Experimental Optimization of Cutting Parameters in Flat-Surface End Milling Using the Taguchi–Desirability Approach

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ABSTRACT

Flat-surface end milling is extensively used in the manufacturing of mechanical components and machine elements, where both surface quality and machining efficiency are important performance indicators. However, the selection of cutting parameters often involves a trade-off between surface roughness and machining time. The optimal conditions reported in the literature are not always directly transferable to different machining systems. In this study, cutting parameters for flat-surface end milling of ALU 6061 were experimentally optimized using the Taguchi method combined with desirability analysis within a practically feasible machining domain. Milling experiments were conducted on a GMS 800 three-axis CNC machine using an 8 mm solid carbide end mill, with spindle speed and feed per tooth selected as the primary control factors. Surface roughness and machining time were evaluated for each experimental run based on an L9 orthogonal array. Signal-to-Noise Ratio (SNR) analysis showed that feed per tooth is the most influential parameter on both surface roughness and machining time, accounting for approximately 65.8% of the total effect on surface quality. Empirical regression models were established to quantify the relationships between cutting parameters and machining responses, and their adequacy was examined through residual analysis. Multi-response optimization using a desirability function identified an optimal cutting condition of 3000 rpm spindle speed and feed per tooth equal to 0.2506 mm/tooth , providing a balanced compromise between surface finish and productivity. Although the study does not propose a new optimization algorithm, it provides an experimentally validated, practically applicable guideline for selecting cutting parameters for flat-surface end milling under a specific machine–tool–workpiece configuration.

Keywords-milling; cutting parameter optimization; surface roughness; machining time; Taguchi method

I. INTRODUCTION

Flat-surface end milling is widely used for producing planar features in mechanical components, molds, and machine elements, and has been applied in the fabrication of various engineering structures, including thin-walled components [1]. The surface quality obtained from milling operations directly affects dimensional accuracy, assembly performance, and the service life of engineering products [2, 3]. Therefore, determining appropriate machining conditions that simultaneously ensure surface quality and productivity is an important issue in manufacturing engineering [4, 5].

The selection of cutting parameters plays a critical role in milling performance. Among the various machining parameters, spindle speed and feed per tooth have a strong impact on surface roughness and process stability [6, 7]. Feed per tooth determines the uncut chip thickness and affects the formation of feed marks on the machined surface, significantly influencing surface finish [8, 9]. Spindle speed also affects cutting dynamics, tool–workpiece interaction, and chip formation behavior, which may lead to variations in machining performance [10, 11].

To identify suitable machining conditions, many statistical optimization methods have been applied, including the Taguchi method, response surface methodology, and multi-objective optimization techniques [12, 13]. These approaches enable systematic investigation of machining parameters while reducing the number of required experiments. However, the optimal cutting conditions reported in previous studies are often dependent on specific machine tools, cutting tools, and machining environments, limiting the direct transferability of the obtained results to other machining systems [14, 15].

In addition, improving surface quality often leads to increased machining time, whereas increasing productivity may deteriorate surface finish. Therefore, it is necessary to determine cutting parameters that provide a balanced compromise between machining efficiency and surface quality [3, 7]. Recent studies on machining parameter modeling and multi-response optimization in milling have further confirmed the effectiveness of experimental–statistical approaches for balancing machining quality and productivity under practical cutting conditions [16].

Although more advanced optimization techniques have been reported, conventional methods such as the Taguchi design and desirability analysis remain valuable in practical manufacturing environments because they require limited experimental data and provide straightforward implementation and interpretation.

The present study contributes by establishing an experimentally validated and practically applicable framework for selecting cutting parameters in flat-surface end milling under a specific machine–tool–workpiece configuration. The contribution of this study is application-oriented, focusing on practical parameter selection under specific machining conditions rather than methodological innovation. Motivated by these considerations, this study experimentally investigates the effects of spindle speed and feed per tooth on surface roughness and machining time in flat-surface end milling of ALU 6061. Experiments were designed using an L9 orthogonal array within a feasible machining domain. Signal-to-Noise Ratio (SNR) analysis, regression modeling, and desirability-based multi-response optimization were employed to determine cutting parameters that simultaneously improve surface quality and machining productivity.

