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Original article

Deep drawing with unconventional tooling: impact of process parameters on a part accuracy

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ABSTRACT

The analysis of influencing factors and their effects on the deep drawing process is essential for producing cost-effective, high-quality workpieces. In this study, the impact of deep drawing process variables, including die radius, blank holder force, and lubrication conditions, on the distribution of wall thickness and changes in radius for axisymmetric workpieces is explored. For the investigation, specialized tooling was created, with core components such as the punch, die, and blank holder made from a two-component resin and fabricated using rapid tooling technology - vacuum casting. The Taguchi method was employed as a statistical tool for planning the experiments, which allowed the impact of process factors to be determined with minimal variability.

Key words: *deep drawing, rapid tooling, Taguchi method,*

1. INTRODUCTION

Deep drawing is a widely applied sheet metal forming process, utilized for the mass production of parts across various industrial sectors [1]. Using this sheet metal forming process, it is possible to produce a drawn part with a complex geometry from a simple sheet metal blank with a minimum number of operations. The key concern in the deep drawing process is ensuring that the drawn part attains the desired geometry without any occurrences of cracks or wrinkles. Achieving this goal entails a comprehensive evaluation of the influencing parameters within the deep drawing process and the optimal selection of process parameters.

In this paper, the feasibility of manufacturing axisymmetric components from 0.8 mm thick DC01 sheet metal using a drawing tool with key components made from a plastic material [3] is investigated, with a particular focus on examining the effect of specific deep drawing process parameters, including die radius, blank holder force, and lubrication conditions, on the fluctuations in wall thickness and radius [6]. Taguchi's method of experimental planning was used in order to accomplish this goal, which involved carrying out nine experiments according to Taguchi's L9 experimental plan. Taguchi's method is a statistical approach that efficiently provides a significant amount of information about the observed process or system while minimizing the number of necessary experiments [7].

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2. EXPERIMENTAL RESEARCH

As illustrated in Fig. 1, the experimental setup employed a customized deep drawing tool in which the core tool components - punch, die, and blank holder - were fabricated from a plastic material, specifically a two-component resin using vacuum casting technology.

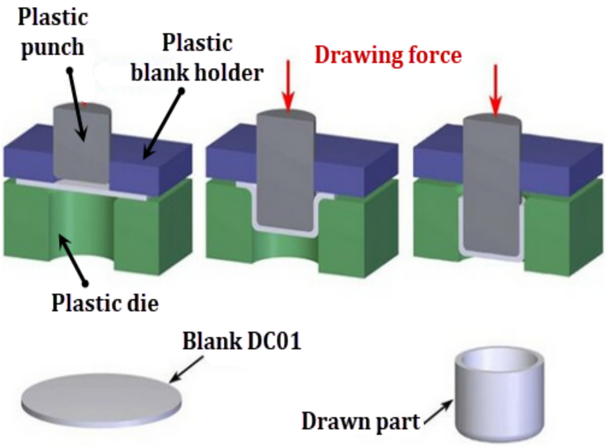

Fig. 1 *Schematic view of deep drawing process with plastic tool elements [2]*

The vacuum casting process requires the creation of "negatives" of the tool elements, from which the casting molds will be made. Additive manufacturing technologies are especially useful in this context because they enable the rapid production of master models needed for silicone mold preparation, even when dealing with complex geometries [4]. It is important to note that silicone molds must accurately replicate the features of deep drawing tool components to prevent the occurrence of system errors on the workpiece. The vacuum casting process, including mold manufacturing, consisted of several steps, as depicted in Fig. 2

1. Preparation of tool parts for the casting process. Setting the parting tape on the tool parts negatives to facilitate silicone mold separation.
2. Bonding plastic gates on tool part negatives to form an inlet channel in the silicone mold and to facilitate negative positioning and fixation in the silicone casting frame.
3. The calculation of the amount of silicone mixture required to produce a silicone mold for molding the deep drawing tool components. This mixture is poured into the frame containing the fixed tool component negatives. Subsequently, the frame with the negatives submerged in silicone is placed in a vacuum chamber to eliminate any residual air bubbles from the silicon
4. Placing the silicone mold in a vacuum chamber. After the silicone has solidified, the silicone mold is cut to the parting line, allowing the negative to be relieved and a silicone mold to be obtained for casting a replica of a given negative.
5. The molding halves are then combined and the next step is to calculate necessary quantities of resin for molding of the deep drawing tool parts. The amount of resin is commonly determined by weighing the individual master model which is increased by 20-30%, taking into account the loss of material in vessels and inlet channels.
6. Once the necessary material quantity and the proportions of its individual components in the total amount are determined, the vacuum casting process commences. This procedure takes place in a vacuum chamber under precise conditions specified for the respective components of the resin mixture.
7. After solidification of the molded material in a vacuum chamber, mold halves are separated. Subsequently, if needed, post-processing of the molded items is carried out.

