Material Removal Rate Study on Turning of Al Alloy

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Abstract. Material removal rate (MRR) can indicate how efficiently the lathe machine is cutting the workpiece, and surface roughness can indicate the quality of the machined part. In this study, the material removal rate (MRR) and surface roughness (Ra) of the turning of aluminium alloy were investigated using turning process parameters such as depth of cut, spindle speed, and feed to find the optimum combinations of parameters. An experiment has been designed with factorial design and the use of an L27 orthogonal array. This work uses a CNC lathe machine to cut the workpieces to a constant length while varying the three parameters: spindle speed, feed, and depth of cut. Then the surface roughness was measured with the surface roughness tester and material removal rate was calculated with turning parameters. The results are used to proceed to find out which is the most influential factor among the three parameters using statistical software and full factorial analysis. The results showed that spindle speed influences both MRR and Ra the most. The best Ra will be produced because the experimental value of 1.932 μm is within the 95% prediction interval. Due to experiment error for MRR, we could not accept the optimum parameters of 1000 rpm spindle speed, 100 mm/min feed and 0.6 mm depth of cut as the experiment MRR value of 2789.76 cm^3/min does not fall within the 95% confidence interval (CI) or 95% prediction interval (PI).

Keywords: material removal rate · surface roughness · spindle speed · depth of cut · feed · factorial design

1 Introduction

Turning is a material removal process by removing excess material from the workpiece to make accurate circular shapes to a higher tolerance level and better surface finishes. Productivity increased as a result of the use of CNC machines. The quantity of material removed (MRR) is a direct indicator of how efficient manufacturing operations are with the use of cutting machines. The more the material is removed, the higher the profit. There are a few cutting parameters that will affect the surface roughness and material removal rate of a machined product, such as cutting depth, feed, and spindle speed. It is crucial for a manufacturer to know the optimum parameter settings for machining. Much research has been conducted to find out the optimum cutting parameters to produce

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high MRR and better surface roughness and which cutting parameters will affect the MRR and surface roughness the most. The Taguchi Method [1–4] was used by many researchers and shows that different combinations of cutting parameters have different MRR and surface roughness. Factorial Design is an experiment setup that can study multiple factors with multiple levels and determine if any of the factors influence the subject of interest in the experiment and how they influence it [5, 8]. The factorial design, more accurate than the Taguchi Method. However, the cost and time to conduct the experiment as it requires all possible combinations of parameters is a disadvantage. The Minitab statistical software is a great tool that can analyse the result with the use of full factorial analysis to find out whether our data is statistically significant and which parameter has the most influence on the MRR. And surface roughness. In this study the chosen factors are cutting depth, spindle speed and feed with three levels of each parameters selected with the reference of previous study.

Aluminium alloy is one of the most commonly extruded alloys which has medium to high strength, good corrosion resistance, machinability and workability and hence it is ideal for a wide range of applications [6]. Carbide cutting tool are cutting tool that are layered with carbide which strengthen and improve its cutting performance [7]. Carbide insert allows faster machining as it is sharper than conventional steel and yield better surface finishes on metal parts as the material we are cutting is Al-6061. During high cutting speeds will produce high machining temperatures but carbide insert can still retain its cutting edge hardness. Besides carbide inserts are cost effective and efficient compared to other cutting tools and they also come in different shapes and grades that can be used in numerous applications.

Palaniappan et al. experimentally investigated on turning parameters optimization on Aluminium 6082 alloy by analysis of variance and Taguchi technique and concluded that the most important parameter for MRR was speed of the spindle [1] while Aryan. et al. investigated on Aluminium material to obtain higher MRR by turning process parameter optimization using signal noise ratio. From the study he concluded that rate of feed is most powerful turning parameters that impact the material removal while turning trailed by cutting depth and speed of cut [2]. Kamal et al. carried out an experimental research of MRR in CNC turning using Taguchi method and concluded that the MRR is primarily impacted by rate of feed and speed of cutting. When the cutting speed increases, the material removal rate is increased and the increase in feed hence the MRR increased [3]. Sayak Mukherjee et al. studied the outcome of process parameters on material removal rate by L25 orthogonal array. The analysis showed that the important factor on material removal is cutting depth followed by feed. When the dep of cut increased material removal increased [4].