II. METHODOLOGY

Experiments were performed on an ALU 6061 workpiece using a GMS 800 three-axis CNC vertical milling machine, as shown in Figure 1. The workpiece was rigidly clamped to ensure machining stability. An 8 mm solid carbide end mill was utilized throughout the experiments, and all tests were conducted under dry climb-milling conditions. Spindle speed and feed per tooth were selected as the control factors based on tool manufacturer recommendations and preliminary machining trials on the GMS 800 CNC milling machine. The selected parameter levels were chosen to ensure stable cutting conditions while remaining within the practical operating capability of the machine–tool system. Surface roughness was measured using a contact-type roughness tester.

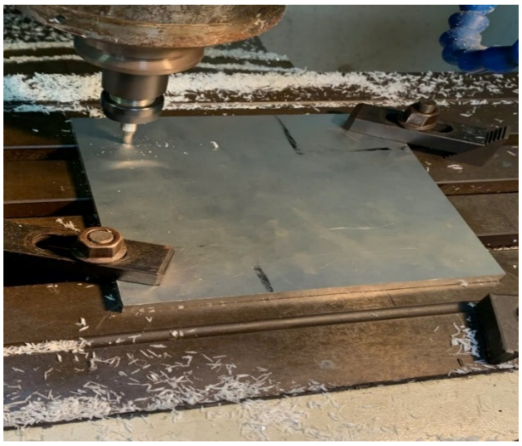


Fig. 1. Experimental setup for flat-surface end milling.

Table I presents the experimental design used in this study. Nine milling tests were performed by combining three spindle speed levels (2000, 2500, and 3000 rpm) with three feed-per-tooth levels (0.20, 0.30, and 0.375 mm/tooth). The parameter ranges were selected based on machine capability and preliminary trials. Figure 2 displays the surface roughness measurement procedure. After each milling test, surface roughness was measured using a contact-type tester along the feed direction. Multiple measurements were taken and averaged to improve measurement reliability.

TABLE I. CUTTING PARAMETERS AND EXPERIMENTAL DESIGN

Test no.	Cutting speed (rpm)	f_z (mm/tooth)
1	2000	0.200
2	2000	0.300
3	2000	0.375
4	2500	0.200
5	2500	0.300
6	2500	0.375
7	3000	0.200
8	3000	0.300
9	3000	0.375

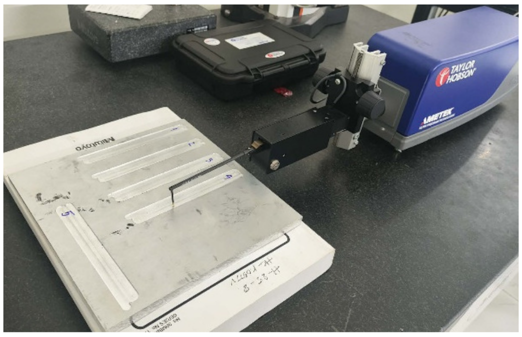


Fig. 2. Surface roughness measurement procedure.

III. RESULTS AND DISCUSSION

After designing the experiments according to the L9 orthogonal array and conducting the machining and measurements following the established procedure, a complete dataset was obtained, including machining time and surface roughness for each combination of cutting conditions.

Table II presents the experimental matrix based on the L9 orthogonal array together with the measured machining time and surface roughness for each cutting condition. The results show that increasing feed per tooth reduces machining time but increases surface roughness. The minimum roughness was obtained at 3000 rpm and 0.20 mm/tooth, highlighting the trade-off between machining efficiency and surface quality.