The blank holder, die, and punch were constructed using Axson Technologies' two-component resin PX 223/HT. Through the combination of these two components, we achieved the tool components with the mechanical and physical properties detailed in Tables 1 and 2.

Table 1. *Mechanical properties of resin PX 223/HT at 23°C [5]*

Flexural modulus of elasticity	Mpa	2300
Flexural strength	Mpa	80
Tensile strength	MPa	60
Elongation at break in tension	%	11
Charpy impact resistance	kJ/m^2	>60
Hardnes at 23°C	Shore D1	80
Hardnes at 23°C	Shore D1	> 65

Table 2. *Physical properties of vacuum casting resin PX 223/HT [5]*

	Part A	***Part B***	***Mixing***
Composition	Isocyanate	Polyol	
Mixing ratio by wight at 25°C	100	80	
Aspect	liquid	liquid	liquid
Color	colorless	black	black
Viscosity at 25°C [Brookfield LVT]	1.100	300	850

The study considered several influencing factors of the deep drawing process. Variations in lubrication conditions were among these factors, with three different lubrication conditions used. These conditions included the use of a special deep drawing lubricant (Martol EP 180), cold-pressed pumpkin seed oil, and deep drawing without lubrication. In addition, three dies with different radii (4.5 mm, 6 mm, and 7.5 mm) were used. As part of the experiment, the blank holder force was also adjusted, with values set at 15 kN, 20 kN, and 25 kN. The specific process parameters and their variations are summarized in Table 3.

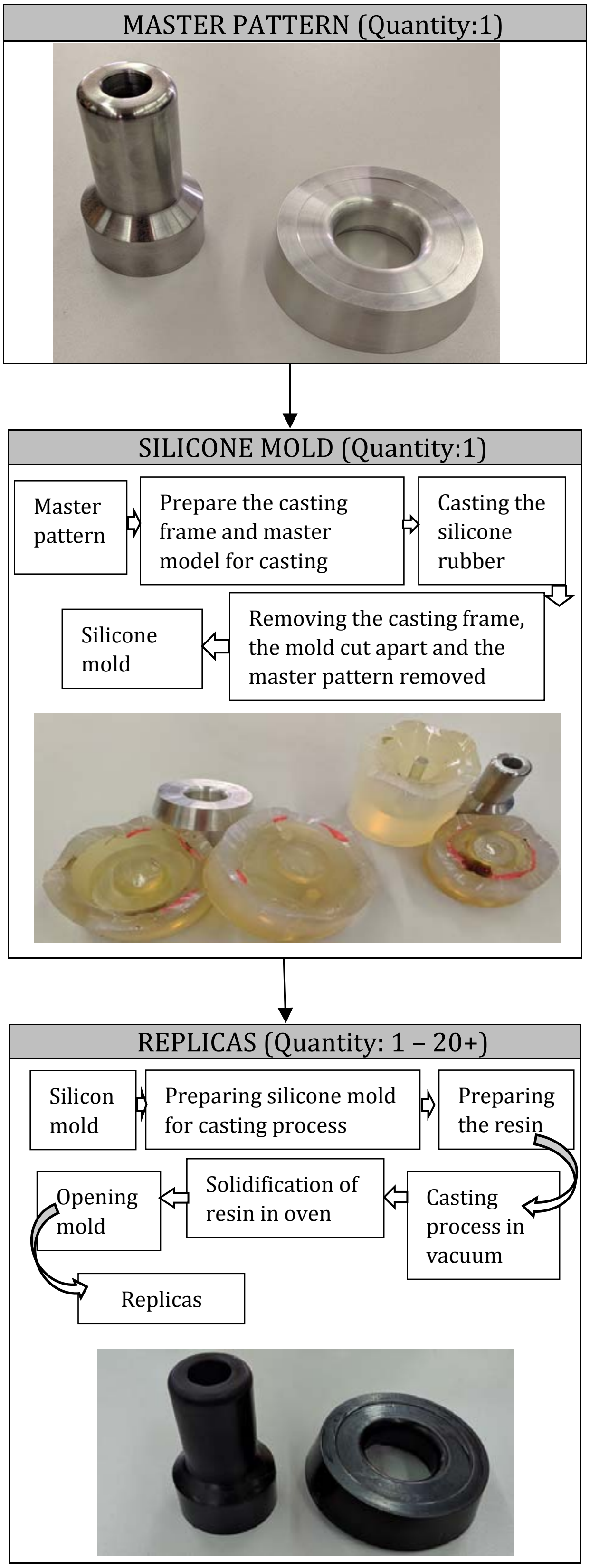

Fig. 2. *Rapid tooling process flowchart*

Sheet metal DC01 with a thickness of 0.8 mm was used in the deep drawing process. Table 4 depicts a complete view of the orthogonal L9 Taguchi sequence.

