punch. Figure 2 shows the pressure distribution during the punch movement. In addition, the blank holder force is 3000 N during the hydromechanical deep drawing.

Table 3. Hydrodynamic deep drawing process parameters and selected levels.

Process parameter		Level 1	Level 2	Level 3
P	Pressure (MPa)	5	22.5	40
FC	Friction Coefficient	0.08	0.14	0.2
R	Die radius (mm)	3	4	5

Table 4. Hydromechanical deep drawing process parameters and selected levels.

Process parameter		Level 1	Level 2	Level 3
P	Pressure (MPa)	5	22.5	40
FC	Friction coefficient	0.08	0.14	0.2
F	Blank holder force (kN)	20	25	30
R	Die radius (mm)	3	4	5

Table 5. DOE of the hydrodynamic deep drawing process.

Exp. no.	P	FC	R
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

(P, FC and R are grouped under the heading "Process parameter".)

2.3 *Design of experiments*

After verification of the finite element model, the stress and strain distribution and thickness variation are investigated through the process parameters. The process parameters of the hydrodynamic deep drawing are shown in table 3. Three levels are selected for investigation. The levels are selected according to the experiences obtained by the authors in pre-tests of manufacturing the conical part and also the articles published by the researchers. The value of the friction coefficient is determined according to the contact constraints (hard vs soft contact) along with the blank holder. Higher friction coefficients result in thinner cups and the forming force will be increased. Wrinkling will be reduced but the probability of failure will be increased in general. Table 4 shows the process parameters

Table 6. DOE of the hydromechanical deep drawing process.

Exp. no.	P	FC	F	R
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

(P, FC, F and R are grouped under the heading "Process parameter".)

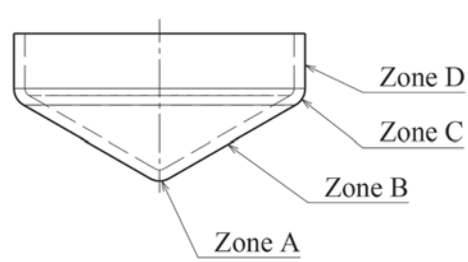

Figure 3. Four defined zones of conical parts.

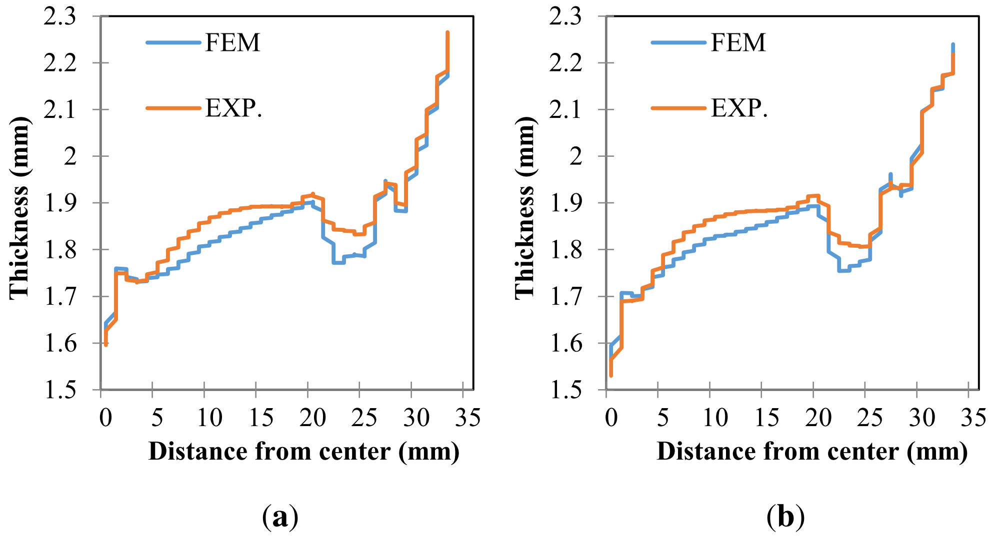

Figure 4. Comparison of thickness for (a) hydrodynamic deep drawing process for P = 5 MPa, FC = 0.08, and R = 3 mm, (b) hydromechanical deep drawing process for P = 5 MPa, FC = 0.08, R = 3 mm, and F = 20 kN.

