International Journal of
Innovation in Mechanical Engineering & Advanced Materials (IJIMEAM)
https://publikasi.mercubuana.ac.id/index.php/ijimeam
Vol.5 (No.2). 2023. pp. 56-62
Published online: December 27, 2023
ISSN: 2477-541X

OPTIMIZATION OF MACHINING PARAMETERS ON THE SURFACE ROUGHNESS OF ALUMINUM IN CNC TURNING PROCESS USING TAGUCHI METHOD

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Abstract

In this research, Taguchi method is employed by focusing on spindle speed, feed rate, and depth of cut to optimize the CNC turning parameters for aluminum alloy 6063. The main goal of this study is to improve the surface roughness of the material. A L9 orthogonal array is used for experimentation, and the results are subsequently analyzed using ANOVA (Analysis of Variance). A spindle speed of 1300 rpm, a feed rate of 0.5 m/min, and a depth of cut of 1.5 mm are the optimal conditions to achieve the minimum average surface roughness (Ra). The main effect plot of the signal-to-noise (S/N) ratio provides significant evidence supporting the primary research goal. Furthermore, the ANOVA table reveals that spindle speed contributes 59.71%, feed rate contributes 29.80%, while depth of cut only contributes minimally at 0.72%. Based on the research findings, spindle speed and feed rate can be adjusted to control surface roughness. Both factors are highly significant in influencing the surface roughness of the material. The prediction equation from the linear regression analysis is Ra = 1.745 – 0.001024 spindle speed + 0.3000 feed rate – 0.0233 depth of cut. A coefficient of determination or R-squared value of 0.9115 indicates that the independent variables can explain 91.15% of the variation in the dependent variable. The experimental and predicted surface roughness (Ra) values have a predicted error percentage of 2.26%.

Keywords: Taguchi Method, CNC, Surface Roughness, Orthogonal Array, Aluminum Alloy 6063

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DOI: 10.22441/ijimeam.v5i2.21679

1. Introduction

The computer numerical control (CNC) turning process is one machining method that utilizes CNC machines. The process can produce products with high precision and smooth surfaces. Therefore, CNC turning is widely used in manufacturing industries such as automotive, aerospace, and others [1,2,3].

Machining parameters are critical to the turning process to achieve high-quality products. Taguchi method is a strategic experimental approach designed to enhance the quality of products and processes while simultaneously minimizing costs and resource utilization. Its main objective is to identify the optimal and efficient conditions that lead to superior outcomes [4]. Several studies have used the Taguchi method and demonstrated its reliability in optimizing the data under investigation [5,6].

Kumar et al. [7] studied how spindle speed and feed rate influence the surface roughness (Ra) of carbon alloy steel in CNC turning using EN8, SAE8620, EN24, EN19, and EN47 materials. Spindle speed and feed rate were found to impact surface roughness, as indicated by the experimental results and the Taguchi method. From the research findings, higher Ra values can be achieved by reducing the feed rate and increasing the spindle speed. Palaniappan et al. [8] conducted experiments and investigations to determine the optimal parameters for maximizing material removal rate (MRR) and achieving the desired surface roughness (Ra) in aluminum alloy 6082 turning. The parameters utilized include spindle speed (800–1600 rpm), depth of cut (0.15–0.25 mm), and feed rate (1–2 mm/rev). In their research, they employed the Taguchi technique and analysis of variance (ANOVA) to analyze the data. The experimental and Taguchi method results concluded that the feed rate level significantly influences surface roughness (Ra). Variations in feed rate play a crucial role in determining the surface roughness of Aluminum Alloy 6082. Das et al. [9] conducted a study on machining AISI D2 steel to optimize machining parameters, including spindle speed, depth

Vol.5 (No.2). 2023. pp. 56-62
Published online: December 27, 2023
ISSN: 2477-541X

of cut, and feed rate, without cutting fluids to reduce tool wear and workpiece temperature. Among the selected characteristic parameters, the results of the experimental and Taguchi methods showed that tool wear could be influenced more significantly by spindle speed and depth of cut. The wear and minimum temperature characteristics were presented based on prediction and experimental results.

