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Prediction of Surface Roughness and Optimization of Machining Parameters in Drilling Process of Aluminum Alloy Al6061

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ABSTRACT

In this paper, an experimental research was conducted to investigate the influence of the tool diameter, spindle speed, and feed rate on the surface roughness in hole drilling process. The Box-Behken experimental matrix that was used with 15 experiments. The Minitab 16 software was used to evaluate the experimental results. The analyzed results showed that the spindle speed was a parameter that has the most important influence on the surface roughness. The second factors that affect on the surface roughness was tool diameter. And, the feed rate was the factor that has smallest effect on the surface roughness. The interaction factor between the tool diameter and the feed rate has the largest degree of the influence on the surface roughness, the second interaction factor that influenced on the surface roughness was the interaction between the diamter and the spindle speed. The interaction between the spindle speed and the feed rate has the smallest effect on the surface roughness. The suitable regression model of surface roughness is quadractic function. The predicted results of surface roughness are very close to the experimental values of that one. The genetic algorithm was used to find the optimal value of surface roughness. In this study, the optimum value of surface roughness was obtained for each case of drill tool diameter. The optimized cutting parameters was applied to improve the surface roughness with very satisfactory results. The optimum value of surface was quite small.

KEYWORDS: *Al6061, cutting parameters, Drilling, prediction, optimization, surface roughness*

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I. INTRODUCTION

Drilling is the most common machining method for making holes in the solid parts. This process is usually done before the next steps such as drilling, boring, tapping. Surface roughness is always an important determinant of product life.

In order to improve the surface quality of the hole after drilling, several next machining steps can be applied such as drilling, boring, etc. These technological steps increase the costs and extend processing time. Therefore, improving the surface quality (reducing the roughness) of the hole surface when drilling is very significant for the machining process [1].

Many studies have been carried out to investigate the effect of technological parameters on the surface roughness of machining holes, predict the hole surface roughness, optimize the technology parameters to control the drilling process, reduce hole surface roughness, and improve the productivity of the machining process.

Evren Kabakli et al. [2] investigated the effect of hole diameter, hole depth, feed rate, and cutting speed to the roughness of the hole surface when drilling hot- rolled low-alloyed medium-carbon steel of 207 HB. Their research has shown that hole diameter and feed rate have a great influence on the surfaces roughness of the machined hole.

Sanjay et al. [3] conduct empirical research on mild steel drilling process and application of the Neural network to predict hole surface roughness. The results of their study showed that all three parameters including hole diameter, cutting speed, and feed rate have a strong influence on the surface roughness. Besides, they also pointed out that all three parameters can be selected as the input parameters to build a prediction model to predict the surface roughness of the machining hole.

Abhinaw Roy et al. [4] studied the application of Neural network to predict the surface roughness of machining hole when drilling the AISI1020 steel. Their study predicted roughness of the machined hole surface quite closely compared to the experimental data. Besides, they also showed that when the cutting speed increases to a certain value, the surface roughness decreases, and then if the cutting speed still increase, the surface roughness also increases. When increasing the feed rate and the depth of the drill hole the surface roughness wil increase. In this study, they also made the comment that the surface roughness of the hole will be the smallest when the feed rate and the hole are small and the cutting speed is the medium value.

Soepangkat et al. [5] studied a combination of back propagation neural network (BPNN) and genetic algorithm (GA) to optimize the GFRP stainless steel drilling process. Their research has shown that the hole surface roughness will decrease when the cutting speed increases, the feed rate decreases, and the point angle of the drill tool decreases.

Deepan Bharathi Kannan et al. [6] applied a genetic algorithm to optimize the stainless steel drilling. In this study, they made the remark that the cutting speed and the feed rate are the parameters that greatly affect on the roughness of the hole surface. These are the two main parameters to control the drilling process to machine the hole surface with small surface roughness. Surface roughness has the smallest value when the spindle speed is 540 (rpm) and the feed rate is 0.03 (mm/rev).

