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APPLICATION OF TAGUCHI METHOD IN OPTIMIZATION OF THE EXTRACTION PROCEDURE OF SHEET METAL

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Abstract:
The process of deep sheet metal drawing is accepted in all industrial branches. This process is, therefore, very important to maintain a certain level of quality. For this reason, measurements and tests must be carried out to determine how much sheet metal deformation occurred after the deep drawing process. For this purpose, an experiment of deep drawing of sheet metal was carried out using the example of kitchen utensils. In addition, the Taguchi method was used in this experiment to test the quality of the obtained kitchenware. In the experiment, three factors were taken with three alternatives that affect the deep drawing of sheet metal, and 27 experiments were used for the Taguchi method. The results of this experiment showed that the best results were achieved by the smallest drawing depth of 65 mm and the worst results were obtained by the drawing thickness of 70 mm. Regarding the thickness of the material, the best results were achieved by the material of 21 mm, and the material of 15 mm achieved the worst results. In addition, an analysis of variance was carried out, which determined the relationship between force and deformation of the material.

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1. INTRODUCTION

Quality is vitally important in today's production process due to the complexity of the operating environment [1] and the conditions associated with deep sheet metal drawing processes [2]. The specificity of deep sheet metal drawing is that various parameters affect the quality of the product [3]. In the process of deep sheet metal drawing, force is applied to the metal, which is modified and adapted to the intended geometrical body provided by the specifications. In this process, there is a possibility of the appearance of uncontrolled factors that affect the quality of the product and are caused by the loading of the material [4]. That load can be tension, compression, bending, or a combination of all these factors. Therefore, a proper selection of quality parameters is necessary and must be clearly defined. The prevention of scrap during deep sheet metal drawing under controlled quality measurements can be reduced by adequately planning the system, parameters, and tolerances, which is the basis of the Taguchi method.

The sheet metal deep drawing process is widely accepted in practice and is used in the automotive, aircraft, military, beverage, and other industries [5]. The process of deep sheet metal drawing is influenced by impact speed, friction factor, initial holding force, initial blank sheet shape, etc. [6]. That is why much has been written about this process in scientific circles. Shisoda et al. [7] emphasize that the sheet metal drawing process is the oldest production technique and research how friction plays a role in optimizing this process itself. Rosenthal et al. [8] presented a methodology for designing lightweight components in deep drawing of sheet metal for complex parts with a lot of

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residual stress in their work, such as gears and the like. Wu et al. [9] examined the surface of the deep drawing of the sheet, whether there were any remaining stresses in the material, and what the material's roughness was. Therefore, it is necessary to use advanced optimization methods for deep sheet metal drawing [10] to reduce material stress and optimize this process.

Based on that, this study used the Taguchi method to investigate how force, drawing depth, and material thickness affect product quality. The material's stress and the sheet metal's deformation at specific parameters will be observed in doing so. The obtained results were analyzed using the analysis of variance (ANOVA) and selecting a particular combination of sheet thickness that gives the best results in terms of the quality of the final product. Based on this, the contribution of this research is examining the role of sheet thickness in the deep drawing process. The research results will help improve this process and thus obtain the highest quality products. In addition, the contribution of this study is reflected in the integration of different methods.

Apart from the introduction, this paper is divided into four selections. The second selection, entitled Theoretical foundations of the Taguchi method, explains the application of this method. The third selection, *Material and Methods*, deals with how the research was carried out, the measurements presented, and the results of the influence of various factors on the quality of the finished product. The fifth part, *Results and Discussion*, deals with calculating the sheet stress when experimenting. In the fifth part of this paper, the conclusions are given about the obtained results of this paper.

