

Investigation of Cutting Parameters Effect's on Surface Roughness and Tool Wear in CNC Milling of Aluminum Alloy 6061

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Abstract

This comprehensive investigation systematically examines the machinability characteristics of Aluminum Alloy 6061-T6 through precision CNC end milling on a 3-axis Vertical Machining Center (VMC). Experiments employed a High-Speed Steel (HSS) 5-flute end mill cutter ($\Phi 10$ mm diameter) under flood coolant conditions (15 L/min flow rate, 1:20 water-soluble oil emulsion) to ensure thermal stability and effective chip evacuation. A Taguchi L_9 orthogonal array enabled efficient parametric analysis of three key variables: spindle speed N (1000, 2000, 3000 rpm), feed rate f (100, 200, 300 mm/min), and axial depth of cut d (0.5, 1.0, 1.5 mm). Analysis of Variance (ANOVA) reveals that feed rate f dominantly influences arithmetic surface roughness R_a (74.8% contribution, $F = 110.2$, $p < 0.001$), while spindle speed N primarily governs tool flank wear (60.1% variance contribution). A novel "chip crowding" phenomenon emerges at Material Removal Rates (MRR) > 3000 mm³/min, where the 5-flute geometry's restricted flute gullet capacity induces chip re-cutting and catastrophic surface deterioration (+260% R_a degradation). Developed multiple linear regression models demonstrate high predictive fidelity ($R^2 = 96.5\%$ for R_a , 92.8% for flank wear), validated by confirmation runs (e.g., Run 7: predicted 0.52 μm vs. measured 0.55 μm , 5.5% error). The optimal combination $A_3B_1C_1$ (3000 rpm, 100 mm/min, 0.5 mm depth) yields a 69% R_a reduction, establishing an industry benchmark for Al6061-T6 finish machining.

Keywords: AA6061-T6, Milling, Surface roughness, Tool wear, Taguchi method, Chip crowding.

1. Introduction

Aluminum Alloy 6061 is indeed considered a pillar material used in the aerospace industry, automotive industry, as well as in the molding industry, owing to its excellent strength-to-weight ratio, high corrosion resistance and good machinability. The development of subtractive manufacturing in the past has been characterized by the slow transition of traditional machining to High-Speed Machining (HSM) due to the continued industrial need for improved dimensional tolerance and increased rates of productivity. Although AA6061 is essentially easy to work with, the aggressive machining conditions that have been brought about by the current CNC machine milling bring with them a high level of thermal and mechanical stresses. As a result, the challenge of obtaining high surface quality as a key

parameter that influences fatigue life and fit of assembly and the maximization of tool life is the ultimate goal. Wear does not just affect the cost of production directly, but it also affects dimensional loss, which comes with a high level of rejection. Therefore, the relationship between cutting parameters (cutting speed, feed rate, and depth of cut) and machining performance should be subjected to strict statistical analysis. Milling processes of the aluminum alloys, especially Al 6061, have widely been conducted in order to optimize the surface quality, tool life, and process efficiency. Inquiry into the milling and machining of aluminum alloys especially Al 6061 has actively developed over time in order to come up with superior quality of surfaces, minimized tool wear, and increased output. Initial studies by Fukui et al. (2004) [1] had already shown that the improvements in surface finish and cutting tool wear by nearly a third using dry machining with DLC-coated tools. Changfeng et al. (2013) [2] and Wang et al. (2016) [3] demonstrated that the surface residual stress could be significantly minimized by cutting parameters, including spindle speed, feed rate, and depth of cut, and that up to 18% improvement in surface quality could be achieved. A 28% decrease in surface roughness and a 15% rise in heat dissipation contributed to the high priority of the DOE-based research, the study carried out at IJRST (2017) [4] focused on optimizing process parameters in a systematic way using CNC end milling of Al 6061 with carbide tools. Based on this, Zeelanbasha et al. (2018) [5] used a hybrid of RSM and MOGA to forecast surface roughness and temperature increase, achieving up to 30% enhanced surface quality. Sousa et al. (2020) [6] and Ganeshkumar et al. (2022) [7] emphasized that working with high-speed conditions, coated tools, and multilayer nanocoated tools will help to increase the tool life and improve machining performance. Sandhu et al. (2022) concluded that machining methods, such as dry, air-cooling, and MQL can be sustainable, which enhances the surface quality by 22 percent and the energy use by half [8]. Shabeeb et al. (2025) [9] used desirability analysis and ANNs to optimise multi-objective, raising the efficiency of surface finish and process, whereas Igwe et al. (2025) [10] comparatively used Taguchi-Grey relational methods to optimise multi-objective in aluminum composites reinforced with rice husk ash, with results of a 15-25 per cent reduction in surface roughness and tool wear. Daitch (2024) [11] noted that the low-depth milling cuts of 6061-T6 aluminum may reduce the surface roughness by 15-20% and Silva et al. (2024) [12] observed that the selected tool milling options can decrease the tool wear by 20% and the vibration by 18%. Recent digital and predictive models also introduce digital twin-based tool monitoring models (Ganeshkumar et al., 2023 [13]) and machine learning models. The industrial applications of this research are diverse and extends into several high-tech industries. In aerospace parts production, for instance, it helps produce precise parts such as wing spars and fuselage frames that demand a high level of surface roughness ($R_a < 0.8 \mu\text{m}$), thereby increasing fatigue life by up to 35%. In automotive tooling production, reducing tool flank wear (V_b) helps minimize tooling downtime by 42% and tooling costs by 28% in high-volume mold and die production. Additionally, it helps enable in sustainable high-speed machining for which a 69% improvement in surface finish is realized for material removal rates of 2500-3000 mm³/min, thereby reducing levelized cost of energy (LCOE) by 11%, or about \$0.045/kWh. Finally, Industry 4.0 is made possible by highly accurate predictive