Table 3. *Process parameters and variation levels*

Process parameters	***Levels***		
	1	***2***	***3***
Die radius (R [mm])	4.5	6	7.5
Blank Holder Force (BHF [kN])	15	20	25
Lubricants (Lub)	Without Lubricant- ***WL***	Martol EP180 ***L1***	Pumpkin Seed Oil ***L2***

Table 4. *Taguchi's L9 experiment plan [7]*

Exp. no.	Parameters		
	R	***BHF***	***Lub***
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

The drawing parts manufactured according to the experiment's plan were subsequently processed by cutting on a grinder to prepare samples. These samples were then polished to enable the measurement of the wall thickness of the components under a microscope. The variation in thickness within the radius area of the parts was measured using a Mitutoyo TM-505 instrument microscope, which featured a high-resolution MOTICAM 5 camera. The microscope was linked to a PC, and data was analyzed using Motic Images Plus 2.0 software.

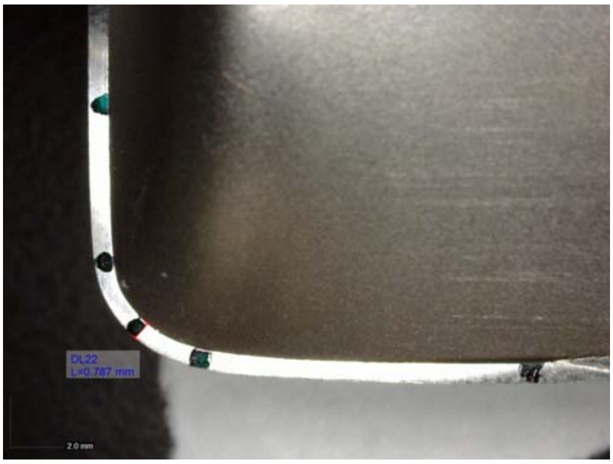

Fig. 3. *Radius thickness shown on microscope*

The results of measurements for both radius deviation and wall thickness variations in the radius zone, conducted in accordance with the predetermined experimental plan, are displayed in Table 5.

Table 5. *Experimental for radius and wall thickness*

Exp.	*Parameters:*			*Radius*	*Thickness*
No.	*R*	*BHF*	*Lub*	*thickness variation*	*deviation*
1	4.5	15	WL	0,793	0,007
2	4.5	20	L1	0,787	0,013
3	4.5	25	L2	0,763	0,037
4	6	15	L1	0,784	0,016
5	6	20	L2	0,75	0,05
6	6	25	WL	0,742	0,058
7	7.5	15	L2	0,76	0,04
8	7.5	20	WL	0,741	0,059
9	7.5	25	L1	0,737	0,063

3. ANALYSIS OF EXPERIMENTAL RESULTS

In the deep drawing process, it is common to assume uniform material thickness throughout the drawn workpiece. However, measurements often reveal variations in thickness across different sections of the workpiece. Hence, the primary objective of this research is to determine the distribution of wall thickness along the radius of the workpiece. The influence of the observed parameters on the wall thickness distribution of the drawn part's radius was analyzed using the Taguchi method.

The analysis started by examining the deviation of the wall thickness from the nominal value of 0.8 mm. It is obviously that the objective function (Eq.1) must be set as: Smaller-the-Better.

$$S/N = -10Log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \qquad (1)$$

The S/N values for each experiment are presented in Table 6, while Table 7 illustrates the S/N response for each input parameter.

Table 6. *S/N values for each experiment*

Exp.	*Parameters:*			*Thickness*	*S/N ratio*
No.	*R*	*BHF*	*Lub*	*deviation*	*[dB]*
1	4.5	15	WL	0.007	43.098
2	4.5	20	L1	0.013	37.721
3	4.5	25	L2	0.037	28.636
4	6	15	L1	0.016	35.917
5	6	20	L2	0.05	26.020
6	6	25	WL	0.058	24.731
7	7.5	15	L2	0.04	27.959
8	7.5	20	WL	0.059	24.583
9	7.5	25	L1	0.063	24.013

Table 7. *S/N response for thickness deviation along radius*

Level	*R*	*BHF*	*Lub*
1	36.49	35.66	30.80
2	28.89	29.44	32.55
3	25.52	25.79	27.54
Delta	10.97	9.86	5.01
Rank	1	2	3