Aswal et al. in his research of optimization of turning parameters for roughness of surface using CNC machine on Al6061 established that for best condition of surface roughness are cutting speed, 45%; feed is 36% and cutting depth, 19%. The estimated error is approximately 5 percentages for the lower surface roughness [9]. Ic investigated turning of Aluminium for cutting parameters optimization using RSM for higher quality and lowering the consumption of energy. The surface roughness is one of the factor which defines the quality. He concluded that among them rate of feed is considered the important parameter for minimizing surface roughness [10].

Vinoth Kumar et al. reported that speed is the utmost prompting parameter for higher material removal trailed by speed and cutting depth. The optimum values of speed is 55 rpm, feed is 50 mm/min [11]. Sunil and Deepak established that the MRR is greatly inclined by depth of cut than the feed and speed. MRR grows with rise of spindle rotation, tool feed and cutting depth. Temperature largely inclined to depth of cut than feed and speed. Temperature shows a lower trend with increase of speed and increasing trend with feed and depth of cut [12]. Lastly, Prasad Kumar et al. in their research concluded that machining with coolant tend to remove more material than without coolant. Material removal quantity is increased at two times with increasing in feed. Increasing cutting speed and depth of cut is found to increase the material removal by 70% and 16% correspondingly [13].

2 Materials and Methodology

The MTAB XL-Turn has been used in this study is a 2-axis, slant bed turner which has multi station turret. This machine uses Fanuc control system with MTAB industrial control. MTAB XL-Turn has an integrated module for automation to create Smart Automation such as flexible and computer integrated automation that uses advanced technologies such as artificial intelligence to analyze data [14].

Each parameter levels were chosen based on the pilot study and within the accepted range of the CNC Lathe MTAB XLTurn machine, are shown in Table 1.

Based on the multilevel factorial design, the L27 orthogonal array was used in this experiment. The input parameter design and the measured output data are shown in Table 2. Turning of workpiece was carried out using the experiment plan. MRR was calculated using the turning parameters used. Roughness of the workpiece measured using Mahr measuring instrument and tabulated.

Table 1. Process parameters and their levels

Parameters	Levels		
Speed, (rpm)	500	700	1000
Feed, (mm/min)	50	70	100
Depth of cut, (mm)	0.2	0.4	0.6

Table 2. L27 Orthogonal Array and output

S.No.	Input parameters			Output	
	Speed (rpm)	Feed (mm/min)	depth of cut (mm)	Surface Roughness (Ra)	MRR (cm^3)
1	500	50	0.2	1.77	251.33
2	500	70	0.2	4.44	329.87

(*continued*)

Table 2. (*continued*)

S.No.	Input parameters			Output	
	Speed (rpm)	Feed (mm/min)	depth of cut (mm)	Surface Roughness (Ra)	MRR (cm^3)
3	500	100	0.2	1.18	471.24
4	500	50	0.4	1.30	502.66
5	500	70	0.4	4.31	659.74
6	500	100	0.4	4.44	1005.32
7	500	50	0.6	3.66	753.99
8	500	70	0.6	1.72	1055.59
9	500	100	0.6	5.47	1507.98
10	700	50	0.2	1.49	351.86
11	700	70	0.2	1.12	461.82
12	700	100	0.2	1.18	659.74
13	700	50	0.4	1.25	703.72
14	700	70	0.4	1.17	923.64
15	700	100	0.4	1.94	1407.44
16	700	50	0.6	1.48	1055.58
17	700	70	0.6	1.69	1477.81
18	700	100	0.6	1.64	2111.16
19	1000	50	0.2	1.93	502.66
20	1000	70	0.2	1.42	659.74
21	1000	100	0.2	0.94	942.48
22	1000	50	0.4	1.44	1005.32
23	1000	70	0.4	1.04	1319.47
24	1000	100	0.4	1.42	2010.64
25	1000	50	0.6	1.08	1507.98
26	1000	70	0.6	1.13	2111.17
27	1000	100	0.6	1.33	3015.96

3 Results and Discussion

Minitab statistical software factorial design is used to analyze the collected data to study the cutting parameters for surface roughness and material removal rate of turning of Al 6061.