2. THEORETICAL FOUNDATION OF TAGUCHI METHOD

Genichi Taguchi's contribution to quality development lies in applying quality design methods, called Taguchi methods [11]. According to this method, adequately spent time designing and planning significantly reduces energy, time, and costs [12]. According to Taguchi, two types of factors influence product characteristics: controlled and uncontrollable [13]. Controllable factors are subject to control and can be managed, such as the choice of raw materials and materials, machinery in production, products, processes used, etc. Uncontrollable factors are challenging to identify and control. Based on that, the factors that need to be controlled and for which control is justified should be singled out, while for other factors, it is important to reduce the impact they have on the company itself.

In the Taguchi method, each experiment is developed for one process or product with the desired functionality expressed through the features and quality characteristics customers require [14]. The idea of the Taguchi method can be expressed as follows: the goal of the global quality system is to design processes and products resistant to the effects of random factors, which is achieved by minimizing the loss caused by deviations in the functional characteristics of products from their nominal, prescribed value [15]. The process of the Taguchi method takes place in three design phases: system design, parameter design, and tolerance design [16].

The implementation of the Taguchi method consists of determining the product quality parameters before making the prototype using particular principles. Then, it is necessary to narrow the dispersion area around the target value (to reduce the probability of noise in production). When reducing variation in production processes, improvement of process technology and quality and cost reduction are achieved. The Taguchi method is used for product design and production processes in which product quality is evaluated through the loss function [17]. Based on the loss function, comparing two products or two processes is possible. Taguchi methods represent a system of quality engineering that aims to reduce costs, emphasizes the efficient application of engineering strategies, and puts advanced statistical methods in the background.

To improve the quality of processes and products, it is necessary to define quality as a deviation from the desired value. The range of variation of the deviation from the desired value, which is influenced by controlled and uncontrolled factors, is determined by experiments. To improve the quality, Taguchi suggests using an orthogonal matrix of the plan of experiments and the plan of experiments for each of the groups of factors (controlled and uncontrolled). This makes it possible to analyze the impact of noise on the production process and products.

When planning a system, the question arises: How can we define a system that will best meet the needs of customers? System planning involves building the system under an initial set of nominal conditions. Technical knowledge in science and engineering is required. Parameter planning is the second step. It is important to choose an optimal level for the system parameters that can be controlled so that the product is functional, shows a high level of wear in different conditions, and is robust to disturbance factors that cause changes. Nuisance factors are those that we cannot control or are too expensive to control.

With the Taguchi method, it is necessary to have a robust design of production processes and products. Robust design refers to producing high-quality, error-free products and services [18]. This design has a high tolerance for uncontrolled factors, i.e. noises. According to Taguchi, it is necessary to consider uncontrolled noise factors and internal process and product design factors using internal and external design. This is how we try to produce a product that will not have errors and will satisfy the customers who will use it even after its exploitation time, and the quality of the product will stay the same.

3. MATERIALS AND METHODS

Sheet metal deep drawing is the process of forming sheet metal effusions through a mold for forming and drawing. The metal is held in the area of the inclined plate, and a part of the press passes through it, resulting in the sheet being pulled out. The material is thickest in the area where the metal loses contact with the indentation - the impact radius, and it is thinnest in the area where the stress is the highest [19]. In the process of deep drawing of sheet metal, compaction and cracking of the material are two basic problems [20]. This process starts with the synchronous downward movement of the puller (2) and the empty holder (1). By moving them down, the pressure holder empties the material or the sheet (3). Underneath the empty holder is the lower part (4) that shapes the sheet (3) (Fig. 1). The most significant forces and deformations are found on the lower rounded part because the lower part remains the same thickness while the sheet on the sides becomes thinner, and therefore, the lower rounded part has the greatest pressure on the material. In this part, the largest deformations occur in the material, which results in material cracking. Usually, in the place where the material is thinnest, it is necessary to take care of the thickness of the sheet.