Prakash et al. [7] applied the response surface methodology to predict the surface roughness of machining hole when drilling the medium density fiberboard panels. The proposed regression model was used to predict surface roughness. The results show that the predicted surface roughness value is very close to the experimental results. Their research has also shown that all three parameters including the feed rate, the cutting speed, and the hole diameter have a significant effect on the surface roughness. The feed rate has the strongest influence, followed by the influence of the drill tool diameter, and the cutting speed is the least influential factor on the surface roughness.

The response surface method was also used by Balaji et al. [8] to optimize the AISI 304 stainless steel in drilling process. Helix angle, feed rate, and cutting speed are used as the input parameters in the study. This study has shown that the helix angle and the interaction between the three above parameters have a significant effect on the surface roughness of the hole. Besides, they also determined the optimum value of the helix angle of the drill tool, the feed rate, and the cutting speed have values of 25^{o}, 10 (mm/rev) and 750 (rpm), respectively. Then all three parameters of driiling process as surface roughness, vibration, and tool wear are also quite small.

Ahmed Basil Abdulwahhab et al. [9] applied the Taguchi method to investigate the effect of the drill diameter, the feed rate, and the cutting speed on the hole surface roughness when drilling the AISI 1015 steel. It is shown that the drill diameter has the greatest influence on the surface roughness, followed by the influence of the feedrate, and the cutting speed has the least effect on the surface roughness. With the value of the drill diameter, the feed rate, and the cutting speed are 11 (mm), 0.038 (mm/rev) and 930 (rpm), respectively, the surface roughness will have the smallest value.

Praksh et al. [10] applied the Taguchi method and the regression model analysis method to investigate the roughness of hole surface when drilling the medium density fiber board panles. In this study, they conclussed that the feed rate that has the greatest impact on surface roughness, followed by the degree of impact of the drill diameter, and the cutting speed has very little impact on the surface roughness.

From the above studies, the parameters such as the drill diameter, cutting speed (spindle speed), and the feed rate are often chosen as the input parameters to investigate the impact level on the surface roughness. However, the degree of influence of these parameters on the surface roughness of machining holes is not the same when drilling the different materials.

Many methods such as response surface method, neural network, genetic algorithm have been applied to predict and optimize roughness of machining hole surface. However, the optimum values of the cutting mode parameters that were performed in those studies are also only applied to specific machining conditions. Based on the summary of the above studies, it seems that: (1) Reseaching to improve the hole drill surface quality has not been performed for the drilling process of aluminum alloy Al6061, while aluminum alloy Al6061 widely applied in the automotive industry, aviation industry, etc, where the hole drilling processes are often applied; (2) The preveous studies mainly focused on studying the effect of cutting parameters on the surface roughness, or build the regression models of surface roughness, or optimizing the cutting parameters of drilling processes. It seems that a comprehensive study on all three issues has not been mentioned in above studies.

In this study, the impact of drill diameter, rotation speed, feed rate to the roughness of hole surface when drilling aluminum alloy A6061 were investigated. The contributions of this study lie in the following points: (1) The degree of the influence of the drill diameter, spindle speed, and feed rate on the surface roughness is determined when hole drilling the aluminum alloy Al6061; (2) The models of surface roughness was proposed to predict the roughness of the machined hole surface; (3) The optimum values of the spindle speed and the feed rate were also determined for each specific case of the drill diameter. The optimized results of cutting parameters were applied to improve the surface roughness in hole drilling process.

II. EXPERIMENTAL METHOD

1. Machine, Workpiece, and Drilling tool

The experiments were performed the CNC milling machine (DMN400 of DOOSAN – Korea) as shown in Figure.1.

Fig 1. Experimental machine

The workpieces that used for experimental were aluminum alloy Al661. The chemistry components of Al6161 were listed in Table 1. This material that is easy for machining, with good corrosion resistance and good plasticity.

The holes were created by drilling processes, and then, the workpiece was cutted by two parts to measure the surface roughness of each hole as described in Figure. 2.