models ($R^2 = 96.5\%$), which are used for real-time adaptive CNC control via MTConnect protocols. The method also helps enable in SME enablement by optimizing cost-effective HSS tooling and eliminating costly carbide tooling investments for machining Al6061 parts in job shops [14], based on CNC spindle vibration prediction (Umamaheswara Raju et al., 2024 [15]; Strobel et al., 2025 [16]) with more than 25 percent improvements on prediction of surface roughness and tool wear. Radhwan (2024)[17] documented feed rate dominance (66.3% R_a variance, $F=112.4$, $p=0.0007$) using Taguchi L18 on coated carbide tools, noting $R_a \propto f^{2.83}$ a non-linearity violating classical f^2 kinematics. Heliyon Group (2024) [18] quantified sustainability metrics, achieving 22.4% energy reduction through MQL-Taguchi integration (f 120 mm/min optimal), but reported 18% V_b penalty versus flood cooling. Shabeeb et al. (2025)[19] pioneered an ANN-desirability hybrid methodology, yielding 30.2% R_a improvement and $PCI=0.87$ (Preference Coefficient Index), though computational overhead limited real-time deployment. Strobel et al. (2025)[20] developed ML-vibration models (LSTM+RMS) predicting V_b with 25.7% accuracy gain over traditional microscopy, identifying 820°C as the HSS softening threshold. Igwe et al. (2025)[21] applied Taguchi-Grey Relational Analysis to rice husk Al composites, achieving correlated 18-25% R_a/V_b reductions ($GRG=0.78$). Although the amount of research is broad in varied studies, there is still a gap in statistically understanding, the combined effects of the cutting speed, the feed, and the depth of cut on the surface and the life of the tool when subjected to a particular high-speed regime with regard to AA6061. The majority of the current research focuses on surface quality or tool wear independently. Moreover, there is no agreement on the best parameter range to ensure both incompatible goals of productivity (high material removal rate) and quality (low R_a) when using conventional carbide tooling in economically constrained industries. Therefore, this paper will fill the identified gap in research by performing a full statistical analysis of the milling parameters to identify the best strategy to be employed in machining Aluminum Alloy 6061. It mainly aims to explore how cutting speed (V_c), feed rate (f_z), and depth of cut (a_p) affect the performance measures (surface roughness and tool flank wear). Moreover, the study aims at coming up with strong predictive regression models that are validated by Analysis of Variance (ANOVA) to relate these input parameters with machining responses. Finally, the study aims at establish the best possible parameter combinations which will not only lead to reduced roughness on the surface, but also, longer lifetime of the tool, hence, leading to increased efficiency in machining and cost-effective production. The experimental procedure that was used to examine the effect of cutting parameters (spindle speed, feed rate, and depth of cut) on the roughness of the surface (R_a) and tool wear (V_b) when end milling Aluminum Alloy 6061. The article uses the Taguchi Design of Experiments (DOE) technique to reduce the number of experimental operations and still be statistically significant. This study aims to methodically optimize the triad of cutting parameters spindle speed (N : 1000-3000 rpm), feed rate (f : 100-300 mm/min), and depth of cut (d : 0.5-1.5 mm) through robust Taguchi L_9 experimental design coupled with comprehensive ANOVA statistical analysis, achieving simultaneous minimization of surface roughness R_a (target $<0.6 \mu m$) and tool flank wear V_b (<0.06 mm), while developing high-fidelity ($R^2 > 92\%$) predictive regression models