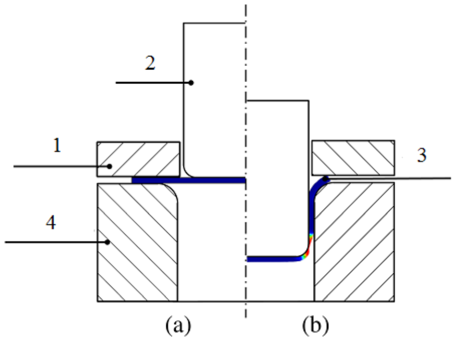

Fig. 1. Schematic representation of deep drawing a) before drawing, b) after drawing [20]

The material used in this experiment was stainless steel type 304L. This metal has at least 18% chromium, 8% nickel, and a maximum carbon of 0.030. It is the standard 18/8 stainless metal most commonly used in plates and cookware (Table 1). It is the stainless steel family's most versatile and widely used alloy. It has excellent corrosion resistance and is extremely easy to manufacture and flexible.

Table 1. Chemical characteristics of iron 304L

Composition table	Iron 304L
Carbon	0.03 Max
Chrome	18.00-20.00
Iron	Balance established
Manganese	2.00 Max
Nickel	8.00-12.00
Nitrogen	0.10 Max
Phosphorus	0.045 Max
Silicone	0.75 Max
Sulfur	0.030 Max

For experimentation, a stainless metal with a diameter of 24 cm was used, and the initial thickness of this material was experimented with. So, materials with 15, 18, and 21 mm thickness were used. The force used and the extraction depth were also taken to examine the influence on the sheet's minimum thickness and deformation and the starting material's thickness. The goal of this experiment is to determine whether the force used and the depth of extraction, together with the thickness of the material, affects the final product of this process, which is the production of a kitchen pan. In addition, the goal is to achieve the best ratio of the parameters used and the thickness of the sheet to obtain a product with the least deformities while the thickness of the final product is of satisfactory quality.

To carry out this experiment, the High-precision bar vessel wheel for forming deep drawing hydraulic press machine manufactured by EMAGCNC was used. It enables the construction of three and four poles for large workspaces, suitable for automatic forming, punching, bending, straightening, and assembly of parts for the creation of an automatic production line. With this machine, it is possible to produce various products by deep sheet metal drawing.

Two devices were used when conducting this experiment: a Fowler 54-815-001-2 digital micrometer and an ATOS portable scanner. The Fowler 54-815-001-2 Digital Micrometer instantly reads 0.00005' on a 6-digit LCD display. Using this micrometer, it is possible to adjust the zero setting, relative, and absolute frequency, while in this experiment, the minimum frequency obtained by measuring the final products was used. This micrometer provides an accuracy of ± 0.0001 mm. With the ATOS portable scanner, it is possible to perform 3D scanning to measure and inspect material deformation. This tool offers various capabilities, such as 3D digitization and analysis of parts, tools, and systems. In this experiment, the surface geometry of the final product will be precisely measured.

4. RESULTS AND DISCUSSION

The Taguchi method was used to find the correct ratio of the material's thickness, the drawing depth, and the force that should be used during the deep drawing of the sheet. Over time, the Taguchi method has become a powerful and robust engineering tool used to optimize and evaluate the influence of parameters [21]. During the optimization, three factors were used, namely the force used in the deep drawing of the 304L material, the drawing depth, and the thickness of the material, and each of these factors has three levels or three possible variants. The parameters and their factors are shown in Table 2. Here are shown the options for conducting the experiment where the control factors are taken as force, depth of extraction, and material thickness. All these factors were investigated through three different alternatives. Based on this, values for safety coefficients for measuring wall thickness and sheet metal deformation were calculated.

Table 2. Level of basic factors

Control factor	**Metrics**	**Level**		
		I	**II**	**III**
A. - Force	kN	80	90	100
B. - Extraction depth	mm	65	70	75
C.- Material thickness	mm	15	18	21

An orthogonal array is chosen based on combinations of observed parameters. Since three factors were observed and all factors have three alternatives, 27 experiments were conducted. Table 3 presents the experiment's plan and the experiment's serial number. The sequence number of the experiment was obtained based on the random function.