TABLE 1. CHEMICAL COMPOSITION OF AL6061

Com.	Si	Mg	Mn	Cu	Fe	Cr	Zn	Ti	Al	Oth.
%	0.6	1.0	0.15	0.3	0.7	0.35	0.25	0.15	96.45	0.05

a) The sample after drilling

b) Cutting sample for surface roughness measurement

Fig 2. Experimental workpiece

The hard alloy drilling tools (WIDIN of Korea) that have the diameter sizes of 8 mm, 10 mm, and 12 mm were used to conduct the experimental researches. This type of tools is often used to drill the aluminum alloys.

Fig 3. Cutting tools

2. Experimental design

The experimental matrix was designed according the Box-Behnke plan. The Box-Behnken designs are often of a rotational center or nearly that this design has a rotational center [11]. An experimental diagram of a Box-Behnken experiment plan with 3 variables x_1, x_2, and x_3 was described as in Figure. 4. According to this diagram, each parameter will receive three values at the encryption levels -1, 0, and 1 as listed in Table 2. Finally, the experimental matrix is presented in Table 3.

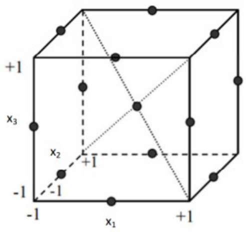

Fig 4. Box-Behnken design for three factors

TABLE 2. DESIGN FACTORS AND THEIR LEVELS

Parameters	Symbol	Level		
		-1	0	1
Tool diameter (mm)	d	8	10	12
Speed (rev/min)	n	2500	3750	5000
Feed rate (mm/rev)	f	0.08	0.1	0.12

TABLE 3. EXPERIMENTAL DESIGN MATRIX

No.	x_1	x_2	x_3	x_1, d (mm)	x_2, n (rev/min)	x_3, f (mm/rev)	Ra
1	-1	-1	0	8	2500	0.1	1.82
2	1	-1	0	12	2500	0.1	0.92
3	-1	1	0	8	5000	0.1	2.51
4	1	1	0	12	5000	0.1	1.96
5	-1	0	-1	8	3750	0.08	1.54
6	1	0	-1	12	3750	0.08	1.30
7	-1	0	1	8	3750	0.12	2.40
8	1	0	1	12	3750	0.12	1.21
9	0	-1	-1	10	2500	0.08	1.12
10	0	1	-1	10	5000	0.08	1.90
11	0	-1	1	10	2500	0.12	1.38
12	0	1	1	10	5000	0.12	2.37
13	0	0	0	10	3750	0.1	1.28
14	0	0	0	10	3750	0.1	1.30
15	0	0	0	10	3750	0.1	1.66

The experiments were carried out at the conditions: the depth of hole is 40 mm. The Emulsion coolant fluid was used with the overflow irrigation method. The flow is 25 liters/ minute.

3. The surface roughness tester

The surface roughness tester that was used is the surface roughness tester Mitutoyo of Japan. At each hole, three time of measurement was performed. The average value of the surface roughness at each experiment was used to analy and evaluate the influence of the tool diameter and cutting parameters on the surface roughness in drilling process.

III. Experimental results and discussions

1. The influence of tool diameter and cutting parameters on the surface roughness

The experimental results of surface roughness in drilling process were stored in Table 3. By using the Minitab 16 software, the analyzed results were obtained and described as in Figure. 5 and Figure. 6.