Table 7. The thinning ratio in different zones of the workpiece obtained by the hydrodynamic deep drawing process.

	The thinning ratio in different zones			
Exp. no.	A	B	C	D
1	0.20060	0.134063	0.099942	0.0798673
2	0.20235	0.134954	0.083807	0.0566298
3	0.19525	0.132119	0.075810	0.0417547
4	0.19670	0.129361	0.098978	0.0545573
5	0.19895	0.130619	0.097738	0.0400020
6	0.19150	0.128226	0.099538	0.0797100
7	0.19725	0.130347	0.113365	0.0565998
8	0.19945	0.131633	0.115487	0.0883037
9	0.19110	0.128999	0.112620	0.0683707

of the hydromechanical deep drawing process and the selected levels of investigation.

The subject of this article is the investigation of process parameters in order of manufacturing the parts by minimum thickness variation (thinning). The thinning ratio can be defined as equation (2).

$$thinning\ ratio = \frac{t_0 - t_f}{t_0} \tag{2}$$

where t_0 is the initial thickness (mm) and t_f is the final thickness (mm). The drawing process included controllable parameters and uncontrollable parameters. The aim of the study is minimizing unwanted effects and producing good quality parts. The Taguchi design of experiments can prepare

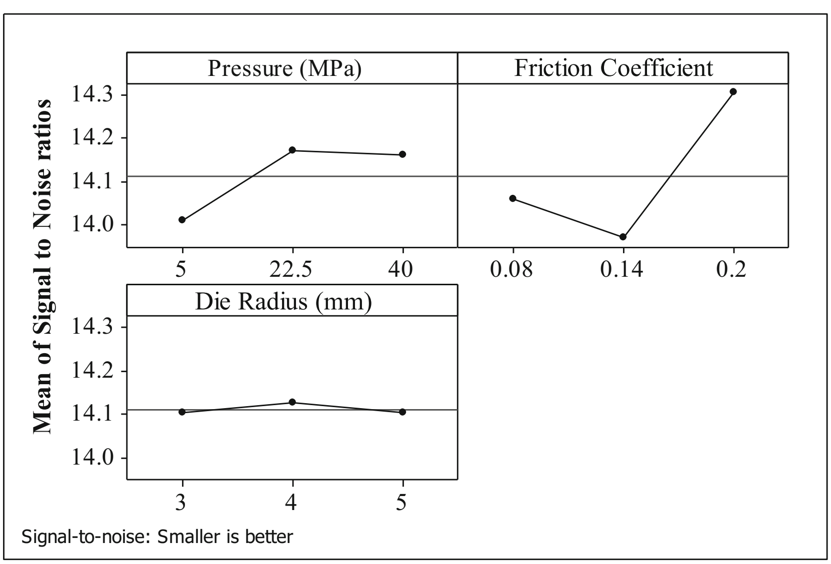

Figure 5. Signal to Noise ratio of thinning ratio at zone A in the hydrodynamic deep drawing process.

Table 8. Order of process parameters influences in the hydrodynamic deep drawing process.

	Rank #1	Rank #2	Rank #3
Zone A	Friction coefficient	Pressure	Die radius
	Level 3	Level 2	Level 2
Zone B	Pressure	Friction coefficient	Die radius
	Level 2	Level 3	Level 3
Zone C	Pressure	Die radius	Friction coefficient
	Level 1	Level 3	Level 3
Zone D	Die radius	Pressure	Friction coefficient
	Level 3	Level 2	Level 2

the objective of the study. Tables 5 and 6 show the Taguchi design of experiments array (L9 array) for hydrodynamic and hydromechanical deep drawing process, respectively.