Table 3. Experimental plan on the example of using the L27 orthogonal array

Experiment plan	Serial number of the experiment	A	B	C
1	4	1	1	1
2	12	1	1	2
3	1	1	1	3
4	25	1	2	1
5	13	1	2	2
6	27	1	2	3
7	11	1	3	1
8	22	1	3	2
9	2	1	3	3
10	9	2	1	1
11	26	2	1	2
12	23	2	1	3
13	5	2	2	1
14	21	2	2	2
15	6	2	2	3
16	7	2	3	1
17	16	2	3	2
18	24	2	3	3
19	14	3	1	1
20	19	3	1	2
21	15	3	1	3
22	10	3	2	1
23	8	3	2	2
24	20	3	2	3
25	3	3	3	1
26	17	3	3	2
27	18	3	3	3

To measure the quality of the characteristic parameters in a controlled way, signal noise (S/N ratio) can be determined as the term "signal" represents the desired effect (mean) and the term "noise" represents the undesirable effect (signal disturbance, SD) z and the output characteristics that affect the output due to external factors namely noise factors. The goal of any experiment is always to find the highest possible S/N ratio for a result that indicates that the signal is much larger than the random effects of noise factors or minimal variance. Table 4 shows the Taguchi model used in the design of the experiment.

Table 4. Experimental design using L27 orthogonal field

BE	C2	C3	C4	Minimal wall thickness (MDZ)	Sheet metal defor-mation (DL)	S/N ratio za MDZ (more is better)	S/N ratio za DL (less is better)
1	80	65	15	1.4128	0.9158	4.4822	2.9258
2	80	65	18	1.6328	1.0684	5.2063	3.4065
3	80	65	21	2.2635	1.2821	7.2319	4.0673
4	80	70	15	1.2631	0.8503	3.9719	2.6700
5	80	70	18	1.5418	0.9921	4.8507	3.1212
6	80	70	21	1.3687	1.1905	4.2974	3.7435
7	80	75	15	2.0275	0.7937	6.3504	2.4852
8	80	75	18	2.2763	0.9259	7.1469	2.9072
9	80	75	21	1.1339	1.1111	3.5504	3.4801
10	90	65	15	1.5565	0.8140	4.8739	2.6007
11	90	65	18	1.8758	0.9497	5.8896	2.9818
12	90	65	21	2.2784	1.1396	7.2794	3.5684
13	90	70	15	1.2834	0.7559	4.0296	3.3225
14	90	70	18	1.5519	0.8818	4.8826	2.7744
15	90	70	21	2.0076	1.0582	6.4014	2.4101
16	90	75	15	1.1413	0.7055	3.5746	2.2381
17	90	75	18	1.3648	0.8230	4.2915	2.5881
18	90	75	21	1.8647	0.9877	5.9156	3.0934
19	100	65	15	1.5404	0.7326	4.8363	2.3406
20	100	65	18	1.8685	0.8547	5.8756	2.6877
21	100	65	21	2.2905	1.0256	7.3180	3.2203
22	100	70	15	1.3088	0.6803	4.0993	2.1691
23	100	70	18	1.5795	0.7937	4.9593	2.4920
24	100	70	21	2.0183	0.9524	6.4353	2.9829
25	100	75	15	1.1489	0.6349	3.5977	2.0143
26	100	75	18	1.3677	0.7407	4.3028	2.3305
27	100	75	21	1.8745	0.8889	5.9469	2.7834

Safety coefficients (S/N) were calculated for the minimum sheet thickness and deformation. Table 5 shows the average value obtained for each control factor. The obtained results show that the material thickness has the most significant variation in the average values of the S/N ratio for the minimum wall thickness; then, the most significant variation is in the force, while the minor variation is in the extraction depth. The rank order shows the values based on the difference of individual levels. Thus, the highest value of this difference is for the material thickness control factor, while the lowest value is for the used force.

Table 6 shows the average S/N ratio for sheet deformation. The largest variation in the average values of the S/N ratio is in the sheet thickness control factor, followed by the force used, while the smallest variation in the average values is in the drawing depth. The rank order according to the values of the difference between individual levels shows that the highest values of these differences are for the thickness of the material, while the lowest values are for the force used.