TABLE II. EXPERIMENTAL MATRIX AND MEASURED RESULTS

Test no.	**Spindle speed, n (rpm)**	**Feed per tooth, f_z (mm/tooth)**	**Machining time, $T_{(s)}$**	**Average surface roughness, $Ra_{(\mu m)}$**
1	2000	0.2	23	3.885
2	2000	0.3	19	4.041
3	2000	0.375	18	4.84
4	2500	0.2	22	4.932
5	2500	0.3	19	4.95
6	2500	0.375	15	5.119
7	3000	0.2	19	3.356
8	3000	0.3	15	4.689
9	3000	0.375	13	4.786

Table III presents the SNR response values for surface roughness R_a calculated using the smaller-is-better criterion in the Taguchi method. The results indicate that spindle speed achieves the highest SNR at Level 3 (–12.51 dB), while Level 2 yields the lowest value. For feed per tooth f_z, the maximum SNR occurs at Level 1 (–12.05 dB), indicating improved surface finish at lower feed values. The delta values show that feed per tooth has a stronger influence on surface roughness than spindle speed. Therefore, the optimal parameter combination for minimizing surface roughness is $n_3 f_{z1}$.

TABLE III. SNR FOR SURFACE ROUGHNESS Ra

Level	**n (rpm)**	**f_z (mm/răng)**
1	-12.54	-12.05
2	-13.98	-13.15
3	-12.51	-13.83
Delta	1.47	1.77
Rank	2	1

Table IV presents the mean response values for surface roughness. The delta values indicate that feed per tooth (f_z) has a stronger influence on surface roughness than spindle speed (n). Increasing f_z leads to higher surface roughness due to the larger uncut chip thickness generated during milling. Figure 3 illustrates the combined effects of spindle speed n and feed per tooth f_z on the surface roughness Ra during flat-surface end milling. An increasing trend in surface roughness is observed with increasing feed per tooth across the investigated spindle speed range. When f_z increases from 0.20 to 0.375 mm/tooth, the surface roughness increases from approximately 3.8–4.0 µm to values exceeding 4.8–5.0 µm, indicating that feed per tooth is the dominant factor influencing surface quality. This behavior can be attributed to the increased uncut chip thickness at higher feed rates, which results in deeper tool marks and higher surface irregularities.

TABLE IV. RESPONSE FOR MEAN SURFACE ROUGHNESS (Ra).

Level	**n (rpm)**	**f_z (mm/tooth)**
1	4.255	4.058
2	5.000	4.560
3	4.277	4.915
Delta	0.745	0.857
Rank	2	1

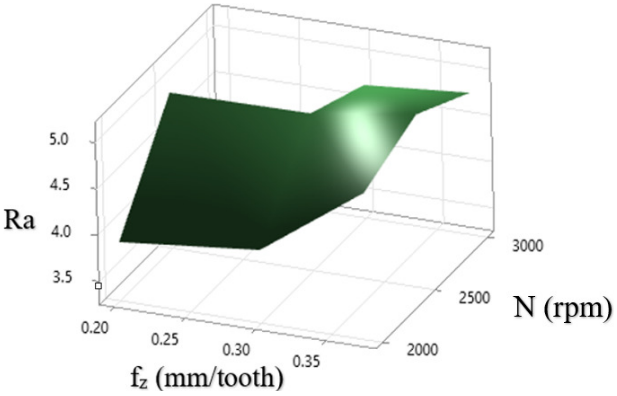


Fig. 3. Effect of spindle speed and feed per tooth on surface roughness.

The influence of spindle speed on surface roughness is less significant than that of feed per tooth. At lower feed levels ($f_z = 0.20$ mm/tooth), increasing spindle speed from 2000 to 3000 rpm slightly reduces surface roughness. However, at higher feed values ($f_z \geq 0.30$ mm/tooth), surface roughness is mainly governed by feed-related effects. Figure 4 presents the contour plot of surface roughness R_a as a function of spindle speed n and feed per tooth f_z. A combined influence of both parameters on surface roughness can be observed. In general, surface roughness increases with increasing feed per tooth, whereas the effect of spindle speed is non-monotonic within the investigated range.