For the investigation of the process parameters, the part is divided into four different zones. The zones are shown in figure 3. Zone A is at the pointed tip of the conical part, zone B is the inclined wall zone, zone C is the lateral fillet zone and zone D is the straight sidewall of the part. The thickness of the formed conical part is measured after completing the run of FEM software. According to equation (2), the thinning is calculated in different zones of the part. Thinning is an unwelcome phenomenon in metal forming. It is desired to be as small as possible. So, the signal to noise (S/N) ratio is

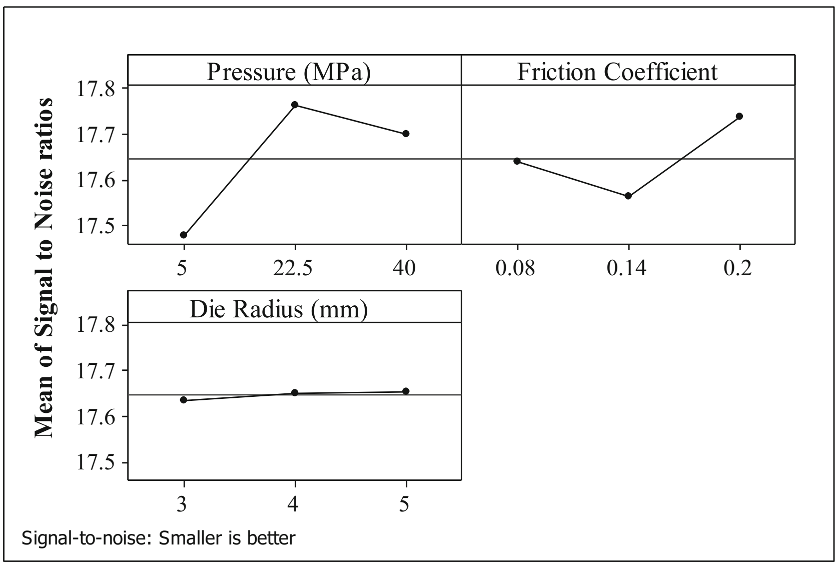

Figure 6. Signal to Noise ratio of thinning ratio at zone B in the hydrodynamic deep drawing process.

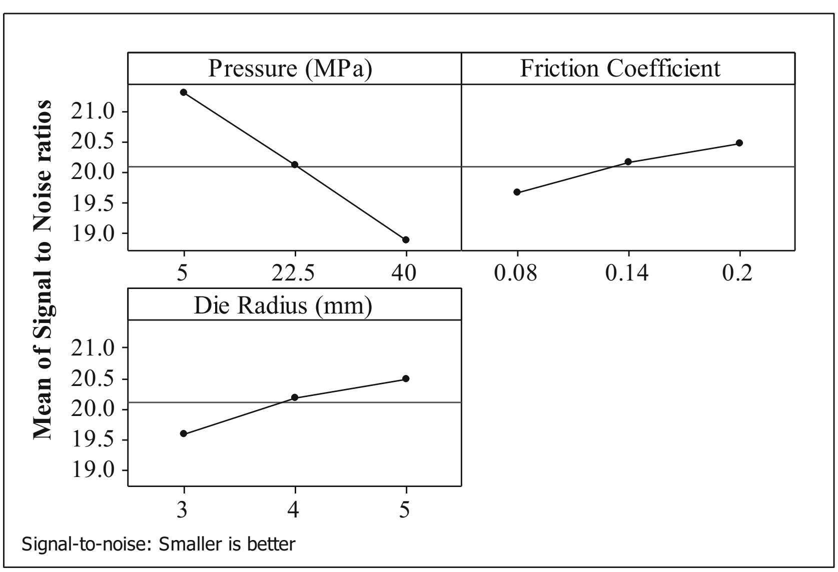

Figure 7. Signal to Noise ratio of thinning ratio at zone C in the hydrodynamic deep drawing process.

