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Original Article

Numerical Investigation of Deep Drawing Process by Response Surface Methodology

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Abstract *- Deep drawing is used widely to manufacture objects out of sheet metal. Several geometric parameters can generate deep drawing products that are free of defects. The radius of the Punch corner, Clearance and radius of the die corner are the three parameters that have the biggest effects on deep drawing. The stress distribution of an SS 316 cylindrical cup was examined in this study while considering these parameters. The finite element simulation of this process is performed in ABAQUS software. FEM simulation using the isotropic hardening law was carried out. Response surface methodology is used to design experiments. When the outcomes of the FEA and the experiments were compared, they agreed well. The most influential parameters were identified by ANOVA analysis. The finding showed that the optimum parameter of the punch corner radius (PCR) should be 5.3 mm, the Die Corner Radius (DCR) should be 6.6 mm, and clearance should be 1.07 mm to minimize stress distribution.*

Keywords *- Deep drawing, Punch corner radius, Die corner radius, Response surface methodology, Stress distribution.*

1. Introduction

Deep drawing is a highly adaptable and popular metal forming technique that is vital in manufacturing a huge diversity of everyday items, including kitchenware, car parts, and even aerospace components. With astounding accuracy and efficiency, flat sheet metal is transformed using this specialized technology into three-dimensional shapes. It is a cold-forming process in which a metal blank is radially drawn into a forming die by the mechanical action of a punch, creating a part with significant depth and contour from a flat sheet. Deep drawing is a crucial procedure in contemporary manufacturing since it makes it possible to create intricate and complicated structures and provides extreme structural integrity and surface finish. The manufacturer is attracted to research in this process due to the huge volume, cheap cost, high productivity, high efficiency, and lightweight. Deep drawing process factors that impact the defects like creasing, thinning, and thickening during the process include blank holder force, size of blank and thickness of blank, radius of die and punch corner, friction coefficient and material properties. Individual researchers attempted to enhance the design parameters of this process using theory, research, computer modeling, and optimization to increase product quality by preventing flaws. In order to anticipate the uniform thickness distribution of AISI 304 steel, Bora Sener et al. [1] experimented to conclude that the Punch corner radius is crucial for achieving maximum thinning in both simulation and experiment. M.T. Browne et al. [2] evaluated the impact of geometry parameters on the punch load and uniformity in thickness. The result concluded that punch and die profiles highly impacted the punch load. In this process, H. Zein predicted geometry parameters and process operating parameters for the uniform thickness distribution on the workpiece. et.al. [3]. Dr Waleed Khalid Jawad et al. [4] experimented on a 100 KN Instron testing machine with a punch nose radius of (P=3,6,9,15,18, & 21.5 mm) and die radius considered constant at 6 mm. They achieved that the increase in punch radius from 3 mm to 21.5 mm cup height increases by 20 % in FE simulation and 18% in experiments, and the value of spring back to (1.75 % for FE Simulation and 1.25 % for experimental work). Masoud Mahmoodi et al. [5] worked on a double-layer sheet to forecast the maximum thinning affected by various input parameters. The result identified the connection between the input parameters and the Square cup's percentage thinning. Yanmin Xie et al. [6] developed an RBM-BPNN technique to enhance drawing process factors. The results indicate the best-optimized solution for the Blank Holder Force (BHF), friction coefficient, and punch and die radius for maximum thinning and percentage of thickened area. Atul et al. performed An Experiment on composite material to eliminate wrinkling, tearing, and thinning [7]. Simultaneously, Philippa M. Horton et al. [8] investigated the impact of punch and die radii and corners on the drawing depth failure criteria on aluminum