Benardos and Vosniakos [10] conducted research using an Artificial Neural Network (ANN) modeling approach to predict surface roughness (Ra). The Taguchi Design of Experiments (DoE) method gathers data from a CNC milling machine. Three components of cutting force, feed rate per tooth, spindle speed, tool binding, tool wear, cutting fluid usage, and depth of cut are some machining parameter components considered in the experiment. The research showed that the 5x3x1 ANN built based on the selected factors can predict surface roughness with an average accuracy of 1.86%. Furthermore, the Taguchi method demonstrated consistent results across all observed value ranges [11]. The CNC turning parameters for EN45 spring steel and standard carbide cutting tool were optimized using the Taguchi technique and regression analysis. The experiments were conducted using an L18 orthogonal array. Surface roughness and Material Removal Rate (MRR) were optimized using cutting speed, feed rate, and depth of cut as cutting parameters in the machining process. The results of the experimental and Taguchi method showed a correlation between spindle speed and feed rate with surface roughness, while depth of cut exhibited an inverse relationship.

Regarding MRR, all three parameters showed a proportional relationship with material removal rate. Vijay Kumar et al. [12] conducted machining of stainless steel EN 19 with CNC turning and investigated factors influencing surface roughness and material removal rate (MRR). The analyzed parameters included feed rate, depth of cut, spindle speed, and the type of coolant used. Carbide tools were used as cutting tools. The Taguchi L18 experimental design was used for optimization through the Taguchi approach. Analysis of variance (ANOVA) was conducted to determine the significance of machining parameters on the response. The research found that the Taguchi method efficiently explores the most influential parameter combinations for surface roughness and MRR. Experimental research also yielded similar results.

Maneesh et al. [13] aimed to observe the effects of process parameters on surface roughness and material removal rate (MRR) to find the best machining parameter settings. Additionally, analysis of variance (ANOVA) is used to observe how cutting parameters influence the machining process. The results of the experimental and Taguchi methods demonstrated that spindle speed and depth of cut had the most significant influence on determining the surface roughness value. Mia et al. [14] conducted testing on AISI 1060 steel under minimum quantity lubrication (MQL) cooling conditions. Considering spindle speed, feed rate, and depth of cut as adjustable parameters while analyzing various quality characteristics, tool wear, and material removal rate (MRR) as responses. The Taguchi method optimizes the hard-cutting process under minimum quantity lubrication (MQL) cooling conditions. Using the Taguchi method, that study has found significant variables in improving the machining process. That study indicated that a specific combination of spindle speed, feed rate, and depth of cut obtained through Taguchi optimization yielded better results in terms of quality characteristics, reduced tool wear, and increased MRR during the hard turning process of AISI 1060 steel with MQL cooling conditions [15]. The Taguchi method is used to optimize machining parameters, including spindle speed (rpm), feed rate (mm/min), and depth of cut (mm). Brass 63/37 was used as the material for the machining process. Orthogonal array L27 was employed for experimentation and analysis. The experimental and Taguchi method results showed that the optimum condition to achieve minimum average surface roughness (Ra) was the main effects plot demonstrates the primary objective of the research with a spindle speed of 1400 rpm, feed rate of 100 mm/minute, and depth of cut of 0.5 mm. Radha Krishnan et al. [16] researched to optimize the turning process using AISI 1030 and TiN-coated cutting tools. To analyze the characterization in the turning process, experiments were conducted using response surface methodology and an L9 orthogonal design.

Furthermore, cylindrical grinding has been performed on AISI 4140 steel by varying spindle speed, feed rate, and depth of cut. The final results of the research indicate that the cut's depth significantly impacts achieving the desired surface roughness level. Through the application of response surface methodology and the Taguchi method, optimal conditions were discovered with a spindle speed of 1100 rpm, a depth of cut of 0.44 mm, a feed rate of 0.2 mm/minute, a hardness of 107 HRC, and a surface roughness of 3.608 μm. Based on the research findings, it can be concluded that these parameters contribute to achieving the best performance in the process.

