Determination of Optimum Test Parameter Level Ranges for Machining Processes

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ABSTRACT

In this study, the ideal experimental design planning for the machining process was investigated. Two experimental designs were created by differentiating the parameter levels considered in the drilling process of stainless-steel. Close and far-level designs were obtained by creating 20% and 40% differences between the parameter levels. In the experimental system prepared according to the Taguchi method, surface roughness and cutting forces were measured as the output parameters. The results were analyzed statistically by optimization, analysis of variance and correlation analysis, and visually by chip morphology examination. According to the findings, it was determined that a 20% difference between the parameter levels was more appropriate in terms of experimental system stability, statistical data significance, and chip morphology.

Keywords-drilling; parameter level range; statistical analysis; surface roughness; cutting force

I. INTRODUCTION

The global competition in manufacturing today focuses on finding ways to produce goods of higher quality at a lower cost. There is a constant need to decrease the tooling cost in order to produce things more affordably, particularly when executing machining processes. One of these needs is to lengthen the lifespan of the cutting tool by choosing the most suitable cutting parameters, resulting in reduced surface roughness and cutting forces [1-3]. In this approach, many experimental designs and methodologies, such as Taguchi and Response Surface methods, are carried out to select optimum experimental parameters, saving time and cost. The system's reliability did not decrease due to the reduction in the number of experiments. A second benefit of experimental design methods is that the optimum points of (maximum, minimum, nominal) machining parameters, such as surface roughness and cutting forces can be determined [4-7]. Owing to the benefits stated above, using experimental design methods in manufacturing-oriented experimental studies is essential.

While creating the experimental design methodology, the parameter levels should be chosen with a significant difference. In cases the difference between the levels is very small, obtaining general information about the system is complex. The difference between the levels is increased as the significance of the effect ratios of the parameters decreases. In addition, there is no study regarding how the parameter levels affect the test results. In this study, two different experimental designs were performed, and the effect of parameter levels on the test results was analyzed. A machining-oriented experimental study for the most appropriate parameter level selection was conducted for the first time. In the first experimental design, the difference between the levels will be kept at a minimum level. In the second experiment design, the level differences will be kept at the maximum level. Optimization, variance, correlation, and regression analysis will be performed for the results obtained from both experimental designs. The results will be compared to obtain information about the selection of the most suitable parameter levels. AISI304 stainless steel was used in the parameter-oriented experimental study and experiments were carried out through the drilling process.

II. MATERIALS AND METHODS

In this study, the experimental sample is made of AISI 304 stainless steel with dimensions shown in Figure 1. This size (120 × 80 × 20 mm) is specified to fit with stationary dynamometer equipment that was installed in a CNC milling machine. In experimentation, 18 holes, each 10 mm in diameter, were drilled in one sample. The twist solid carbide drill, which has a 10 mm diameter and 120 mm length, was utilized (Figure 2).

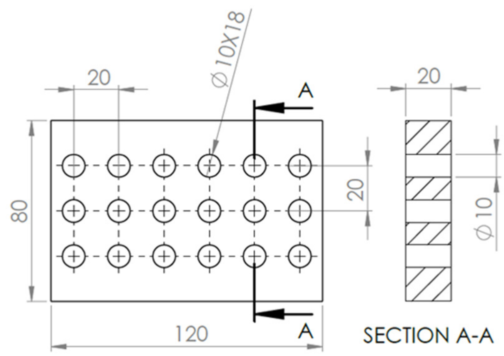

Fig. 1. Geometry of AISI304 test sample.

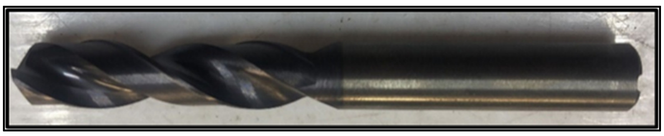

Fig. 2. Geometry of the tool.

All experimental work was conducted on a CNC milling machine, Falco, HAAS VF-2SS (Figure 3). A stationary dynamometer was deployed to measure the cutting forces. The dynamometer was firmly mounted on the table of the CNC milling machine, whereas the workpiece was clamped on the top of the Dynamometer surface. In addition, the Multichannel Charge Amplifier was employed to convert the high-impedance charge input into a usable output voltage. Surface roughness measuring device SJ-410 was utilized. The surface roughness was measured at six different locations to minimize the deviation. Mean surface roughness values (Ra) were considered at 0.8 mm cut length. The average value of Ra was considered in the statistical analysis. Boron-based cutting fluid was sprayed to the cutting area at a 75° angle with a double nozzle. The flow rate of the cutting fluid was 10 l/min. To obtain microscopic images of the chips, the 1000×2 MP Digital Stand 8 Led USB Microscope was engaged.