5251 with and without a blank holder. The author developed a novel micro-forming technique that considers a floating ring to avoid wrinkling. Ihsan and Zaid [9] studied the influence of punch nose radii, initial sheet thickness, and rubber height in this process, considering SS304 material. Liang Luo et al. [10] performed a test to determine the impact of the blank holder-die gap on the micro deep drawing using 50 µm SUS304 foils. Yusop and Abdullah[11] worked on ANSYS Explicit Dynamics software to predict material thinning when considering AA6061-T6 material. M. Gavas et al. [12] developed, produced and evaluated a new blank holder tool with spiral springs. Wang Wu-rong et al. [13] performed an experiment with two types of blank holders one is flat, and the second is a cone type used with variable BHF to avoid tearing & wrinkling in the workpiece. Comparing both flat and cone-type blank holders, the novel design cone-type blank holder gives a wrinkle-free product in FEM and validated by experiments. Soren Tommerup et al. [14] suggested an active system for governing the BHF in this process. Lucian Lazarescu et al. [15] developed variable BHF to predict its effect on drawing force & thickness distribution. L. Chen et.al. [16] worked on the forecasting of wrinkling occurring on the flange of a product by varying the gap of blank holder. Masoud Kardan et al. [17] used Abaqus/explicit software for the analysis of this process to Minimize residual stresses and validate with experiment. A novel blank holder tool with a segmental blank holder was developed by Minh Tien Tran et.al. [18] Various researchers have worked on blank holder force optimization and novel design in blank holder force to achieve defect free products from deep drawing process. But limited research work carried out by researchers based on Geometric parameters affecting stress distribution. Besides, Radius of punch corner & Die corner play a crucial role in success of this process and the excellence of final product by minimizing stress concentration with improved flow of material and enhanced tool life. By integrating a statistical technique based on the Response Surface Methodology and Finite Element Method, the objective of this inquiry is to ascertain the influence of geometric parameters on stress distribution. To execute the finite element analysis of this process, ABAQUS software is used.

2. Materials and Methods

In investigations, the Response Surface approach (RSM) was utilized to plan trials and ascertain how geometric parameters affected the characteristics of manufactured parts. By modeling and examining the links between input elements and response variables, RSM is a practical and methodical approach to improving processes and systems, ultimately leading to better product quality and efficiency. The von Mises stress is enjoyable in our inquiry since it falls under the best nominal category.

2.1. Design of Experiments

Three levels were considered for Punch Corner Radius (PCR), Die Corner Radius (DCR), and Clearance (CL). The central composite Design examined the impact of the three parameters demonstrated in Table 1. The Response Surface Methodology (RSM) frequently employs a Central Composite Design (CCD) experimental design style, as displayed in Table 2, to study and optimize systems or processes. When examining the response surface both in the center and at the borders of the design space, CCD is beneficial since it enables the evaluation of curvature and non-linearity in the connection between the input and output variables. RSM provides insights into the interaction between variables and their effects on responses. It also requires fewer experiments than traditional methods, reducing time and resources. The regression equation was used in the same way as Equation 1.

$$\text{Stress} = -32813 - 142\,PCR - 388\,DCR + 64840\,CL + 0.56\,PCR\times PCR + 5.80\,DCR\times DCR - 30144\,CL\times CL + 22.66\,PCR\times DCR - 16\,PCR\times CL + 163\,DCR\times CL \quad (1)$$

2.2. Finite Element Simulation

The objective of the present study is to use FEM modeling to determine how process variables affect the deformation behavior of 0.8 mm thick SS 316 sheet metal during deep drawing. SS 316 was selected due to its exceptional corrosion resistance, durability and mechanical properties.

Table 1. Selection level of different parameters

Parameters (mm)	Level		
	1	2	3
Punch Corner Radius	3.2	4	4.8
Die Corner Radius	4	5	6
Clearance	1.08	1.09	1.1

Table 2. Simulation run of parameters

Simulation No.	PCR (mm)	DCR (mm)	Clearance (mm)
1	3.2	6	1.1
2	3.2	4	1.08
3	4.8	6	1.08
4	4	5	1.09
5	4	5	1.09
6	4.8	4	1.1
7	4	3.367	1.09
8	4	5	1.09
9	5.3064	5	1.09
10	4	5	1.07367
11	4	5	1.09
12	2.6936	5	1.09
13	4	5	1.10633
14	4	6.633	1.09
15	4	5	1.09
16	3.2	4	1.1
17	3.2	6	1.08
18	4	5	1.09
19	4.8	6	1.1
20	4.8	4	1.08

It has diverse industrial, marine, medical, construction, architecture, and transportation applications. During FEM simulation, the isotropic hardening law is taken into account. Material behavior is defined by a power law relationship the same as Equation 2

$$\sigma = K\,\epsilon^{n} \qquad (2)$$

Where σ true stress in MPa, K strength coefficient in MPa, ϵ true strain, and n strain hardening exponent. The geometrical information from the deep drawing technique used to create the CADD model is displayed in Table 3. The material properties mentioned are demonstrated in Table 4. In the ABAQUS-based module, an axisymmetric CAD model was created with the necessary dimensions, as displayed in Table 3. By assigning distinct material properties to the SS 316 while accounting for its isotropic hardening behaviour defined by the power law, the material is created virtually in the ABAQUS environment. Figure 1.