In this study, cutting parameters are optimized using the L9 orthogonal array Taguchi table to

Vol.5 (No.2). 2023. pp. 56-62
Published online: December 27, 2023
ISSN: 2477-541X

Fig. 1. Aluminum Alloy 6063

Fig. 2. CNC lathe machine type PZC51

investigate the influence of cutting parameters on surface roughness in the machining of Aluminum 6063. Using the Taguchi method, the cutting parameters that provide the optimum surface roughness value (Ra) are determined, and the relationships between these parameters are examined. Determining surface roughness values is based on machining parameters that yield the most optimal surface roughness value.

2. Experimental and Procedures

2.1 Materials

To determine the impact of spindle speed at 900, 1000, and 1300 RPM, Feed rate at 0.5, 1, and 1.5 m/min, and depth of cut at 0.5, 1, and 1.5 mm, experimental research is conducted on surface roughness (Ra) in a CNC lathe machine. Table 1 shows the variations of the parameters used. The experimental design of orthogonal arrays is shown in Table 2. In this research, Fig. 1 shows the material, Aluminum 6063. Table 2 shows the orthogonal array L9. Table 3 shows the chemical composition of Aluminum Alloy 6063.

Fig. 2 shows the CNC lathe machine type PZC51 that was used. Before the experimental study began, the parameter settings and lathe machine axes were inspected, and necessary adjustments were made. After the experiments, As shown in Fig. 3, the surface roughness tester instrument was used to measure surface roughness.

2.2 Experiment

The experimental method used in this research is the Taguchi Method. The Taguchi Method employs a special orthogonal array (OA), signal-to-noise ratio (S/N), main effects, and analysis of variance (ANOVA)[17]. The signal-to-noise (S/N) ratio can be calculated in three ways: the nominal is the best, the larger is the better, and the smaller is the better. The "smaller is better" method will be employed in this study because the desired surface roughness value is the smallest considered the best. The formula for calculating the "smaller is better" criterion will be demonstrated in Equation 1 [18].

$$S/N = -\log 10 \left(\frac{1}{n}\sum_{k+1}^{n} yi^2\right) \quad (1)$$

3. Results and Discussion

3.1 Surface Roughness (Ra)

The experimental data for this research originates from surface roughness (Ra) measurements on the workpieces. This data is subsequently processed and analyzed using the Taguchi method. The results of the Ra measurements are presented in Table 4. According

Table 1. DOE 3 factors and 3 levels

	Factors	Level A	Level B	Level C
1	Spindle speed (rpm)	900	1000	1300
2	Feed rate (m/min)	0,5	1	1,5
3	Depth of cut (mm)	0,5	1	1,5

Table 2. Orthogonal array L9

Test	*Spindle speed*	*Feed rate*	*Depth of cut*
1	900	0.5	0.5
2	900	1	1
3	900	1.5	1.5
4	1000	0.5	1
5	1000	1	1.5
6	1000	1.5	0.5
7	1300	0.5	1.5
8	1300	1	0.5
9	1300	1.5	1

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Published online: December 27, 2023
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Fig. 3. Surface roughness tester

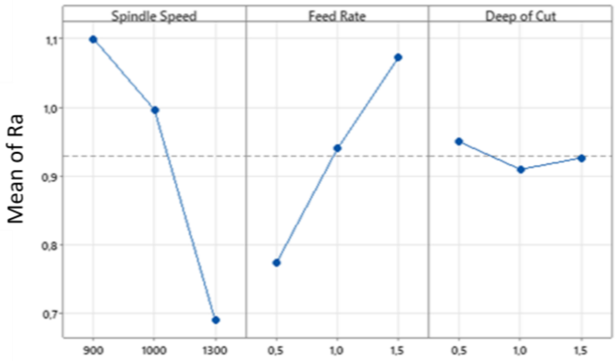

Fig. 4. The influence of machining processes on surface roughness

to the initial analysis of the table, surface roughness values increase with the rise in spindle speed and the decrease in feed rate. A spindle speed of 1300 RPM, feed rate of 0.5 m/min, and depth of cut of 1.5 mm yield the most optimal surface roughness (Ra) value.