Table 3. Result of ANOVA for MRR

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	6	8870381	1478397	36.95	0.000
Linear	6	8870381	1478397	36.95	0.000
Spindle Speed	2	1930568	965284	24.13	0.000
Feed Rate	2	2304131	1152066	28.80	0.000
Depth of Cut	2	4635682	2317841	57.93	0.000
Error	20	800157	40008		
Total	26	9670538			

3.1 ANOVA for MRR

Table 3 shows the result of the Analysis of Variance (ANOVA) for MRR. The F-value shows no changes within the data mean, where the greater the F-value, the greater the difference between the data means relative to the difference within the samples. Thus, we can see that the depth of cut has the largest F-value. This is evidence that there is a difference between the group means. The alpha, or, α with a value of 0.05 indicates the significance level, where $\alpha = 0.05$ denotes that there is a 5% risk of making a conclusion that there is a difference occurring in the design, but in fact, the design does not. As we can see from Table 3, the p-value is extremely small and rounded to 0, as the software shows only 3 digits of significant figures, so we can assume they are $P < 0.001$ where the null hypothesis of the ANOVA states that the design does not describe any differences in the response. Hence, we can further investigate if there is a statistically important factor between the mean of the three factors.

Table 4 shows the coefficient table for MRR. As we can see, the P-value for the 3 cutting parameters is larger than 0.05 so it is evident that the null hypothesis is well established as $P > \alpha$ means we lack enough proof to state that among the cutting parameters there is a statistically significant factor. The variance inflation factor (VIF) is 1.33 where $1 < \text{VIF} < 5$ means the predictors are moderately correlated. If $\text{VIF} > 5$ it will be highly correlated where the coefficients are unstable, which means that even though there is a crucial correlation between the predictor and the response, it is shown to be statistically insignificant.

As we can see all three cutting parameters crossed the reference line of 2.09 in Fig. 1. Thus, all three parameters are statistically significant.

Figure 2 is the residual plots for MRR which include the residuals versus fits, normal probability plot of residuals, residuals versus orders plot and a histogram. As seen in the normal probability plot there is a point, RESI1 with a value of 517.50 which is far away from the red line and versus fits graph plot show a nonlinear pattern where the residual values are positive when the fitted values are small and negative residual values when the fitted values are in the middle and positive when the fitted values are large. In histogram, the 350,450 bar is far away from the 150,250 bar and left a gap between them indicates there is an outlier which are the parameters of speed of 1000 rpm, feed of

Table 4. Coefficients table for MRR

Term	Coef	SE Coef	T-value	P-value	VIF
Constant	1042.6	38.5	27.08	0.000	
Speed					
500	−305.3	500	−6	0.000	1.33
700	−40.6	500	−1	65.000	1.33
Feed					
50	−331.7	500	−6.09	0.000	1.33
70	−47.4	500	−1	0.390	1.33
Depth					
0.2	−510.2	54.4	−9.37	0.000	1.33
0.4	5.5	54.4	0.1	0.92	1.33

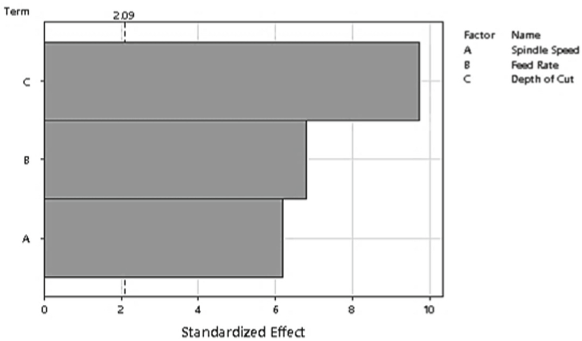

Fig. 1. Pareto chart of the standardized effects for MRR

100 mm/min and 0.6 mm cut depth. Outliers will cause the mean of our data to be much higher and will skew our results and affect our mean value by a significant amount. The outlier test is carried out and the result is as shown in Fig. 3 and it shows that the MRR of 2789.76 cm^3/min is an outlier.

Figure 4 is the main effect plot for MRR. From main effect plot we can know that depth of cut has the most influence on the MRR as it has the longest line and the greatest slope of gradient accompanied by the feed and speed respectively. We can also find out that at speed 1000 rpm, a feed 100 mm/min and a 0.6 mm cut depth will produce the largest MRR.

As we can see in Fig. 5, there are no interactions at all between the process parameters which are the factors. There is no interaction among the three factors so we accept the null hypothesis.