Clearly illustrates the assembly of tooling components. The entire FEM simulation of this process was built in two distinct steps. While the blank holder and die are fixed during this stage, the punch was supplied velocity to distort the sheet into a cylindrical cup. The coefficient of friction defined between the contact surfaces is 0.05. The SS 316 was designated to create a solid homogenous section for deep drawing since the blank sheet was conceived as a deformable object. A three-dimensional C3D8R was used to mesh the blanks, and R3D4 was used to discretize discrete rigid pieces of tooling. The element type and characteristics involved for each part of the FEM model are provided in Table 5. The punch could only move vertically during simulation, and all other degrees of freedom were restricted. After that, the punch was given a velocity. Following mesh conversion, a mesh size of 1 mm was chosen since it was big enough to include all of the circular geometry's features. An analysis was run after creating identical boundary conditions, and the outcomes were compared with experiments. Fully confirmed FE model. A condition to have the least residual stresses in the process is achieved, and the ANOVA is considered to assess the result.

Table 3. Geometric parameters

No.	Geometric Parameters	Value in mm
1	Blank thickness	0.8
2	Diameter of Punch	64.4
3	Diameter of Die	66.16
4	Diameter of Blank	120

Table 4. Mechanical properties of BLANK

No.	Mechanical Parameters	Value	Unit
1	Density	7850	Kg/m^3
2	Modulus of Elasticity	193000	MPa
3	Poisson's Ratio	0.275	NA
4	Yield strength	313	MPa