The Taguchi analysis has been conducted using Minitab for more detailed analysis. This analysis encompasses mean plots, signal-to-noise ratios (S/N ratios), and ANOVA (analysis of variance) results to assess differences.

3.2 The Influence of Machining Processes on Surface Roughness

Fig. 4 illustrates how process parameters impact the surface roughness (Ra) values. It can be observed that increasing the spindle speed tends to reduce the Ra value. It occurs because the cutting tool will engage the material more smoothly and efficiently when the spindle operates at a higher speed. The smoother movement reduces scratches and fluctuations on the surface profile of the workpiece, resulting in a lower Ra value [19]. Furthermore, as illustrated in Fig. 4, the Ra value increases with higher feed rates. The cutting tool moves more quickly with increased feed rates, resulting in higher material removal rates. It can lead to rougher scratches and an increase in surface roughness. Surfaces processed with higher Feed rates will have deeper scratches and more fluctuations in their surface profiles, which is reflected in higher Ra values [20].

In the literature, Selvaraj et al. [21] Spindle speed, feed rate, and depth of cut as machining process parameters to be used, along with employing Taguchi analysis, were performed on surface roughness during their research. The findings of this study are consistent with the results reported in the literature [7,13,21].

Table 3. Chemical composition of Aluminum Alloy 6063

	Si	Cu	Mg	Zn	Mn	Ti
Composition	0.20	0.10	0.45	0.10	0.10	0.10

Table 4. Surface roughness value

Run	Spindle speed	Feed rate	Depth of cut	Ra	S/N
1	900	0.5	0.5	1,05	-0,42
2	900	1	1	1,08	-0,67
3	900	1.5	1.5	1,17	-1,36
4	1000	0.5	1	0,75	2,50
5	1000	1	1.5	1,09	-0,75
6	1000	1.5	0.5	1,15	-1,21
7	1300	0.5	1.5	0,52	5,68
8	1300	1	0.5	0,65	3,74
9	1300	1.5	1	0,90	0,92

Table 5. S/N ratio response table for surface roughness

Symbol	Level	Spindle speed	Feed rate	Depth of cut
X	1	-0.82	2.59	0.70
Y	2	0.18	0.77	0.92
Z	3	3.45	-0.55	1.19
	Delta	4.26	3.14	0.49
	Rank	1	2	3

3.3 Optimal Machining Parameter Selection

Table 5 presents the S/N ratio response table for Ra, and Fig. 5 illustrates the average S/N ratio plot generated using Minitab software.

In Fig. 5, a spindle speed of 1300 rpm, feed rate of 0.5 m/minute, and depth of cut of 1.5 mm exhibit the highest average S/N ratio for Ra. Bold font is used to enhance table comprehensibility. X3, Y2, and Z3 represent the predicted optimal combinations for surface roughness.

3.4 Analysis of Variance (ANOVA)

In analysis of variance (ANOVA), F-value, P-value, degrees of freedom, and sum of squares are used to indicate the contribution of each examined factor. From the main effects plot, spindle speed and feed rate are the two main factors influencing the Ra value. However, the extent of the machining

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Published online: December 27, 2023
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Table 6. Analysis of variance (ANOVA) for surface roughness

Source	DF	Seq SS	Contribution (%)	Adj SS	Adj MS	F	P
Spindle speed	2	29.85	59.71	29.85	14.93	6.11	0.14
Feed rate	2	14.90	29.80	14.90	7.45	3.05	0.25
Depth of cut	2	0.36	0.72	0.36	0.18	0.07	0.93
Residual error	2	4.88	9.77	4.88	2.44		
Total	**8**	**49.99**	**100**				

Table 7. Percentage of prediction error and experimental value surface roughness value (Ra)

Spindle speed	Feed	Depth of cut	Experimental value	Prediction value	% Error
1300	0.5	1.5	0.53	0.52	2.26

parameters' contribution to the Ra value must be quantified. Therefore, ANOVA is used to calculate Adj SS (adjusted sum of squares), Adj MS (adjusted mean squares), F-value, and P-value to determine the contributions of the factors considered in this investigation. Table 6 provides the contributions from all these factors. The most influential factor is spindle speed, contributing 59.71%. The feed rate contributes 29.80%, and the depth of cut contributes 0.72%.