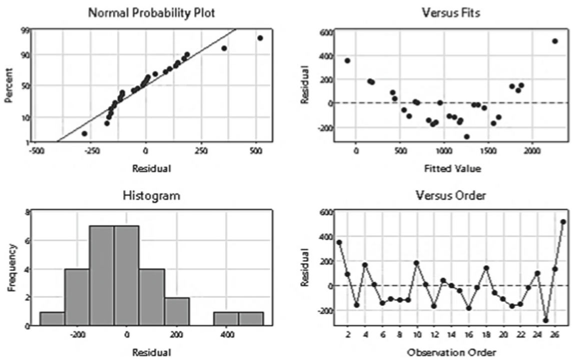

Fig. 2. Residual plots for MRR

Method

Null hypothesis All data values come from the same normal population

Alternative hypothesis Smallest or largest data value is an outlier

Significance level $\alpha = 0.05$

Grubbs' Test

Variable	N	Mean	St Dev	Min	Max	G	P
MRR	27	1043	610	251	2790	2.9	0.049

Outlier

Variable	Row	Outlier
MRR	27	2789.76

Fig. 3. Outlier test for MRR

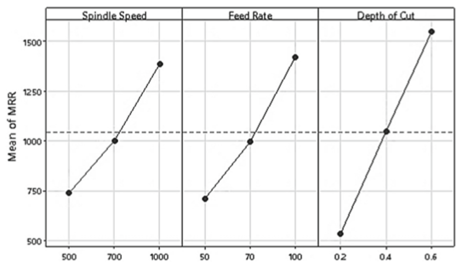

Fig. 4. Main effect plot for MRR

The response optimization is also carried out for MRR to confirm whether the simulated or fitted values are within the range of the true MRR with parameters of spindle rotation of 1000 rpm, feed of 100 mm/min and 0.6 mm cutting depth which is 2789.76 cm^3/min. As shown in Fig. 6 the predicted MRR is 2272.26 cm^3/min with the setting of maximizing MRR which is the greater the MRR the better. As the result is not statistically significant mentioned previously therefore our true MRR does not fall in the range of 95% Confidence Interval (CI) and 95% Prediction Interval (PI) in Fig. 7.

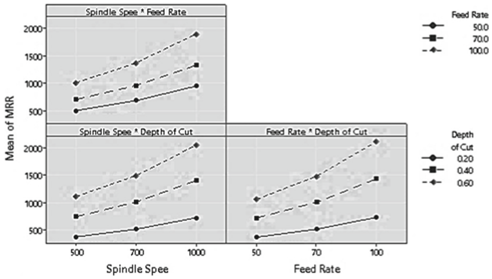

Fig. 5. Interaction plot for MRR

Parameters

Response	Goal	Lower	Target	Upper	Weight	Importance
MRR	Maximum	251.33	2709.76		1	1

Solution

Solution	Speed	Feed Rate	Depth of Cut	Fit	Desirability
1	1000	100	0.6	2272.3	0.79613

Fig. 6. Results of response optimization for MRR

Variable	Setting
Spindle Speed	1000
Feed Rate	100
Depth of Cut	0.6

Response	Fit	SE Fit	95% CI	95% PI
MRR	2272	102	(2060, 2485)	(1804, 2740)

Fig. 7. Multiple response prediction for MRR

3.2 ANOVA for Surface Roughness

As we can see in Table 5 which is the table for the result of ANOVA for surface roughness, Ra, the F-value for spindle speed is the largest which is 8.97 and the P-value is 0.002, $P < 0.005$ hence we deny the null hypothesis. The spindle speed is the only statistically significant factor as the P-value for feed and depth of cut are larger than 0.05.

From Table 6 which is the coefficient table for Ra, we can see that only spindle speed is statistically significant and the VIF is 1.33 which is moderately correlated. Thus, we have enough evidence to reject the null hypothesis.

From the fits and diagnostics for unusual observations in Fig. 8, we can see that there are no unusual observations as they can produce misleading results like causing significant results to be insignificant with the denote of R circled. If there is an unusual observation, it will show X instead of R.

Through the Pareto Chart for Ra as shown in Fig. 9, we can see that only factor A which is the spindle speed crossed the red line of 2.086. Thus only the spindle speed is statistically significant among the three parameters.