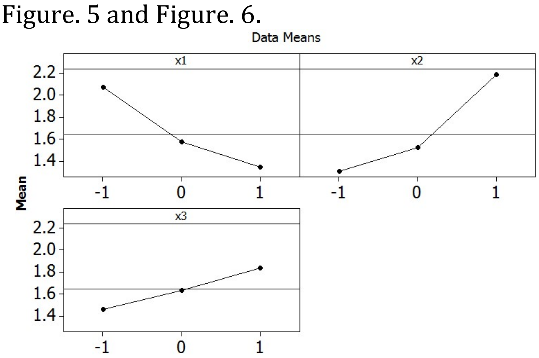

Fig. 5. Main effects for Ra

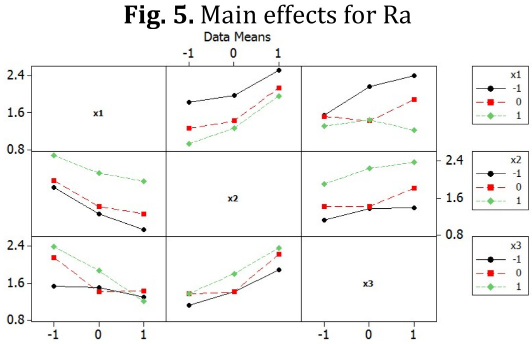

Fig. 6. Interaction Plot for Ra

These figures shown that:

- Tool diameter, spindle speed, and feed rate have significant influence on the surface roughness. But, the influence of each factor on the surface roughness is different. The spindle speed (x_2) was a parameter that has the most important influence on the surface roughness. The second factors that affect on the surface roughness was tool diameter (x_1). And, the feed rate (x_3) was the factor that has smallest effect on the surface roughness.

The interaction factor between the tool diameter and the feed rate has the largest degree of the influence on the surface roughness, the second interaction factor that influenced on the surface roughness was the interaction between the diamter and the spindle speed. The interaction between the spindle speed and the feed rate has the smallest effect on the surface roughness.

2. Regression of surface roughness in hole drilling processes

From the Table 3, the surface roughness in drilling process was modeled by Eq. (1). This is a function of the input coded factor of tool diameter, spindle speed, and feed rate. In this case, the determination coefficient is very close to 1 (R^2 = 0.9736). So, the suitable regression model of surface roughness is quadractic function.

$$\begin{aligned} R_a &= 1.41333 - 0.36 * x_1 + 0.4375 * x_2 + 0.1875 * x_3 \\ &+0.15458 * x_1^2 + 0.23458 * x_2^2 + 0.04458 * x_3^2 \\ &+0.0875 * x_1 * x_2 - 0.2375 * x_1 * x_3 + 0.0525 * x_2 * x_3 \end{aligned} \quad (1)$$

The regression model was used to predict the surface roughness. The predicted and experimental values of surface roughness were presented as in Table 4.

TABLE 4. MEASURED VS. PREDICTED SURFACE ROUGHNESS

No.	x_1	x_2	x_3	Meas. Ra	Pred. Ra	Error (%)
1	-1	-1	0	1.82	1.81	0.41%
2	1	-1	0	0.92	0.92	0.27%
3	-1	1	0	2.51	2.51	0.10%
4	1	1	0	1.96	1.97	0.38%
5	-1	0	-1	1.54	1.95	26.54%
6	1	0	-1	1.30	1.70	31.05%
7	-1	0	1	2.40	2.80	16.61%
8	1	0	1	1.21	1.60	32.54%
9	0	-1	-1	1.12	1.52	35.82%
10	0	1	-1	1.90	2.29	20.59%
11	0	-1	1	1.38	1.79	29.80%
12	0	1	1	2.37	2.77	16.93%
13	0	0	0	1.28	1.41	10.42%
14	0	0	0	1.30	1.41	8.72%
15	0	0	0	1.66	1.41	14.86%
Means						16.34%

The results from Table 4 showed that the predicted results of surface roughness are very close to the experimental values of that one. The average difference is about 16.34 %. The proposed model of surface roughness can be used to predicted the surface roughness when hole drilling the aluminum alloy.