Fig. 3. Photographs of experimental set-up.

Experimental parameters and levels were determined according to [8-12]. Additionally, preliminary experiments were conducted to test the suitability of the parameters. Three levels of the input parameters cutting speed, feed rate, and drilling depth were considered. The parameters determined for the close- and far-level tests are given in Table I and II, respectively. Cutting speed and feed rate values are differentiated in the relevant tables, but drilling depth levels are not differentiated due to the experimental setup conditions. The design was planned to have a minimum of 20% difference between the parameter levels in Table I and a 40% difference between the parameter levels in Table II. The Taguchi method was followed to minimize the number of experiments, and the experiment was designed according to the L9 orthogonal index [13]. Surface roughness and cutting force were taken into account as output parameters and minimization was aimed for both parameters [14]. Taguchi's minimization function is provided in (1). Experimental results were evaluated by signal/noise (S/N), analysis of variance (ANOVA), and regression analysis.

$$\frac{S}{N} = -10\log\left[\frac{1}{n}\left(\sum_{i=1}^{n} y_i^2\right)\right] \quad (1)$$

TABLE I. PARAMETERS AND LEVELS FOR THE FİRST GROUP

Close levels (20%)			
Parameters	**Level (1)**	**Level (2)**	**Level (3)**
Feed rate (mm/min)	0.13	0.17	0.2
Cutting speed (rpm)	512	640	768
Drilling depth (mm)	5	8	10

TABLE II. PARAMETERS AND LEVELS FOR THE SECOND GROUP

Far levels (40%)			
Parameters	**Level (1)**	**Level (2)**	**Level (3)**
Feed rate (mm/min)	0.13	0.22	0.3
Cutting speed (rpm)	774	1270	1766
Drilling depth (mm)	5	8	10

III. RESULTS AND DISCUSSION

A. Comparison of Surface Roughness (Ra) Values

The Ra values acquired from the close-level and far-level designs are portrayed in Table III. The correlation coefficient value obtained for the Ra values in Table III is positive and is 0.26.

TABLE III. EXPERIMENTAL RESULTS FOR SURFACE ROUGHNESS

Close levels (20%)				
Exp. No.	**Feed rate (mm/min)**	**Cutting speed (rpm)**	**Drilling depth (mm)**	**Ra (μm)**
1	0.13	512	5	2.385
2	0.13	640	8	1.919
3	0.13	768	10	2.348
4	0.17	512	8	1.297
5	0.17	640	10	1.553
6	0.17	768	5	1.870
7	0.2	512	10	0.841
8	0.2	640	5	1.607
9	0.2	768	8	1.591
Far levels (40%)				
Exp. No.	**Feed rate (mm/min)**	**Cutting speed (rpm)**	**Drilling depth (mm)**	**Ra (μm)**
1	0.13	774	5	1.303
2	0.13	1270	8	2.543
3	0.13	1766	10	1.946
4	0.22	774	8	2.093
5	0.22	1270	10	1.522
6	0.22	1766	5	1.599
7	0.3	774	10	1.070
8	0.3	1270	5	1.280
9	0.3	1766	8	1.880

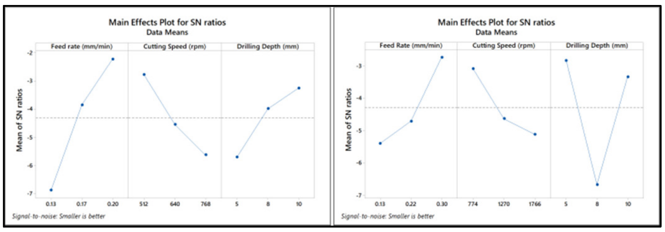

Fig. 4. Signal/Noise ratios for the Ra results.

For the close-level design, the optimum points in terms of Ra were identified as 512 rpm, 0.2 mm/min, and 10 mm for cutting speed, feed rate, and depth of cut, respectively (Figure 4). The optimum points in terms of Ra for the far-level design were denoted as 774 rpm, 0.3 mm/min, and 5 mm for cutting speed, feed rate, and depth of cut, correspondingly (Figure 4). According to the Taguchi results, it was noted that the best findings were acquired when using the highest feeding rate and the lowest speed for both groups. However, there are differences between the optimum points of drilling depth values. As the level ranges determined for the feed rate and speed increased, the irregularity at the tool-chip interface rose with increasing drilling depth. The low correlation value of 0.26 can be explained by the incompatible interaction of drilling depth values. According to the results, it was determined that a 20% difference between parameter levels would be sufficient for a stable experimental design in terms of surface roughness.