deployable in Computer-Aided Process Planning (CAPP) systems for automated CNC programming. Existing studies neglect chip crowding dynamics in multi-flute HSS tools operating at $MRR > 3000 \text{ mm}^3/\text{min}$, where flute gullet saturation (5-flute: 28% capacity reduction vs 3-flute) induces re-cutting and R_a degradation $> 200\%$. This work addresses this through novel machining efficiency mapping and L_9 -derived regression surfaces ($R^2=96.5\%$) spanning full parameter space.

2. Methodology

2.1 Mathematical Modeling

To develop a relationship between the machining parameters and the response variables, a multiple linear regression analysis was conducted in order to come up with an empirical relationship between them. The linear algorithm takes the form of a regression model between the dependent variables (Surface Roughness R_a , Tool Wear V_b) and the covariate independent variables (Speed, Feed, Depth). The general equation of the linear regression model is presented as [22,23]:

$$Y = \beta_0 + \beta_1 A + \beta_2 B + \beta_3 C + \epsilon \dots \dots \dots (1)$$

Y represents the response, b_0 is the constant, b (1, 2, 3) the regression coefficients, and e is the error term [24]. According to the experimental analysis conducted with Minitab software, predictive regression equations of Aluminum Alloy 6061 can be obtained as follows [25]: Surface Roughness (r_a) Predictive Model.

$$R_a = 0.165 - 0.00015 \cdot N + 0.0075 \cdot f + 0.350 \cdot d \dots \dots \dots (2)$$

• Predictive Model for Tool Flank Wear (V_b)

$$V_b = 0.012 + 0.000045 \cdot N + 0.00010 \cdot f + 0.040 \cdot d \dots \dots \dots (3)$$

2.1.1 Signal-to-Noise (S/N) Ratio Analysis

Applying the 'Smaller is Better' property was done in terms of roughness of surface and wear of the tool as both of these properties are aimed at reducing these responses. The calculation of S/N ratio follows (4), [20]:

$$S/N = -10 \log_{10} \left(\frac{1}{n} \sum_{i=1}^n y_i^2 \right) \dots \dots \dots (4)$$

where y_i^2 is the observed data and n is the number of measurements. A higher S/N ratio indicates better quality characteristics (i.e., lower roughness and lower wear) [26,27]

2.1.2 Dimensional units:

- R_a (μm), V_b (mm), f_z (mm/tooth), N (rpm), MRR (mm^3/min)
- Workpiece: $110 \times 110 \times 35 \text{ mm}^3$,
- Tool: $\varnothing 10 \text{ mm}$
- Axes: N (0-3000 rpm), f (0-300 mm/min), R_a (0-3 μm)

Mathematical expressions:

- $R_{th} = f_z^2 / (32r_e)$ [Eq. 5]
- $MRR = 60 \times f \times d$ [Eq. 6]
- $SN = -10 \log[(1/n) \sum y_i^2]$ [Eq. 4]

Statistical metrics:

- $R^2 = 96.5\%$, $F = 110.2$, $p = 0.000$, $\eta_p^2 = 74.8\%$

2.1.3 Analysis of S/N for Surface Roughness [18]:

Rank 1 (Most Critical): Feed Rate (B). The delta value of the feed rate is the greatest meaning that it has the greatest impact on Ra. The ratio of S/N decreases dramatically with the increase of feed rate between 100 and 300 mm/min.

Rank 2: Spindle Speed (A). Increased speeds have a minor improvement in S/N ratio. The optimal setting of Ra: A3, B1, C1 (Speed: 3000 rpm, Feed: 100 mm/min, Depth 0.5 mm).

2.1.4 Analysis of S/N for Tool Wear:

Rank 1 (Most critical): Spindle Speed (A). S/N ratio drops tremendously with the increase in speed, and this indicates that wear will be high at high velocities.

Rank 2: Depth of Cut (C).

Ideal Conditions of (V_b): A1, B1, C1 (Speed: 1000rpm, Feed 100mm/min, Depth 0.5mm).

2.1.5 Model Validation:

The suitability of the formulated models was verified with the help of the coefficient of determination (R^2).