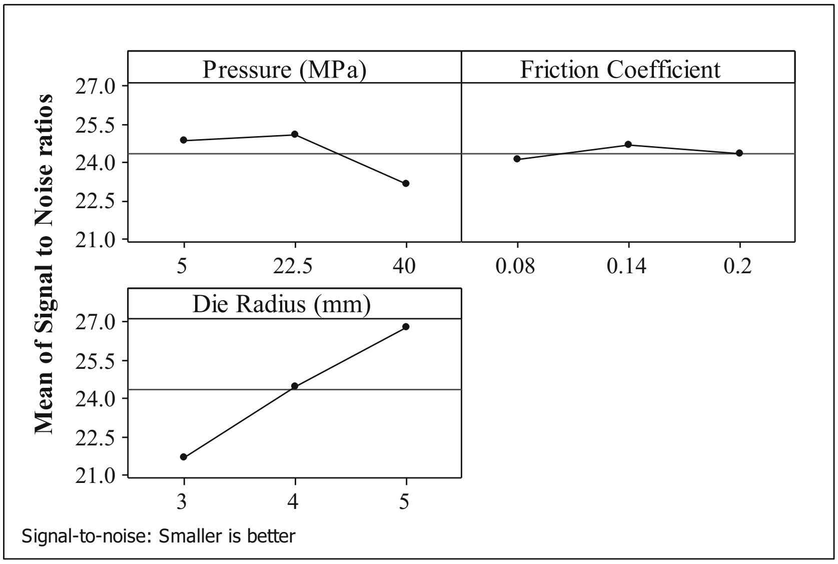

Figure 8. Signal to Noise ratio of thinning ratio at zone D in the hydrodynamic deep drawing process.

Table 9. The thinning ratio in different zones of the workpiece obtained by the hydromechanical deep drawing process.

	The thinning ratio in different zones			
Exp. no.	A	B	C	D
1	0.23150	0.161658	0.109014	0.0829439
2	0.23505	0.163917	0.097131	0.0578693
3	0.22615	0.160857	0.092330	0.0372531
4	0.22415	0.156017	0.121112	0.0362026
5	0.23130	0.161259	0.124707	0.0774894
6	0.21820	0.154056	0.122937	0.0540442
7	0.22725	0.158291	0.136956	0.0748335
8	0.22660	0.157494	0.135433	0.0598349
9	0.21905	0.155200	0.146396	0.0931079

calculated in different zones of the part and the proper level of parameters are determined such that minimum thinning is desired. The signal to noise (S/N) ratio is calculated according to “small is better” condition (equation (3)). The signal to noise ratio determines the variation of a single parameter on the output (thinning ratio) regardless of the effects of other input process parameters.

$$S/N\ ratio = -10\log_{10}\left(\frac{\sum y^2}{n}\right) \tag{3}$$

3. Results and discussion

In this section, firstly, the verification of the finite element model will be presented, then the process parameter influence on thinning will be carried out and at last, the proper process parameters will be found by S/N ratio analysis.

3.1 *FE model verification*

Figure 4 shows the comparison of thickness obtained from finite element analysis and experimental measurement for hydrodynamic deep drawing and hydromechanical deep drawing process. The initial thickness of the blank was 2 mm. The process parameters in the experimental tests are selected according to the Exp. No. 1 of tables 5 and 6 for both manufacturing processes (P = 5 MPa, FC = 0.08, R = 3 mm, and F = 20 kN). Minimum thickness in the produced part happens at the head of the conical part and zone A, B, and C will experience thinning in both processes. Thickness at the head is 1.618 and 1.563 mm for hydrodynamic deep drawing and hydromechanical deep drawing process, respectively. A comparison of finite element results and experimental results show good agreement and accuracy of the numerical model. Also, the ratio of kinetic energy to internal energy is checked to be lower than 0.05 in an explicit solution.

3.2 *Main effects of hydrodynamic process*

Table 7 shows the results of the thinning ratio for the hydrodynamic deep drawing processes. The thickness in different zones of the workpiece is measured and the thinning ratio is calculated along the radial distance. The average of thinning ratio in each zone is calculated and reported in table 7.