The effect ratios of the parameters in terms of surface roughness for the close-level and far-level experimental designs were determined by analysis of variance (ANOVA), and the results obtained are displayed in Table IV. The statistical significance of the input parameters for the output parameter is evaluated with the p-value. Parameters with a p-value less than 0.05 are considered significant in terms of the output parameter, and parameters with a p-value between 0.05 and 0.1 are regarded borderline significant. %). According to the ANOVA table, it was determined that statistically and physically significant results were obtained for the close-level experimental design. In the far-level experimental design, no significant statistical results could be acquired due to the negative interaction of the feed rate and cutting speed parameters with the drilling depth parameter concerning Ra.

TABLE IV. ANOVA RESULTS FOR SURFACE ROUGHNESS

Close levels (20%)			
Source	Adj SS	P-Value	Effect Rate (%)
Feed rate	1.2249	0.100	64.48
Cutting speed	0.2773	0.338	14.54
Drilling depth	0.2635	0.349	13.82
Error	0.1413		
Total	1.9070		
Significance	R-Sq=88.59% R-Sq(adj)=81.74%		
Far Levels (40%)			
Source	Adj SS	P-Value	Effect Rate (%)
Feed rate	0.41580	0.147	24.03
Cutting speed	0.18875	0.275	10.91
Drilling depth	1.05409	0.064	60.92
Error	0.07172		
Total	1.73035		
Significance	R-Sq=95.86% R-Sq(adj)=83.42%		

In line with Table IV, it is seen that the feed rate is the most effective (64.48%) and significant (p value = 0.1) parameter in the close-level experimental design. This result is not in accordance with the results obtained in [15-17]. It was determined that the most effective parameter in the far-level experimental design was the depth of cut (60.92%), whereas, pursuant to [18, 19], the drilling depth parameter is a parameter with lower significance than the feed rate and cutting speed. However, in the far-level experimental design, the drilling depth parameter was incompatible with the literature. As per the ANOVA results, it was established that the 20% level range was sufficient and significant regarding Ra. As a result, regression values (R-Sq(adj)) of 81.74% and 83.42% were attained for the close-level and far-level experimental designs, respectively. The fact that R-Sq(adj) values are greater than 70% for both experimental designs exhibits that the identified drilling parameters are sufficient to explain the surface roughness [20].

B. Comparison of Cutting Force Values

The cutting forces obtained in the close and far-level experimental designs are depicted in Table V. A positive (strong) correlation value of 0.85 was acquired between the close and far-level values. The strong correlation value obtained is important for the meaningfulness of experimental designs. The average cutting force value attained for the close and far-level experimental design was 1718.9 N and 2265 N, accordingly. When the increase in level range was 20%, the augmentation in cutting forces was 31.77%. As the level range raises, the experimental error rate will increase as the increase in the cutting force value will have a negative effect on the surface roughness, tool vibration, and uncalculated dynamic forces. For this reason, the choice of close-level design is important for the meaningfulness of the experimental data and repeatable experimental results.

TABLE V. EXPERIMENTAL RESULTS FOR CUTTING FORCES

Close Levels (20%)				
Exp. No.	**Feed rate (mm/min)**	**Cutting speed (rpm)**	**Drilling depth (mm)**	**Force-Mean (N)**
1	0.13	512	5	1346
2	0.13	640	8	1367
3	0.13	768	10	1593
4	0.17	512	8	1654
5	0.17	640	10	1690
6	0.17	768	5	2117
7	0.2	512	10	1726
8	0.2	640	5	1799
9	0.2	768	8	2178
Far Levels (40%)				
Exp. No.	**Feed rate (mm/min)**	**Cutting speed (rpm)**	**Drilling depth (mm)**	**Force-Mean (N)**
1	0.13	774	5	1612
2	0.13	1270	8	1604
3	0.13	1766	10	1852
4	0.22	774	8	2010.2
5	0.22	1270	10	2230
6	0.22	1766	5	2567
7	0.3	774	10	2713
8	0.3	1270	5	2890
9	0.3	1766	8	2910

The optimum points determined for close and far-level designs to minimize cutting forces according to S/N ratios are given in Figure 5. The optimum points differ in terms of drilling depth. The significant trend obtained for the drilling depth in the close-level design (cutting forces decreased as it increased) created a meaningless trend in the far-level design. This situation can be explained depending on the ANOVA results (Table VI). As the level ranges increase, the effect of the feed rate parameter on the forces increases compared to other parameters, making the drilling depth parameter statistically and physically meaningless. Increasing the feed rate will increase the plastic forming rate. The augmentation in the rate of plastic deformation means that more energy is required to deform the material; that is, more force acts on the material. The increase in force due to the rise in feed rate caused the effect of other input parameters to decrease, and the effects of these values could not be examined. Both experimental data and statistical results (S/N ratio and ANOVA) show that the close-level design is more meaningful in terms of analysis.