The S/N ratio analysis reveals which of the three evaluated characteristics has the greatest impact on thickness variation along the portion radius. The effect ranking in Table 8 and Figure 4 shows that die radius has the greatest influence on thickness in the radius zone, whereas lubricant has the least. According to the impact ranking in Table 8 and Fig.4, it is clear that die radius exerts the most significant influence on thickness in the radius zone, while the lubricant has the least impact. Table 7 and the graph in Figure 4 illustrate the optimal deep drawing parameters within the given ranges when considering the "smaller-the-better" criterion. The best combination of the selected parameters includes die radius at level 1, blank holder force (BHF) at level 1, and lubrication condition at level 2

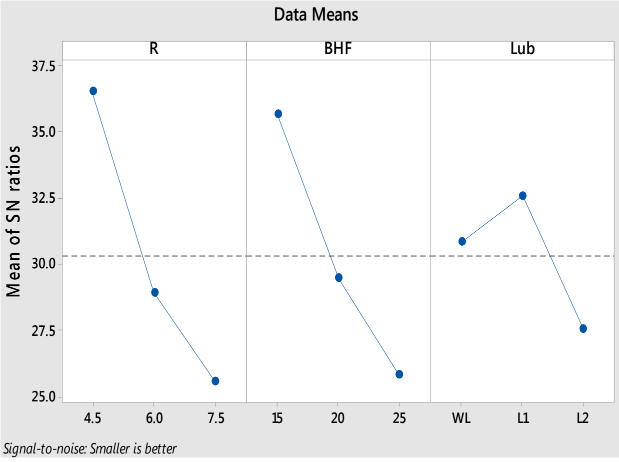

Fig. 4 *S/N response for thickness deviation along the radius*

The statistical relevance of die radius, blank holder force, and lubrication condition on the variation in radius thickness of a deep-drawn component was determined using analysis of variance. The results of the analysis of variance are presented in Table 9. The analysis was carried out with a 95% confidence level. It is evident from Table 9 that two process parameters, die radius, and blank holder force, significantly affect the variation in radius thickness of deep-drawn parts.

The P-values associated with these factors confirm their strong influence, as they exceed a confidence level of 95.00%. The P-values associated with these factors confirm their strong influence, as they exceed a confidence level of 95.00%. Lubrication conditions, although at the borderline of significance, do not exert a significant influence. The influence of die radius, blank holder force, and lubrication conditions was further quantified by determining their individual (percentage) contributions. The analysis revealed that the percentage contribution of die radius (factor R) to the variation in radius thickness of deep-drawn parts was the most significant, amounting to 51.13%. Following this, blank holder force (factor BHF) contributed 41.63%, and lubrication condition (factor Lub) had a smaller contribution of 6.81%. The remaining 0.43% can be attributed to experimental error, signifying the influence of other unaccounted factors. Given the minimal error in the experiment, it can be concluded that the experiment is well-designed, and in this particular case, there are no substantial external factors affecting radius thickness of deep-drawn parts.

Table 8. *Results of the analysis of variance*

Source	*DF*	*Adj SS*	*Adj MS*	*F-Value*	*P-Value*	*Involvement %*
R	2	0.001884	0.000942	116.15	0.009	51.13
BHF	2	0.001534	0.000767	94.53	0.010	41.63
Lub	2	0.000251	0.000125	15.47	0.061	6.81
Error	2	0.000016	0.000008			0,43
Total	8	0.003685				100

3. CONCLUSIONS

In this study, the impact of die radius, blank holder force, and lubrication condition on the variation of radius thickness of deep-drawn parts was analyzed. Taguchi's L9 orthogonal array was followed in the experiment. The ANOVA analysis was used to determine the degree of influence of deep drawing parameters on the variation of radius thickness of deep-drawn parts. Based on the research findings and the S/N analysis, the parameters with the most favorable influence on the variation of radius thickness of deep-drawn parts were identified.

The optimal combination of deep drawing parameters comprises a die with a radius of 4.5 mm, a blank holder force of 15 kN, and the use of Total Martol EP 180 lubricant. The ANOVA analysis revealed that the most influential factor affecting the variation in radius thickness on a deep-drawn part was the die radius, contributing 51.13%, followed by blank holder force and lubrication conditions with contributions of 41.63% and 6.81%, respectively. With an experimental error of only 0.43%, it is evident that significant process parameters have been accurately observed, and the influence of other process parameters is minimal. The analysis also indicated that the lubrication condition has no significant impact on the thickness distribution along the radius of the deep-drawn part. This finding supports the hypothesis of deep drawing without lubricants when the main tool elements are made of plastic. This is especially important in terms of environmental protection. It also leads to cost reductions in the deep drawing process and the subsequent degreasing of components.

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NOTE

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