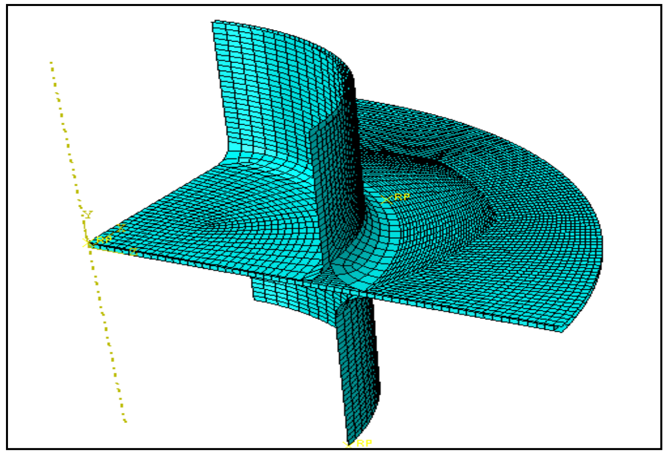

Fig. 1 Finite element model of deep drawing tool

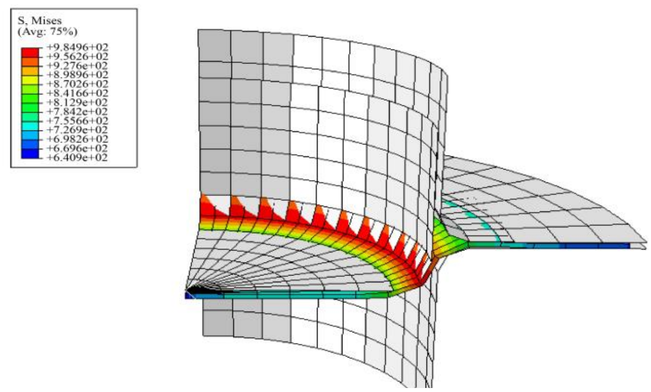

Fig. 2 Von mises stress for simulation no. 20

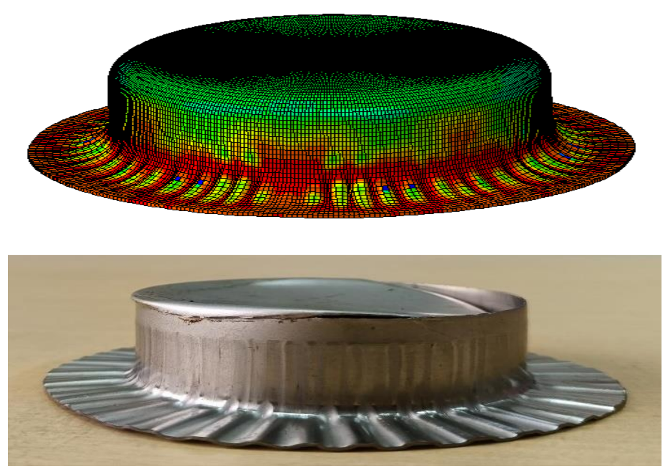

Fig. 3 FEM Vs Experimental cylindrical cup formation

3. Experimental Setup

The deep drawing process was performed on the universal testing machine of 1000 KN, which was fully computer controlled, as shown in Figure 6. The experimental set up prepared by punch and die is represented in Figure 5. Various sets of punch and die are used for experiments, as shown in Figure 4.

Fig. 4 Punch and die set

Fig. 5 Experimental set up on universal testing machine

Fig. 6 Universal testing machine

4. Results and Discussion

In ABAQUS/explicit, the experiments were simulated, as displayed in Table 2. The outcome of the von Mises stress is demonstrated in Figure 2. For the simulation no. 20. In Table 6. The von mises stresses from the FE simulation were presented. The Cylinder cup was obtained after experiments, as displayed in Figure 3. Shows that there is a good correlation between the FEM results and experimental outcomes. As a result, it is confirmed that the current FE model works well for measuring residual stress in the deep-drawing process.

4.1. Effect of DCR, PCR, and CL on Stresses

The Analysis of Variance is anticipated to help establish the most crucial parameters that minimize the von misses stress. Table 7 demonstrates the outcomes of the variance analysis, considering the von Mises stress. As displayed in Figure 4. The Contour plot represents an increase in the punch corner radius, and an increase in the radius of the die corner decreases the stress intensity considering clearance value 1.09.

Table 5. Detail of FEM model with element type

No.	Name of Component	Element type	Characteristics
1	Punch	R3D4	A 4-node 3-D bilinear rigid quadrilateral
2	Die	R3D4	A 4-node 3-D bilinear rigid quadrilateral
3	Blank Holder	R3D4	A 4-node 3-D bilinear rigid quadrilateral
4	Blank	C3D8R	An 8-node linear brick reduced

Table 6. Von mises stresses from FE Simulation

Simulation No.	Von mises stress (Mpa)
1	915
2	1076
3	893
4	968
5	968
6	979
7	1096
8	968
9	915
10	974
11	968
12	1044
13	967
14	892
15	968
16	1072
17	913
18	968
19	895
20	984

While considering the radius of the Die Corner, 5 mm increases the radius of the punch corner and decreases the stress value, as detailed in Figure 5. Considering the radius of the punch corner 4 mm, increasing the radius of the die corner decreases the stress value, as displayed in Figure 6. It is possible to state that the Die corner radius significantly influences von Mises stress. This research study reduces the trial and error method for producing deep-drawn cups.