Signal to noise ratio (S/N) is calculated for the results of designed experiments. Figures 5–8 show the signal to noise ratio for the different zone of the conical part. Also, table 8 shows the order of influence for process parameters in the hydromechanical deep drawing process. Also, the proper level of each parameter is determined according to the S/N ratio analysis. The most important parameter on thinning of the conical nose (zone A) is friction coefficient, while it has a negligible effect in zone C and zone D. Pressure is always one of the important parameters of thinning (rank #1 or rank #2 in all zones). The amount of die radius has the highest effect on thinning in zone D. The results of table 8 show that proper condition for fabricating the conical part is pressure 22.5 MPa (level 2), friction coefficient 0.2 (level 3) and die radius 5 mm (level 3).

As it is seen from figures 5 and 6, with an increase in the pressure the thinning of the formed sheet is decreased due to a more sticking phenomenon between sheet and punch. In this condition, the punch supports the sheet and the thinning is decreased at zones A and B. Also, it is concluded from figures 5 and 6 that with increasing the friction coefficient to a certain value, the thinning of the sheet increases due to increased frictional forces at zones A and B. However, if the friction coefficient increases to a high value, the sheet thinning is reduced due to the increase in the sticking phenomenon between sheet and punch. In addition, it is shown from figures 5 and 6 that die radius changes have not an important effect on the sheet thinning at zones A and B due to sticking of the sheet to punch at the first moments of the process. From figure 7, it is concluded that with increasing the pressure, the thinning ratio of the sheet is increased. The reason is that in zone C, due to the presence of tensile strains, increasing the pressure leads to increasing those tensile strains and consequently the thickness of the formed sheet is decreased. However, it is seen from figure 7 that with an increase in the friction coefficient, thickness reduction decreased due to an increase in the sticking phenomenon between sheet and punch. In addition, an increase in the die radius leads to decreasing the thinning ratio of the sheet due to an increase in the length of the deformation area and consequently decreasing the tensile stresses. From figure 8, it is concluded that increasing the pressure leads to a decrease in the thinning of the sheet. This is because of the increase in the sticking of zones A, B, and C to the punch surface and accumulation of the material flow in the vertical wall (zone D). For the same reason, changes in the friction coefficient are negligible. Also, with increasing the die radius the thinning ratio of the formed sheet is decreased due to increasing in the length of the deformation area and consequently decreasing the tensile stresses.

3.3 *Main effects of hydromechanical process*

The results of the thinning ratio at different zones of the deep-drawn workpiece are calculated and the average of thinning ratio is reported in table 9.

Figures 9–12 show the signal to noise ratio for the different zone of the conical part fabricated by the hydromechanical deep drawing process. The data of the S/N ratio in different zones are summarized in table 10. The S/N ratio analysis of experiments can determine the prompting parameters and their suitable level in the hydromechanical deep drawing process. Similar to hydrodynamic deep drawing, the most important parameter on thinning of the conical nose (zone A) is friction coefficient, while it has a negligible effect in zone C and zone D. Pressure is one of the significant parameters of thinning (rank #1 or rank #2 in all zones). The amount of die radius has maximum effect on thinning in zone D. The blank holder force has little effect on the thinning ratio but it cannot be eliminated from the process (prevention of the buckling or wrinkling). The main point is the existence of the blank holder force not the

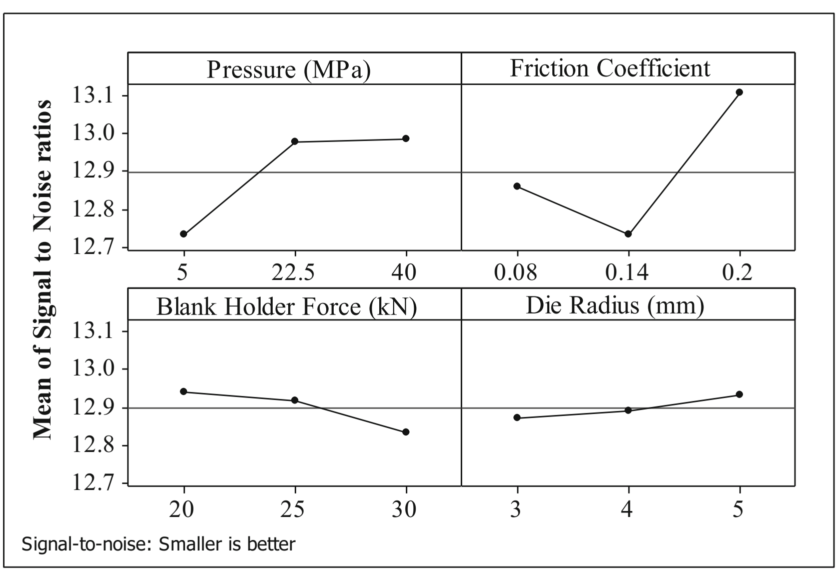

Figure 9. Signal to Noise ratio of thinning ratio at zone A in the hydromechanical deep drawing process.