Table 5. Average S/N ratio for minimum wall thickness

Level		A	B	C
I		5.232	5.888	4.424
II		5.238	4.881	5.267
III		5.263	4.964	6.042
Delta	II-I	0.006	-1.007	0.843
	III-I	0.031	-0.924	1.618
	III-II	0.025	0.083	0.775
Rank	II-I	2	3	1
	III-I	2	3	1
	III-II	3	2	1

Table 6. Average S/N ratio for sheet deformations

Level		A	B	C
I		3.201	3.089	2.530
II		2.842	2.854	2.810
III		2.558	2.658	3.261
Delta	II-I	-0.359	-0.235	0.280
	III-I	-0.643	-0.431	0.731
	III-II	-0.284	-0.196	0.451
Rank	II-I	3	2	1
	III-I	3	2	1
	III-II	3	2	1

Based on the conducted experiment, 27 values were obtained for different combinations of control factors. To better understand the values obtained by this experiment, it is necessary to determine the main effect of the S/N ratio and analyze the variance.

Fig. 2 shows the result of the main effect of S/N ratios for applied force, extraction depth, and material thickness. Based on this figure, the best results were obtained with the force of 100 KN, followed by the force of 90 KN and then 80 KN. It can be concluded that if a greater force is used when pulling out the sheet, the product’s wall thickness will be greater. When looking at the depth of the material, it can be said that the best results were obtained when the smallest drawing depth was 65 mm, followed by a drawing thickness of 75 mm, and the worst results were obtained with a drawing thickness of 70 mm. When looking at the thickness of the material, the best results were achieved by the 21 mm material, followed by the 18 mm material, and the worst results by the 15 mm material. These results were to be expected because it is logical that if the initial material is thicker, then the sides of the product will be thicker.

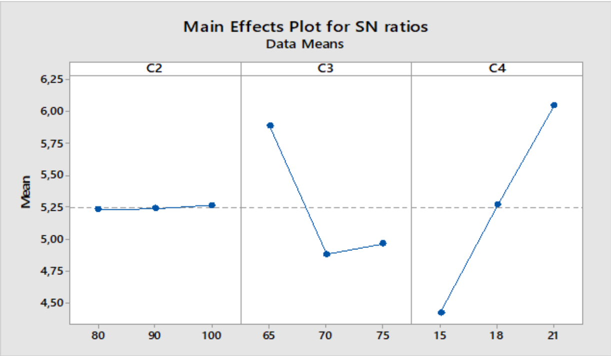

Fig. 2. Main effect plot for S/N ratio for minimum wall thickness

The following results were obtained when applying the variance calculation analysis (Table 7) to the minimum wall thickness. When studying the effect of force on the minimum wall thickness, results show no significant effect of force on the product's wall thickness (F = 0.002, p = 0.998). Moreover, the results show that the force used has no effect on the minimum wall thickness of the product because the p-value is almost one, and when it is one, there is no statistical association. With the extraction depth used, results were obtained showing no significant statistical relationship between the extraction depth and the minimum wall thickness of the product (F = 2.056; p = 0.150). In contrast to the force, there is a specific statistical relationship with the extraction depth, but it is insignificant. When looking at the material's thickness, results show a significant statistical relationship between the material's thickness and the product's minimum sheet thickness (F = 5.300; p = 0.012). Based on the obtained results, the following conclusions can be drawn. The force used during the deep drawing of the sheet does not influence the minimum thickness of the sheet. In contrast, the thickness of the material has a significant statistical influence on the minimum thickness of the sheet, which entails the conclusion that if the starting point is thicker, then the product resulting from the deep drawing will also be thicker material.