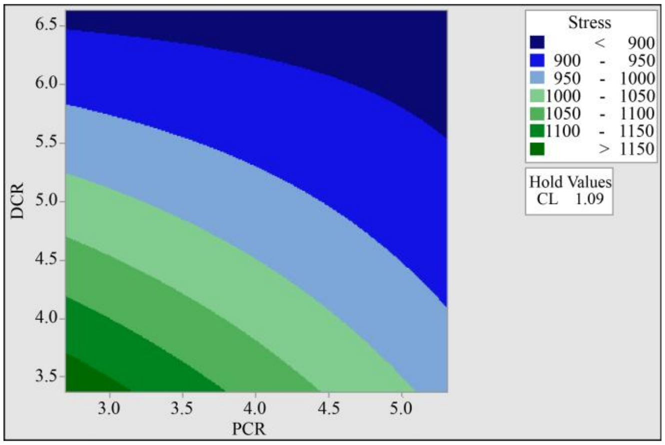

Fig. 4 Contour plot of stress vs DCR, PCR

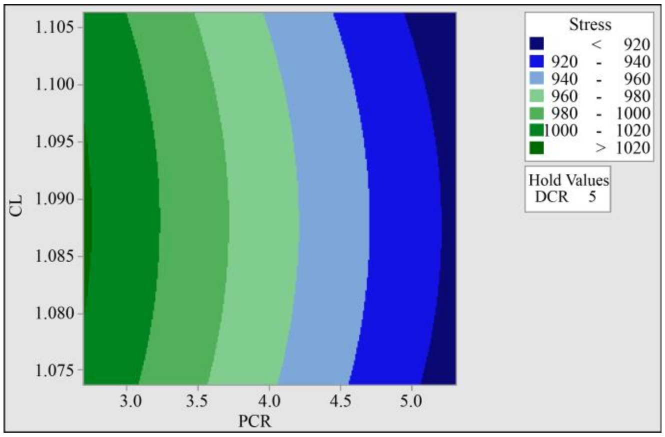

Fig. 5 Contour plot of stress vs CL, PCR

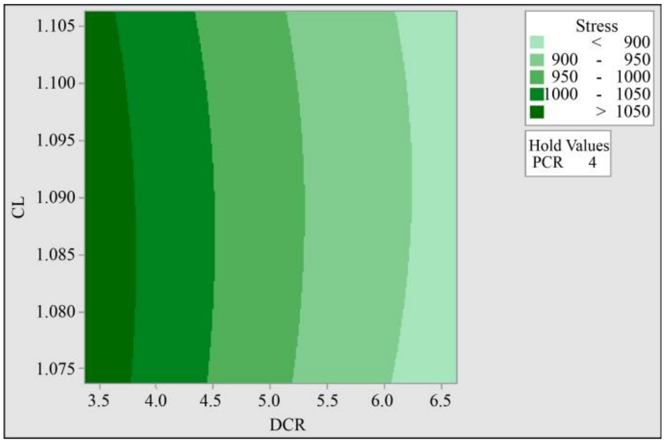

Fig. 6 Contour Plot of stress vs CL, DCR

Table 7. ANOVA for (von misses) stresses

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	11	69565.5	6324.1	76.30	0.000
Blocks	2	625.7	312.9	3.77	0.070
Linear	3	65690.0	21896.7	264.20	0.000
PCR	1	14234.7	14234.7	171.75	0.000
DCR	1	51435.0	51435.0	620.59	0.000
CL	1	20.2	20.2	0.24	0.634
Square	3	600.4	200.1	2.41	0.142
PCR*PCR	1	1.7	1.7	0.02	0.889
DCR*DCR	1	444.0	444.0	5.36	0.049
CL*CL	1	120.0	120.0	1.45	0.263
2-Way Interaction	3	2649.4	883.1	10.66	0.004
PCR*DCR	1	2628.1	2628.1	31.71	0.000
PCR*CL	1	0.1	0.1	0.00	0.970
DCR*CL	1	21.1	21.1	0.25	0.627
Error	8	663.0	82.9		
Lack-of-Fit	5	663.0	132.6	*	*
Pure Error	3	0.0	0.0		
Total	19	70228.6			

Table 8. Optimum solution

Solution	PCR	DCR	CL	Stress Fit	Composite Desirability
1	5.3064	6.633	1.07367	868.242	1
2	5.3064	6.633	1.10633	872.217	1
3	2.6936	6.633	1.10633	882.930	1

5. Conclusion

This study investigated the significant parameters influencing various industries' deep drawing processes and critical manufacturing techniques. The cylindrical cup segment deep drawing process was investigated numerically to prevent stress localisation. The optimum choice of the influencing parameters, including the punch corner radius, clearance, and radius die corner, was achieved. Utilizing the MINITAB program, the Response surface method was applied to create the FE simulations and analyse the impact of parameters on the deep drawing process. The development of stress is mostly affected by the punch corner and die corner radius. It can be noted that the radius of the punch corner should be 5.3 mm, the radius of the die corner should be 6.6 mm, and clearance should be 1.07 mm to produce the desired product with the least stress distribution 868.24 MPa, as displayed in Table 8. The conclusions section should clearly explain the main findings and implications of the work, highlighting its importance and relevance. This research's findings contribute to optimising the deep drawing process, enabling manufacturers to improve product quality and consistency and reduce material waste and energy consumption. This study's outcomes provide valuable insights for industries relying on deep drawing, such as automotive, aerospace, and consumer goods manufacturing. Future research needs further investigation into the effects of these parameters on the uniform thickness distribution.

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