magnitude of it. The proper condition for fabricating the conical part can be selected according to the results of table 10 as pressure 40 MPa (level 3), friction coefficient 0.2 (level 3), blank holder force 20 kN and die radius 5 mm (level 3).

From figures 9–12, the behaviors of the pressure, friction coefficient and die radius on thinning of the deformed sheet are similar between hydrodynamic and hydromechanical deep drawing processes which were explained previously. By increasing the blank holder force the thinning at zones A and B is increased due to decreasing the material flow. Also, with increasing the blank holder force the thinning of the sheet is not changed considerably due to the sticking of zones A and B to the punch surface and accumulation of the material flow. In other words, with increasing the material flow in the sheet wall not only the thinning is decreased but the wrinkling of the sheet is also decreased.

It should be noted that the attitude of the article is developing the use of a statistical tool as the signal to noise ratio to determine the finest condition for the manufacturing process. So, the target is finding the proper condition for the fabrication of a sharp conical part regardless of the reasons for the observed behavior. The Taguchi design of

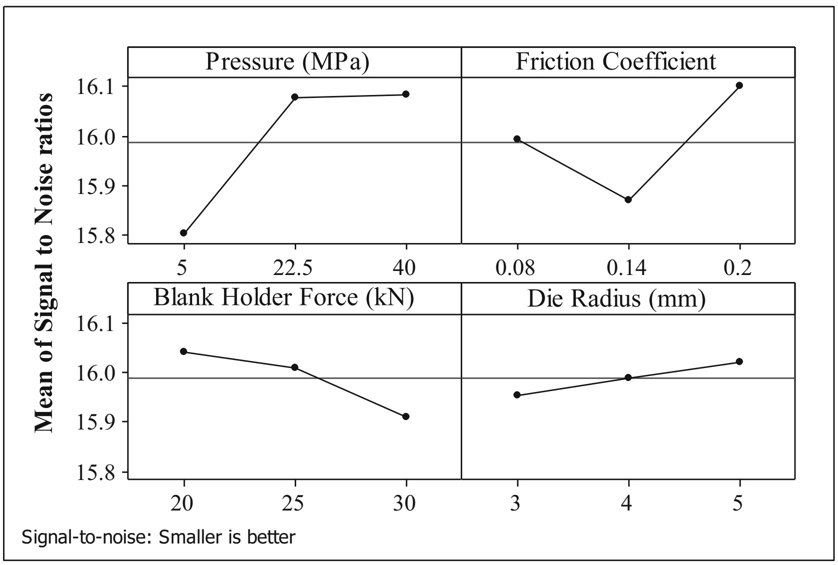

Figure 10. Signal to Noise ratio of thinning ratio at zone B in the hydromechanical deep drawing process.