At low feed per tooth values ($f_z \approx 0.20$–0.25 mm/tooth), relatively low surface roughness values are obtained, with R_a remaining below approximately 4.0 µm across most spindle speeds. The minimum roughness region is located at low feed per tooth and either low ($n \approx 2000$ rpm) or high spindle speeds ($n \approx 3000$ rpm), where R_a values below 3.75 µm are observed.

As the feed per tooth increases beyond 0.30 mm/tooth, surface roughness increases markedly. In particular, at high feed per tooth levels ($f_z \approx 0.35$–0.375 mm/tooth), R_a exceeds 4.75 µm for most spindle speeds, indicating a dominant influence of feed per tooth on surface finish. This trend is consistent with the increase in uncut chip thickness, which leads to more pronounced feed marks and higher surface irregularities.

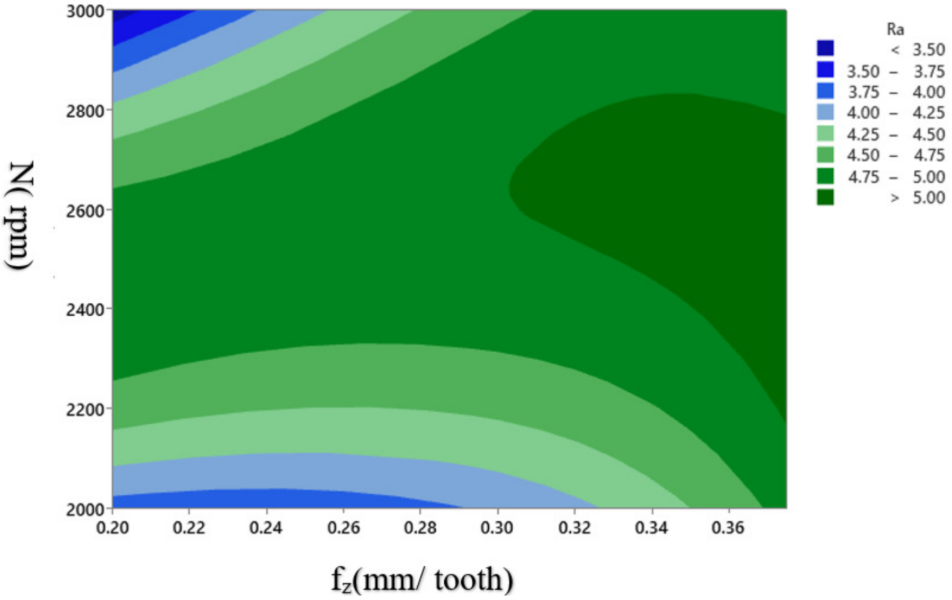


Fig. 4. Contour plot of surface roughness as a function of spindle speed and feed per tooth.