3. Optimization of machining parameters in hole drilling process

From the Eq. (1), the surface roughness model can be rewritten for each value of drill tool diameter as Eq. (2) to Eq. (4).

$$\begin{aligned} R_{a(d=8,x_1=-1)} &= 1.92791 + 0.35 * x_2 + 0.425 * x_3 \\ &0.23458 * x_2^2 + 0.04458 * x_3^2 + 0.0525 * x_2 * x_3 \end{aligned} \quad (2)$$

$$\begin{aligned} R_{a(d=10,x_1=0)} &= 1.41333 + 0.4375 * x_2 + 0.1875 * x_3 \\ &+0.23458 * x_2^2 + 0.04458 * x_3^2 + 0.0525 * x_2 * x_3 \end{aligned} \quad (3)$$

$$\begin{aligned} R_{a(d=12,x_1=1)} &= 1.20791 + 0.525 * x_2 - 0.05 * x_3 \\ &+0.23458 * x_2^2 + 0.04458 * x_3^2 + 0.0525 * x_2 * x_3 \end{aligned} \quad (4)$$

For each drill tool diameter, in order to determine the values of x_2, x_3 with the smallest of surface roughness, this is an optimization problem. The Eq. (2), Eq. (3), and Eq. (4) can be rewritten as Eq. (5) for each drill tool diameter.

$$\begin{cases} R_a = f(x_2, x_3) \to min \\ R_a > 0 \\ -1 \le x_2, x_3 \le 1 \end{cases} \quad (5)$$

TABLE 5. GENETIC ALGORITHM PARAMETERS

Parameters	Value
Population	100
Crossover probability	0.25
Mutation probability	0.05

The optimization process of surface roughness was solved by using the genetic algorithm for minimization problems. Optimization has been achieved by determination of three control parameters of the genetic algorithm. The size of the population, the crossover probability, and the mutation probability values were 100, 0.25 and 0.05, respectively, as listed in Table 5, [12-14]. In each case of drill tool diameter, the graph of the adaptive function is shown in Figure 7, Figure 8, and Figure 9, respectively.

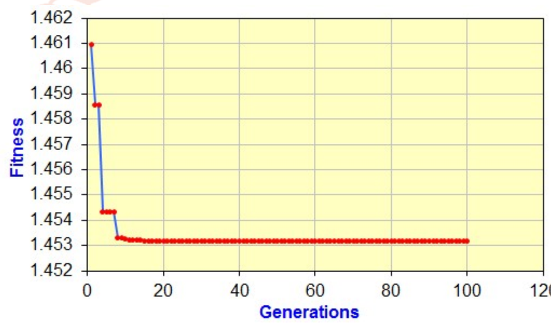

Fig 7. Genetic algorithm graph (d=8)

Fig 8. Genetic algorithm graph (d=10)

Fig 9. Genetic algorithm graph (d=12)

The optimal values of cutting mode parameters and surface roughness values in three cases were obtained and stored in Table 6. The optimum values of surface roughness were compared to the tested results with very satisfactory results. The maximum difference between optimum and tested values of surface roughness was 9.54 %. The optimized values of cutting parameters can be used to improve to surface quality of machined surface in hole drilling processes.

TABLE 6. OPTIMIZED AND TESTED VALUES

Tool diameters	d =8 mm	d =10 mm	d =12 mm
x_2	-0.6341	-0.8206	-1
x_3	-1	-1	1
n (rev/min)	2957.4	2724.3	2500.0
f (mm/rev)	0.08	0.08	0.12
Optimized Ra (μm)	1.4532	1.1124	0.8596
Test Ra (μm)	1.3519	1.2297	0.8901
Different (%)	7.49	9.54	3.43

IV. CONCLUSSIONS

In this study, the influence drgrees of drill tool diameter, spindle speed, and feed rate, and the interaction of these factors on the surface roughness were determined in hole drilling process of aluminum alloy Al6061.

The surface roughness models were successfully built and verified by experimental. The predicted and experimental result is close to each other (average difference: 16.34 %).

The Genetic Algorithm was used to find the optimal value of surface roughness. In this study, the optimum value of surface roughness was obtained for each case of drill tool diameter. The optimum values of surface roughness were compared to the tested results with very satisfactory results. The maximum difference between optimum and tested values of surface roughness was 9.54 %.

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