3.5 Validation Test

The prediction formula was generated using Minitab software, and a confirmation test was conducted to ensure its accuracy. The confirmation test was carried out with the optimal parameters of 1300 rpm spindle speed, 0.5 m/minute feed rate, and 1.5 mm depth of cut. The obtained research results in this study, where the surface roughness value (Ra) is measured at 0.532 µm, greater than the initial value, demonstrate highly favorable outcomes in the confirmation test. The experimental and predicted results exhibit minimal disparity, with an error percentage of approximately 2.26%. Table 7 displays the comparison between predicted and experimental values. The Taguchi technique has proven effective in predicting and optimizing the response.

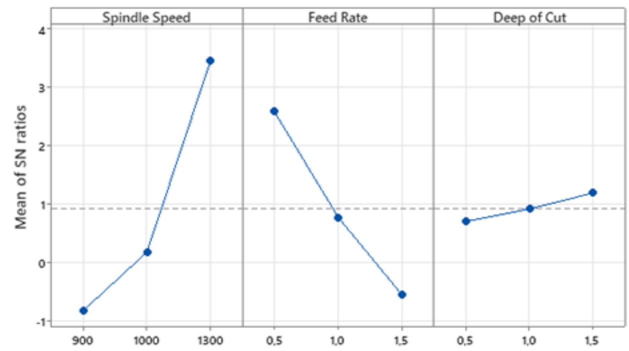

Fig. 5. Means surface roughness ratio S/N

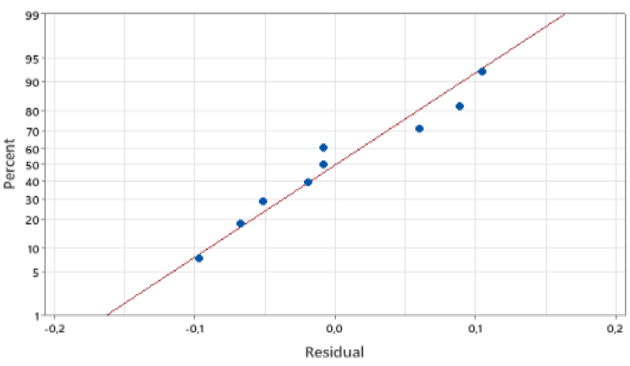

Fig. 6. Normalized probability plot of the residuals for surface roughness

3.6 Regression equation

This study employed Minitab software to construct a mathematical prediction model for the variable Ra, utilizing machining parameters such as spindle speed, feed rate, and cutting depth and employing linear regression analysis. Equation 2 represents the prediction equation for linear regression analysis.

$$Ra = 1{,}745 - 0{,}001024\ \textit{spindle speed} + 0{,}3000\ \textit{feed rate} - 0{,}0233\ \textit{depth of cut} \quad (2)$$

The coefficients in the predicted model were examined using a residual plot. Residual plots are utilized to determine the significance of coefficients in the prediction model. The appearance of a straight line in the residual plot indicates that residual errors in the model are normally distributed and that the coefficients are statistically significant. The residual plot for Ra is depicted in Fig. 6, indicating that the developed model has significant coefficients, as the residuals cluster around the straight line. It indicates that the residual errors of the model follow a normal distribution and that the coefficients are significant. These findings are consistent with previous research [7,13,21].

4. Conclusions

To achieve the smallest surface roughness, the ideal combination of cutting condition parameters is a spindle speed of 1300 rpm, a feed rate of 0.5 m/min, and a depth of cut of 0.6 mm. The ANOVA analysis shows that spindle speed contributes 59.71%, feed rate contributes 29.80%, and depth of cut contributes 0.72%. Based on the developed mathematical model, the experimental and predicted surface roughness (Ra) values have a prediction error percentage of 2.26%.

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Vol.5 (No.2). 2023. pp. 56-62
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