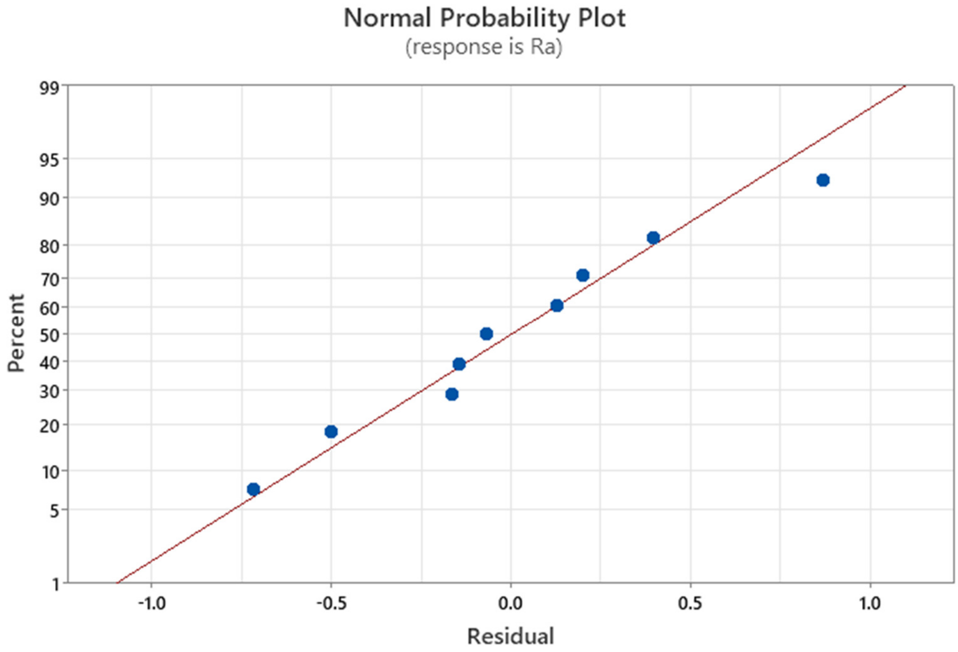


Fig. 5. Normal probability plot of residuals for surface roughness.

The contour plot also reveals that intermediate spindle speeds around $n \approx 2500$ rpm tend to produce higher surface roughness compared to lower and higher spindle speeds, especially at medium-to-high feed per tooth values. This behavior can be attributed to unfavorable dynamic conditions or increased tool–workpiece interaction at this spindle speed range. Based on the experimental results, a linear regression model was developed to describe the relationship between surface roughness and the selected cutting parameters. The resulting regression equation is expressed as:

$$R_a = 3.03 + 0.000022\,n + 4.91\,f_z \qquad (1)$$

where R_a is the surface roughness (μm), n is the spindle speed (rpm), and f_z is the feed per tooth (mm/tooth).

The regression coefficients indicate that both spindle speed and feed per tooth influence surface roughness. However, the coefficient associated with $f_z$is significantly larger, confirming that feed per tooth is the dominant factor. Increasing f_z leads to higher surface roughness due to the larger uncut chip thickness generated during milling.

As shown in Figure 5, the residuals are approximately aligned along the reference straight line, indicating that they follow a normal distribution. This behavior suggests that the regression model assumptions are satisfied and that the developed model is statistically adequate for predicting surface roughness within the experimental domain.

Table V presents the SNR response for machining time T using the smaller-is-better criterion. The results show that feed per tooth (f_z) has a greater influence on machining time than spindle speed (n), as indicated by the larger delta value. Increasing f_z reduces machining time by increasing the material removal rate. Figure 6 illustrates the combined effects of spindle speed n and feed per tooth f_z on machining time T. Machining time decreases as both parameters increase, consistent with the material removal rate relationship in end milling.

TABLE V. RESPONSE FOR SNR OF MACHINING TIME (T) (SMALLER-IS-BETTER)

Level	n (rpm)	f_z (mm/tooth)
1	-25.97	-26.55
2	-25.32	-24.89
3	-23.79	-23.64
Delta	2.18	2.92
Rank	2	1

At a low feed per tooth of $f_z = 0.20$ mm/tooth, machining time decreases from approximately 23–24 s at $n = 2000$ rpm to about 20–21 s at $n = 3000$ rpm, corresponding to a reduction of roughly 12–15%. This indicates that increasing spindle speed has a moderate but noticeable effect on reducing machining time when the feed per tooth is kept constant.

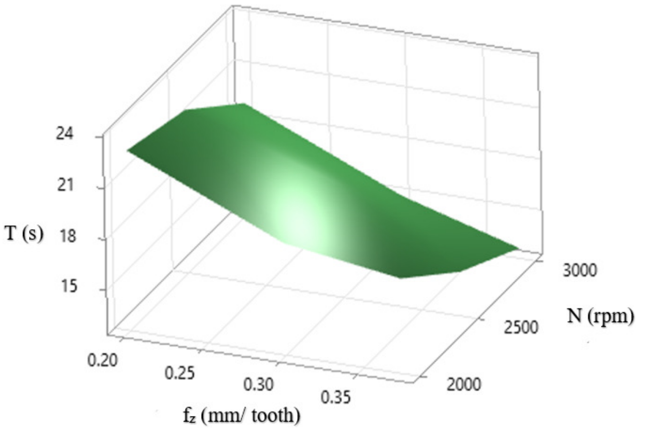


Fig. 6. Effect of spindle speed and feed per tooth on machining time.