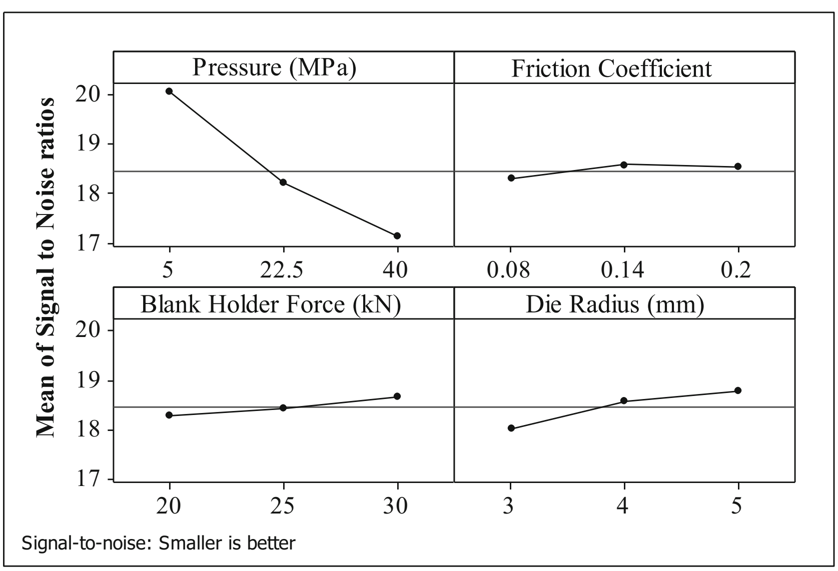

Figure 11. Signal to Noise ratio of thinning ratio at zone C in the hydromechanical deep drawing process.

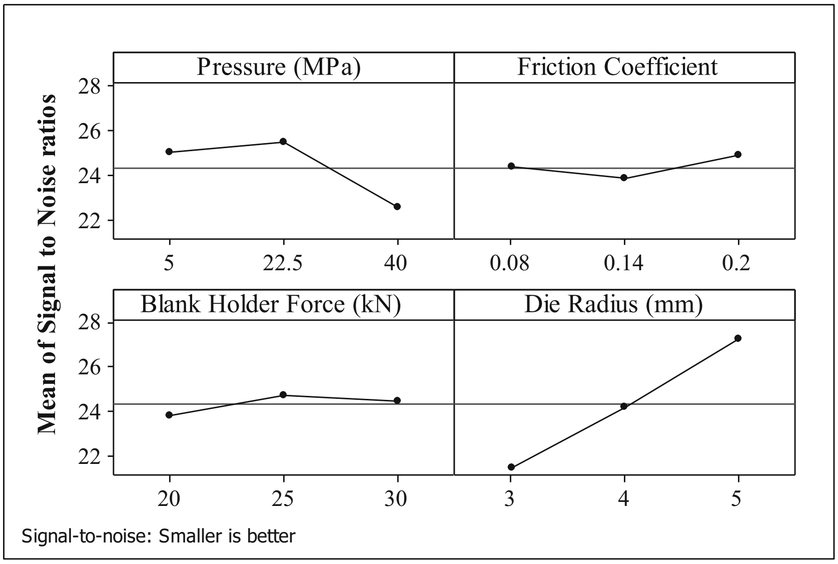

Figure 12. Signal to Noise ratio of thinning ratio at zone D in the hydromechanical deep drawing process.

experiments method is used because it can reduce the effect of uncontrollable input process parameters to minimize the variation of the output parameter (in this article, the thinning ratio).

3.4 *Non-linear regression (NLR)*

The thinning ratio can be estimated by non-linear regression (NLR). The basic formula of prediction selected as equations (4) and (5) for hydrodynamic and hydromechanical deep drawing processes, respectively.

$$thinning\ ratio = \alpha_0 + (1 + \alpha_1 P)(1 + \alpha_2 FC)(1 + \alpha_3 R) \quad (4)$$

$$thinning\ ratio = \alpha_0 + (1 + \alpha_1 P)(1 + \alpha_2 FC)(1 + \alpha_3 F)(1 + \alpha_4 R) \quad (5)$$

The regression equations had calculated at different zones of the conical part. Equation (6) and equation (7) show the non-linear regression for hydrodynamic and hydromechanical deep drawing process respectively. The Mean Square Error (MSE) used for assessment of fitting quality. Table 11 shows the MSE results of non-linear

Table 10. The order of process parameters influences the hydromechanical deep drawing process.

	Rank #1	Rank #2	Rank #3	Rank #4
Zone A	Friction coefficient Level 3	Pressure Level 3	Blank holder force Level 1	Die radius Level 3
Zone B	Pressure Level 3	Friction coefficient Level 3	Blank holder force Level 1	Die radius Level 3
Zone C	Pressure Level 1	Die radius Level 3	Blank holder force Level 3	Friction coefficient Level 2
Zone D	Die radius Level 3	Pressure Level 2	Friction coefficient Level 3	Blank holder force Level 2

Table 11. MSE calculated for NLR.