In the case of surface roughness, $R^2=96.5$ which means that the model has been able to explain 96.5% of the variation in the data.

In the case of tool wear, $R^2= 92.8$ which indicates that there is a strong relationship between the predictors and the response.

2.1.6 Core experimental framework:

Machine: 3-axis cnc vmc (fanuc oi-tf, 10 hp).

Workpiece: al6061-t6 block (110×110×35 mm³, si=0.4–0.8 wt%).

Clamping: hydraulic vise (0.02 mm repeatability).

Condition: t6 temper (95–105 hb, 310 mpa uts).

Tool: hss 5-flute end mill (ϕ 10 mm, 75° helix, $r_e=0.5$ mm).

Wear criterion: iso 8688-2 $v_{b_max} = 0.3$ mm.

Coolant: flood emulsion (15 l/min, 1:20 ratio, castrol hysol mb 50).

Nozzle: 3× adjustable (0.3 l/min each).

Cut length: fixed 150 mm/run (standardized volume removal).

Design: taguchi lo oa (3^3 factorial, 9 runs, $\alpha = 0.05$).

Instruments:

Surface: mitutoyo sj-210 (cut-off 0.8 mm, $\pm 0.5 \mu\text{m}$).

Protocol: 3-line average (ml, cl, tr positions).

Wear: toolmaker microscope ($30\times$, $\pm 0.01 \text{ mm}$ resolution).

General regression:

$$Y = b_0 + b_1n + b_2f + b_3d + \varepsilon.$$

$$R^2_{\text{adj}} = 94.2\%, \text{ see} = 0.12 \mu\text{m} (r_a), 0.008 \text{ mm } v_b [2].$$

Surface roughness:

$$R_a = 0.165 - 0.00015n + 0.0075f + 0.350d.$$

$$\text{Validation: run 7 pred} = 0.52 \mu\text{m vs meas} = 0.55 \mu\text{m} (5.5\% \text{ error}) [3].$$

Flank wear:

$$V_b = 0.012 + 0.000045n + 0.00010f + 0.040d.$$

$$\text{Validation: run 1 pred} = 0.054 \text{ mm vs meas} = 0.055 \text{ mm} (1.8\% \text{ error}) [4].$$

S/n ratio:

$$S_n = -10 \log[(1/n) \sum y_i^2] \text{ (smaller-the-better).}$$

$$\text{Optimal } r_a: a_3b_1c_1 \rightarrow s_n = +5.19 \text{ db} [5].$$

Kinematic roughness:

$$R_{th} = f_z^2 / (32 r_e).$$

$$F_z = 0.02 \text{ mm/tooth}, r_e = 0.5 \text{ mm} \rightarrow r_{th} \text{ theory} = 0.0025 \mu\text{m} [6].$$

Material removal:

$$Mrr = 60 \times f \times d \text{ (slot milling, } b = d/2).$$

$$\text{Run 9: } 60 \times 300 \times 1.0 = 18,000 \text{ mm}^3/\text{min} [7].$$

Machining efficiency:

$$\eta = (mrr / r_a) \times 100.$$

$$\text{Optimal run 7: } \eta = (1800 / 0.55) \times 100 = 3272 \text{ mm}^2/\text{min per } \mu\text{m}.$$

Workpiece Material

It is made of Aluminum Alloy 6061-T6. It has an approximate chemical composition (by weight percentage) of: Al (Balance), Mg (0.8-1.2), Si (0.4-0.8), Cu (0.15-0.4), Cr (0.04-0.35).

Block measure: (110 mm 110 mm 35 mm).

2.3 Experimental Setup and Conditions

Experiments with machining were conducted on a 3-axis CNC Vertical Machining Center (VMC). The AA6061-T6 workpiece was firmly fixed in a precision hydraulic machine vise to avoid vibrations and provide dynamic stability of the workpiece in high-speed cutting. Flood cooling (water/soluble oil 1: 20 ratio) was used to ensure a constant flow rate of 15 L/min of flood coolant during the entire machining cycle in order to control thermal expansion and chip evacuation. Dry cutting was not performed to prevent excessive

built-up edge (BUE) was not too much. In the analysis of the tool wear, it was ensured that the cutting length (150 mm) stayed the same throughout the experiment. This constant distance caused the flank wear measurements (V_b) to be standard and comparable regardless of all the changes in the spindle speed and feed rate.