The influence of feed per tooth is more pronounced. At a fixed spindle speed of $n = 2500$ rpm, increasing f_z from 0.20 to 0.375 mm/tooth reduces machining time from approximately 22 s to 16–17 s, representing a reduction of about 25–30%. This demonstrates that feed per tooth is the dominant parameter governing machining time in the investigated parameter range. The surface response further reveals a relatively smooth gradient, indicating stable process behavior without abrupt changes in machining time. The lowest machining time region is located at the combination of high spindle speed (≈3000 rpm) and high feed per tooth (≈0.375 mm/tooth), where machining time approaches its minimum value of approximately 15 s. Conversely, the longest machining time occurs at low spindle speed and low feed per tooth, exceeding 23 s.

Figure 7 illustrates the contour plot of machining time Tas a function of spindle speed n and feed per tooth f_z. A monotonic trend is observed with respect to feed per tooth. As f_z increases from 0.20 to 0.375 mm/tooth, the machining time decreases significantly across the entire spindle speed range. Quantitatively, at a low feed per tooth of $f_z \approx 0.20$ mm/tooth, the machining time exceeds 22 s, whereas at the highest feed per tooth of $f_z \approx 0.375$ mm/tooth, the machining time is reduced to below 14–16 s, corresponding to a reduction of approximately 30–40%. The influence of spindle speed on machining time is less pronounced than that of feed per tooth. Increasing spindle speed from 2000 to 3000 rpm slightly reduces machining time due to the higher material removal rate. The contour plot indicates that the minimum machining time occurs at high feed per tooth ($f_z \geq 0.35$ mm/tooth) and high spindle speed ($n \geq 2800$ rpm). Feed per tooth is the dominant factor affecting machining time.

The relationship between machining time and the cutting parameters was modeled using linear regression analysis. The resulting regression equation is expressed as:

$$T = 38.98 - 0.004333\,n - 34.41\,f_z \quad (2)$$

where T is the machining time (s), n is the spindle speed (rpm), and f_z is the feed per tooth (mm/tooth). The negative coefficients indicate that increasing either parameter reduces machining time, with f_z having the strongest influence.

Figure 8 presents the results of the multi-response optimization performed using the desirability function approach to simultaneously minimize surface roughness R_a and machining time T. The optimization was conducted within the predefined feasible working domain, with equal importance and weighting assigned to both responses.

The optimal cutting parameters obtained from the analysis are a spindle speed of 3000 rpm and a feed per tooth of 0.2506 mm/tooth. Under these conditions, the predicted surface roughness is $R_a = 4.32\,\mu m$, while the corresponding machining time is $T = 17.36\,s$. The composite desirability value achieved at this operating point is 0.506, indicating a balanced compromise between surface quality and productivity.

TABLE VI. INFLUENCE OF CUTTING PARAMETERS ON SURFACE ROUGHNESS BASED ON SNR ANALYSIS

Test no.	Factor level	Factor	
		n (rpm)	f_z (mm/tooth)
1	1	-12.538	-12.055
2	2	-13.979	-13.148
3	3	-12.512	-13.827
4	Mean(m)	-13.01	-13.01
5	Max	-12.512	-12.055
6	Max – m	0.497	0.955
7	% of effect	34.2%	65.8%
8	Delta (max – min)	1.466	1.772
9	Rank	2	1