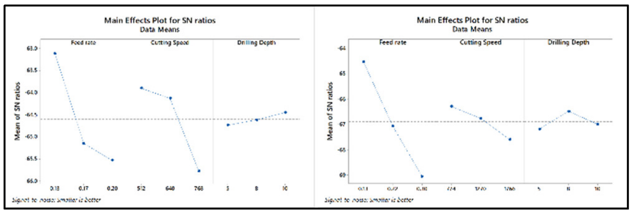

Fig. 5. Signal/Noise ratios for cutting forces.

TABLE VI. ANOVA RESULTS FOR CUTTING FORCE

Close Levels (20%)			
Source	**Adj SS**	**P-Value**	**Effect rate (%)**
Feed rate	371578	0.016	56.34
Cutting speed	270241	0.022	40.98
Drilling depth	11564	0.346	1.75
Error	6126		0.93
Total	659509		100.00
Significance	R-Sq=99.07% R-Sq(adj)=96.28%		
Far Levels (40%)			
Source	**Adj SS**	**P-Value**	**Effect rate (%)**
Feed rate	1201242	0.098	59.96
Cutting speed	480782	0.213	24.00
Drilling depth	191354	0.405	9.55
Error	130105		6.49
Total	2003482		100.00
Significance	R-Sq=93.51% R-Sq(adj)=74.02%		

C. Visual Analysis

Figure 6(a) and (c) illustrate the chip images obtained for parameter values of 0.13 mm/min, 512 rpm, and 5 mm, and 0.2 mm/min, 768 rpm, and 8 mm, respectively. Figures 6(a) and (c) express the lowest and highest parameter levels of the close-level experimental design. Figure 6(b) and (d) demonstrate the chip images attained for parameter values of 0.13 mm/min, 774 rpm, and 5 mm, and 0.3 mm/min, 1766 rpm, and 8 mm, respectively. These Figures express the lowest and highest parameter levels of the far-level experimental design. In parameter selection, conditions creating minimum and maximum cutting power were considered. Spiral-shaped and discontinuous chip formation were observed in the close-level experimental design, whereas as the level of the values increased, no significant change was noticed in the chip form, only the chip thickness increased. This is crucial for the stability of the experimental results. In the far-level experimental design, large-form spiral and mixed-type (discontinuous and continuous) chips were acquired under minimum power conditions, and continuous and flat-form chips were obtained under maximum power conditions, whereas as the level values increased, the chip thickness increased, and a flat-surfaced and continuous chip was formed, which increased the wear behavior on the tool surface. The change in chip form has the effect of causing serious changes in both tool wear and surface roughness values [21-23]. For this reason, in machining experiments, the parameter levels must be determined so that the chip form change is at a minimum level.

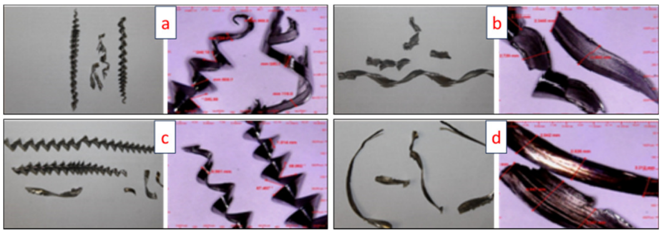

Fig. 6. Chip micrographs from (a) lowest parameter levels of the of the close-level design, (b) lowest parameter levels of the of the far-level design, (c) highest parameter levels of the of the close-level design, (b) highest parameter levels of the of the far-level design.

IV. CONCLUSIONS

In this study, the effects of different parameter levels on the drilling process were investigated, and the optimum level range was determined. The obtained results are.

- In terms of surface roughness, the close level (20%) experimental design gave more stable results. In far-level design, the negative interaction of the drilling depth with the other input parameters created insignificance on the output parameters.
- It was determined that the close-level design (20%) gave more stable results than the far-level design (40%) regarding the cutting forces. As the level of intervals increased, the cutting forces increased, and accordingly, a significant effect ratio distribution could not be obtained in the ANOVA analysis.
- Considering chip morphology, discrete and spiral-shaped chips were obtained in the low-level design, and continuous and flat chips were acquired in the far-level design. It has been determined that the chips attained with low-level design were formed in more suitable morphology in terms of tool life and surface quality.

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