Figure 10 is the residual plots for surface roughness produced by Minitab which include the residuals versus fits, normal probability plot of residuals, a histogram and residuals versus orders plot. As you can see in the plots below, they are randomly

Table 5. ANOVA results for surface roughness

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	6	20.752	3.459	3.280	0.021
Linear	6	20.752	3.459	3.280	0.021
Speed	2	18.930	9.465	8.970	0.002
Feed	2	0.973	0.487	0.460	0.637
Depth of Cut		0.849	0.424	0.400	0.674
Error	20	21.096	1.055		
Total	26	41.849			

Table 6. Coefficient table for surface roughness

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	1.963	0.198	9.93	0.000	
Speed					
500	1.182	0.280	4.23	0.000	1.33
700	−0.524	0.280	−1.87	0.076	1.33
Feed					
50	−0.250	0.280	−0.90	0.381	1.33
70	0.042	0.280	0.15	0.883	1.33
Depth of cut					
0.2	−0.244	0.280	−0.87	0.393	1.33
0.4	0.073	0.280	0.26	0.796	1.33

Obs	Surface Roughness	Fit	Read	Std Reed	
7	1.181	3.109	-1.928	-2.18	R
9	5.472	3.525	1.947	2.2	R

R Larger residual

Fig. 8. Fits and diagnostics for unusual observations

dispersed where the plots for Ra in the plot form an almost straight line pattern which means the design is acceptable, the residuals versus fits plot does not show a nonlinear pattern, the histogram is normally distributed with the mean of 0. The residual versus order plot is also good as the data does not show a trend, shift or cycle pattern. The outlier test is carried out for surface roughness as shown in Fig. 11 and there is no outlier.

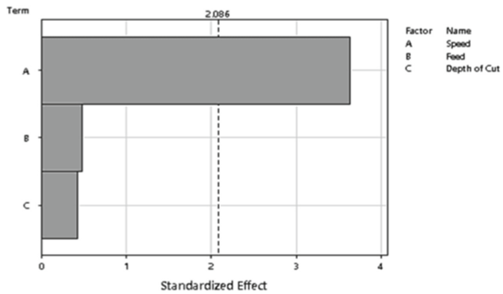

Fig. 9. Pareto chart for surface roughness

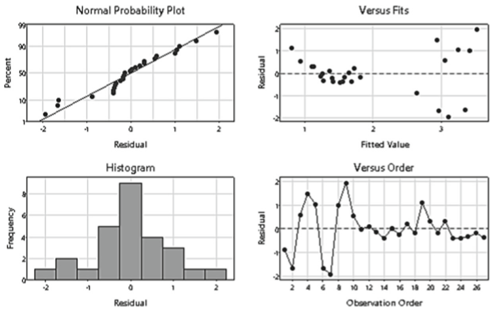

Fig. 10. Residual plots for surface roughness

Method
Null hypothesis All data values come from the same normal population
Alternative hypothesis Smallest or largest data value is an outlier
Significance level α = 0.05
Grubbs' Test

Variable	N	Mean	StDev	Min	Max	G	P
Surface Roughness	27	1.963	1.269	0.944	5.472	2.77	0.075

• NOTE • No outlier at the 596 level of significance

Fig. 11. Outlier test for surface roughness

Figure 12 is the surface roughness main effects plot that is created by Minitab, from this main effect plot we can know that spindle speed has the most influence on the surface roughness as it has the longest line and the greatest slope or gradient accompanied by the feed and depth of cut. We can also find out that with spindle speed of 1000 rpm, a feed of 50 mm/min and 0.2 mm depth of cut will produce the smallest surface roughness.

Figure 13 is the interaction plot for surface roughness, we can see that the three graphs have a lot of crossed interaction or nonparallel lines, which means the strength of the interactions is great. From the main effect plot, we can see that 1000 rpm speed, 50 mm/min feed and 0.2 mm cutting depth produce the low roughness. Through the spindle speed and feed interaction plot, we can see with the rise of speed, the Ra decreases significantly while the difference between the feeds does not influence the surface roughness that much at high spindle speed. The result is similar for the second interaction plot among speed and cut depth. Hence we can say that speed affects the most among the