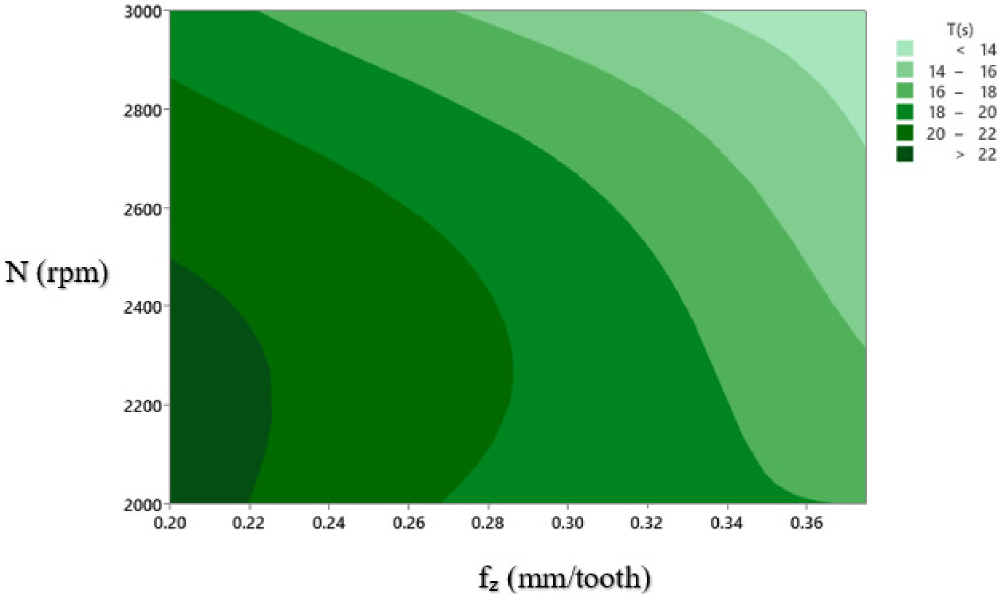
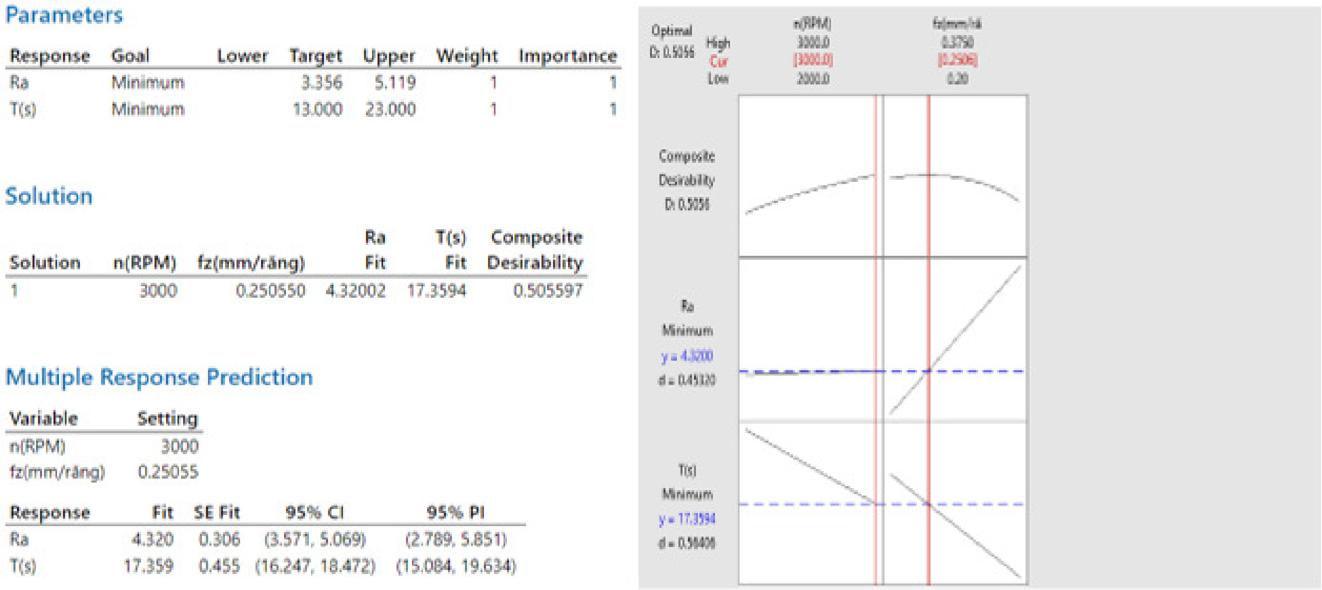


Fig. 7. Contour plot of machining time as a function of spindle speed and feed per tooth.