Table 7. Analysis of variance for S/N ratio for minimum sheet thickness

	Source	Variance	F-Value	P-Value	Percent (%)
C2	Force	0.00254	0.000	0.998	0.03
C3	Extraction depth	2.81316	2.673	0.094	32.30
C4	Material thickness	5.89258	5.602	0.012	67.67

Fig. 3 shows a graphical representation of the main effect of the S/N ratios for sheet deformation. The obtained results show that when looking at the force, the best results were achieved by a force of 80 KN because the lowest value of the S/N ratio and the goal was less is better; then comes the force of 90 KN, while the force of 100 KN achieved the worst results. Based on this, a lower force is a better result because it deforms the sheet itself less than a higher force. When looking at the extraction depth, the most profound extraction depth of 75 mm had the best effects, followed by a depth of 70 mm, and a depth of 65 mm was the worst. Since they are of similar depth, the difference between them is this. Similar results were achieved in the research of Chaitanya and Swapna [19] and the research of Tricarico and Palmieri [22]. When observing the sheet thicknesses, the results were obtained that the thinnest sheet showed the least deformations, i.e. the 15 mm material used, followed by the 18 mm material. In comparison, the 21 mm material achieved the worst results. The reason for this should be that a thinner sheet is more accessible to pull out and causes less deformity compared to a thicker material, which confirmed the results of Tricarico and Palmieri research [22].

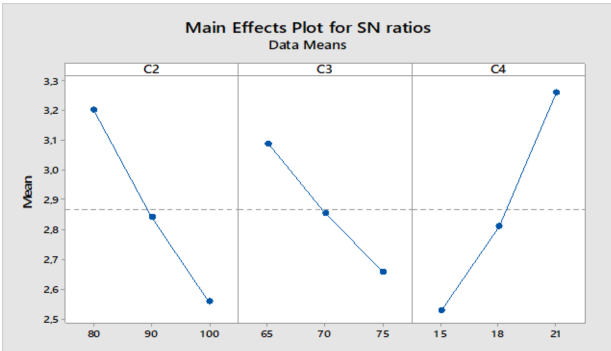

Fig. 3. Main effect plot for S/N ratio for sheet deformation

The results obtained in the analysis of variance (Table 8) show that there is a significant statistical dependence on the used force concerning the deformations of the sheet (F = 4.590, p = 0.021); in the used extraction depth, the results showed that there is no significant statistical dependence to the deformations sheet metal (F = 1.700; p = 0.204), while for material thickness, the results showed that there is a significant statistical dependence to sheet metal deformations (F = 6.839; p = 0.004). Based on this, it can be concluded that the force used and the thickness of the material have a role in the deformation of the sheet.

Table 8. Analysis of variance for the S/N ratio for sheet deformation

	Source	Variance	F-Value	P-Value	Percent (%)
C1	Force	0.93413	11.712	0.000	36.22
C2	Extraction depth	0.41904	5.251	0.015	16.25
C3	Material thickness	1.22568	15.370	0.000	47.54

5. CONCLUSION

By applying the analysis of variance, it was determined that the thickness of the material to be drawn (67.67%), then the depth of the drawing (32.30%), while it was shown that the force in general does not affect the thickness of the material (0.03%) and its share is negligible. When applying the variance analysis for sheet deformation, it was shown that material thickness has the greatest influence on deformation (47.54%), followed by applied force (36.22%), and the slightest influence on sheet deformation is drawn depth (16.25%).

Observing the obtained results, it can be concluded that the best result in terms of minimum sheet thickness was achieved by the material to which a force of 100 KN was applied, where a 65 mm pullout was performed. In contrast, a material with a thickness of 21 mm was used. With this material, the highest force, the smallest extraction, and the thickest material were used, so it was also logical that the minimum value of the extracted sheet should be the smallest. When the deformation of the sheet was observed, the best result was achieved by the material to which a force of 100 KN was applied, a drawing depth of 75 mm, and a material thickness of 15 mm. This means that the most significant force, the most excellent extraction, and the most negligible thickness of the material were applied, and the best result of the sheet deformation was achieved.

Conflicts of Interest

The authors declare no conflict of interest.

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