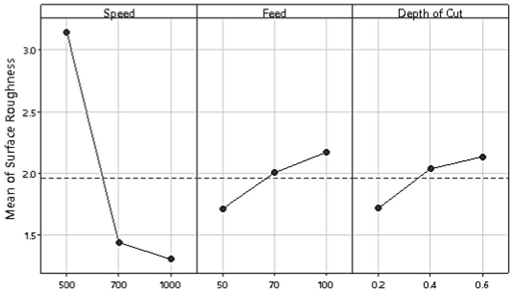

Fig. 12. Main effect plot for surface roughness

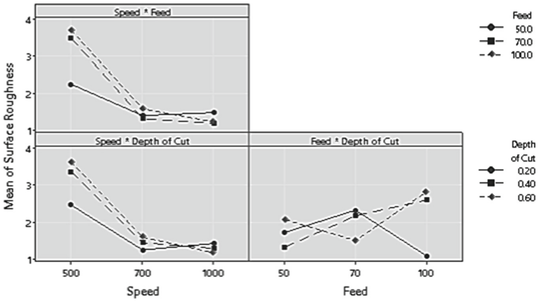

Fig. 13. Interaction plot for surface roughness

three factors. With the interaction plot between feed and cut depth, we can see that as the feed increase, the surface roughness is getting larger so we want the lowest rate of feed possible. From the last graph on the right, we can clearly see that 0.40 mm cut depth increase the Ra with the increment of feed so it is eliminated and 0.2 mm has the lowest surface roughness at 50 mm/min feed. Thus, the best possible combination of process parameters with a speed of 1000 rpm, feed of 50 mm/min and 0.2 mm cutting depth is accepted.

The response optimization is also carried out for surface roughness with the use of Minitab to confirm whether the simulated or fitted values are within the range of the true surface roughness with parameters of spindle speed of 1000 rpm, feed rate of 50 mm/min and 0.2 mm cutting depth, which is 1.932 μm. As shown in Fig. 14, the predicted MRR is 0.8101 μm with the setting of minimising surface roughness, which means the smaller the surface roughness, the better. In Fig. 15, we can see that our true surface roughness with the optimised parameters is slightly outside the 95% CI range, but it is still within the 95% PI, indicating that if the experiment is repeated, there is a 95% chance that 1.932 m of surface roughness will be contained within the prediction interval.

Parameters

Response	Goal	Lower	Target	Upper	Weight	Importance
Surface Roughness	Minimum		0 .944	5 472		1

Solution

Solution	Speed	Feed	Depth of Cut	Surface Roughness Fit	Composite Desirability
1	1000.	50.	0.	0.810108	

Fig. 14. Response optimization for surface roughness

Variable	Setting
Spindle Speed	1000
Feed	50
Depth of Cut	0.2

Response	Fit	SE Fit	95% CI	95% PI
Surface Roughness	0.81	0.523	(-0.281,1.901)	(-1.594, 3.214)

Fig. 15. Multiple response prediction for surface roughness

4 Conclusion

A factorial design is used to study the surface roughness and material removal rate on the turning of the Aluminium 6061 alloy. The experiment design used was the L27 orthogonal array. The Minitab Statistical Software is used to analyse the data for this experiment. The conclusions drawn from the present experimental work are as follows:

Through the analysis of the results, it is concluded that the cutting depth is the most influential cutting parameter that will affect the MRR on the turning of Aluminium 6061 and followed by feed and spindle speed, respectively. However, it is regrettable that we cannot accept the results for the experiment for MRR as it is nullified by the null hypothesis as the data does not show any variations or interactions between the parameters in the software. Maybe this is due to my MRR data being calculated through a formula, as the MRR increases proportionally with increasing spindle speed, cutting depth, and feed in the formulas used. Thus, the MRR increases as the parameter value increases and shows no variations or interactions in the results.

According to the findings, the spindle speed is the only cutting parameter that influences the surface roughness on the turning of aluminium 6061. Through the plot between spindle speed and cutting depth and the interaction plot between spindle speed and feed, we can clearly see that with increasing spindle speed we can obtain better surface roughness with a smaller Ra, while the level of cutting depth and feed does not change too much in these two plots. The optimum parameters for surface roughness are 1000 rpm, 0.2 mm cutting depth, and 50 mm/min feed through the response optimization with Minitab. The experimental surface roughness of 1.932 μm is accepted as it falls within the range of 95% PI.

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Authors' Contributions. Author 2, designed and planned the experiment. Author 1, carried out the experiment under the supervision of author 2. Author 1, collected the data and perform data analysis with the help of author 2. Author 1, drafted the paper. Both the authors contributed to the final version of the paper.

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