Parameters

Response	Goal	Lower	Target	Upper	Weight	Importance
Ra	Minimum		3.356	5.119	1	1
T(s)	Minimum		13.000	23.000	1	1

Solution

Solution	n(RPM)	fz(mm/răng)	Ra Fit	T(s) Fit	Composite Desirability
1	3000	0.250550	4.32002	17.3594	0.505597

Multiple Response Prediction

Variable	Setting
n(RPM)	3000
fz(mm/răng)	0.25055

Response	Fit	SE Fit	95% CI	95% PI
Ra	4.320	0.306	(3.571, 5.069)	(2.789, 5.851)
T(s)	17.359	0.455	(16.247, 18.472)	(15.084, 19.634)

Fig. 8. Multi-response optimization results based on desirability analysis.

Based on the SNR analysis summarized in Table VI, feed per tooth was identified as the most influential factor affecting surface roughness, contributing 65.8% of the total effect, while spindle speed accounted for 34.2%. The optimal cutting condition for minimizing surface roughness corresponds to the parameter levels yielding the maximum SNR (smaller-is-better criterion). Accordingly, the optimal quantitative cutting mode was determined as a spindle speed of $n = 3000$ rpm (Level 3) and a feed per tooth of $f_z = 0.20$ mm/tooth (Level 1). This combination provides the most stable and robust surface finish within the investigated parameter range and was therefore selected as the final optimal setting for flat-surface end milling of ALU 6061.

IV. CONCLUSION

This study experimentally investigated the optimization of cutting parameters for flat-surface end milling of ALU 6061 using a Taguchi-based experimental design combined with regression modeling and desirability analysis. The results show that feed per tooth is the dominant factor affecting both surface roughness and machining time, contributing approximately 65.8% to the variation in surface roughness. Increasing feed per tooth significantly reduces machining time but leads to higher surface roughness, indicating a clear trade-off between productivity and surface quality.

Multi-response optimization identified an optimal cutting condition of 3000 rpm spindle speed and 0.2506 mm/tooth feed per tooth, yielding a predicted surface roughness of about 4.32 µm and machining time of 17.36 s. The proposed experimental–statistical framework provides a practical guideline for selecting cutting parameters in flat-surface end milling under a specific machine–tool–workpiece configuration. The contribution of this work is primarily application-oriented, focusing on practical parameter selection under realistic machining conditions rather than methodological innovation. The use of conventional materials and standard carbide tooling reflects common industrial practice, particularly in environments where advanced tools and complex optimization methods may not be readily available.

The developed regression models are valid only within the tested parameter range. In addition, a separate confirmation experiment at the predicted optimum was not conducted in the present study, and this should be considered in future work. It should also be noted that advanced cutting tools, coatings, and modern machining strategies were not considered in this study. Future work may extend the proposed framework by incorporating these factors and exploring more advanced optimization techniques. The study focused only on spindle speed and feed per tooth under fixed machining conditions. Other factors, such as axial depth of cut, tool coating, lubrication strategy, and tool wear, were not included and should be considered in future work to extend the applicability of the proposed framework.

COMPETING INTERESTS

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

ACKNOWLEDGMENT

Not applicable to this work.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

AI USE AND DECLARATION

The authors used generative AI tools to assist with language refinement, grammar correction, and manuscript editing during the preparation of this work. All scientific content, analysis, interpretation of results, and final decisions regarding the manuscript were performed and verified by the authors.

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