	Hydrodynamic deep drawing	Hydromechanical deep drawing
Zone A	0.0000110	0.0000268
Zone B	0.0000042	0.0000083
Zone C	0.0000170	0.0000123
Zone D	0.0000326	0.0000752

regression. The low value of MSE in table 11 demonstrates the good quality of curve fitting. It should be noted that the equations (6), (7) valid for the selected workpiece and material and can not be developed for other cases but the similar formula can be written by using finite element results and statistical tools. The mean square error can be used for the goodness of regression.

$$\begin{aligned}
&\text{Zone A} \quad \textit{thinning ratio} \\
&\quad = -0.7939 + (1 - 0.001742\ \mathrm{P})(1 - 0.002792 FC) \\
&\quad \times (1 - 1.372 \times 10^{-5} R) \\
&\text{Zone B} \quad \textit{thinning ratio} \\
&\quad = -0.8637 + (1 - 0.001695\ \mathrm{P})(1 - 0.0007406 FC) \\
&\quad \times (1 - 1.393 \times 10^{-4}\ \mathrm{R}) \\
&\text{Zone C} \quad \textit{thinning ratio} \\
&\quad = -0.9105 + (1 + 0.01388\ \mathrm{P})(1 - 0.003992\mathrm{FC}) \\
&\quad \times (1 - 0.004592\ \mathrm{R}) \\
&\text{Zone D} \quad \textit{thinning ratio} \\
&\quad = -0.9121 + (1 + 0.006042\ \mathrm{P})(1 - 0.0002717 FC) \\
&\quad \times (1 - 0.01804 R)
\end{aligned} \tag{6}$$

$$\begin{aligned}
&\text{Zone A} \quad \textit{thinning ratio} \\
&\quad = -0.7614 + (1 - 0.003321\ \mathrm{P})(1 - 0.003268 FC) \\
&\quad \times (1 + 0.001431\ \mathrm{F})(1 - 0.0008395 R) \\
&\text{Zone B} \quad \textit{thinning ratio} \\
&\quad = -0.8352 + (1 - 0.002578\ \mathrm{P})(1 - 0.0009798\ \mathrm{FC}) \\
&\quad \times (1 + 0.001213 F)(1 - 0.0006308 R) \\
&\text{Zone C} \quad \textit{thinning ratio} \\
&\quad = -0.9030 + (1 + 0.02039\ \mathrm{P})(1 - 0.0009364\ \mathrm{FC}) \\
&\quad \times (1 - 0.002231 F)(1 - 0.005076 R) \\
&\text{Zone D} \quad \textit{thinning ratio} \\
&\quad = -0.9071 + (1 + 0.008703\ \mathrm{P})(1 - 0.001790\ \mathrm{FC}) \\
&\quad \times (1 - 0.001373\ \mathrm{F})(1 - 0.01983 R)
\end{aligned} \tag{7}$$

4. Conclusions

In this article, the fabrication of the conical part by hydrodynamic and hydromechanical deep drawing process had been studied. The main parameters of processes are selected and three levels are selected according to the Taguchi method for experimentation. The main finding of the study can be listed as follows:

- The friction coefficient has the highest effect on thinning ratio in the pointed tip of the conical part (zone A) and the inclined wall zone (zone B) while it has a negligible effect in the lateral fillet zone (zone C) and the straight sidewall of the part (zone D).
- The applied pressure in the inclined wall zone (zone B) and in the lateral fillet zone (zone C) is the most influencing parameter but in the straight sidewall of the part (zone D), it is negligible.
- The die radius is important in the thinning ratio of the straight sidewall of the part (zone D).
- The blank holder force has little effect on the thinning ratio but it cannot be eliminated from the process.
- A non-linear regression equation was developed for the estimation and prediction of the thinning ratio in both hydrodynamic and hydromechanical deep drawing processes.

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