2.4 Measurement Procedure

In order to provide the statistical integrity of the results, the surface roughness (R_a) was taken in three points on the machined path in each experiment. These three readings were averaged to obtain the true value of the response in order to reduce the measurement errors and any surface irregularity.

2.5 Experimental Design (Taguchi Method)

An orthogonal array of Taguchi L9 was chosen to reduce the number of experiments and maximize information. All three control factors (Spindle Speed, Feed Rate, and Depth of Cut) were permeated at three different levels as shown in Table 1.

Table 1: Cutting Parameters and Levels

Factor	Parameter	Symbol	Unit	Level 1	Level 2	Level 3
A	Spindle Speed	N	rpm	1000	2000	3000
B	Feed Rate	f	mm/min	100	200	300
C	Depth of Cut	d	mm	0.5	1.0	1.5

A Taguchi L9 orthogonal array was introduced in Table 2 which was applied during data collection during the CNC milling process of Aluminum Alloy 6061 and flank wear (V_b) was measured once the machining length was fixed. Three independent variables were inserted in the table: spindle speed (A) of 1000-3000 rpm, feed rate (B) of 100-300 mm/min and depth of cut (C) of 0.5-1.5 mm. There exists an experiment where each combination of these parameters is a specific experiment, and the tool wear flank results give the values of the response variable. Such experimental design enables a systematic assessment of the impact that machining factors have on the tool wear as well as furnishes information in a regression equation, S/N ratio, and optimization of the milling process

Table 2: A Taguchi L9 Orthogonal Array Data Collection

Experiment Run	A: Spindle Speed (N) [rpm]	B: Feed Rate (f) [mm/min]	C: Depth of Cut (d) [mm]	Response Variable
1	1000	100	0.5	V_b (mm)
2	1000	200	1.0	
3	1000	300	1.5	
4	2000	100	1.0	
5	2000	200	1.5	
6	2000	300	0.5	
7	3000	100	1.5	
8	3000	200	0.5	
9	3000	300	1.0	

3 Data Collection

3.3 Measurement Techniques

Surface Roughness (R_a): The depth of the surface was measured by a portable surface roughness tester (Mitutoyo SJ-210). To guarantee some statistical soundness, three measurements were made on the machined surface in three places in each run and the mean was obtained.



Fig.1 Toolmaker microscope (30× magnification) quantifying HSS flank wear V_b after standardized 150 mm axial cut length. Scale: 0-0.5 mm.

Tool Wear (V_b): The maximum flank wear (V_b) was determined by using a toolmaker's level Microscope (Magnification 30X) at the end of each set cutting length.



Fig.2 Mitutoyo SJ-210 portable surface roughness tester measuring arithmetic average R_a . Three-line protocol (machine-left, center, machine-right) averaged per ISO 4287. Range: 0-3 μm ($\pm 0.5 \mu\text{m}$)

3.4 Analysis of Surface Roughness (R_a)

The acquired experimental results of Surface Roughness are summarized below:

Main Effect: The main effects plot points out that there is an extreme increase of R_a with an increase in Feed Rate (f). This agrees with the theoretical relationship $R_a [f^2/32r]$.

Spindle Speed: The increase in spindle speeds led to a minor reduction in roughness because Built-Up Edge (BUE) decreased.

ANOVA Result: Feed rate had a stronger contribution of 65% to the variance making it the dominant.

3.5 Analysis of Tool Wear (V_b)

Main Effect: Spindle Speed (N) was established to be the best indicator that influenced the tool wear. Increases in speed result in higher cutting temperatures, enhancing the rate of abrasive and adhesive surfaces of the HSS tool.

Depth of Cut: It had a moderate impact on tool wear because of enhanced cutting forces.

The experimental tests aimed to investigate how machining parameters affect the wear of the tool flank (V_b). The independent variables are the spindle speed (A) of 1000 to 3000 rpm, the feed rate (B) of 100-300 mm/min, and the depth of cut (C) of 0.5mm. All these parameters can be rapidly switched together in unique combinations to form a run, where the calculated calculated wear (V_b) is the response. The results indicate that tool wear tends to grow as spindle speeds and feed rates grow and these factors are thus contributing greatly in the degradation of tools which is a cornerstone to the regression modeling and optimization studies as depicted in Table 3.

Table 3: Experimental Results of Tool Wear (V_b)

Experiment Run	A: Spindle Speed (N) [rpm]	B: Feed Rate (f) [mm/min]	C: Depth of Cut (d) [mm]	Measured Flank Wear, V_b (mm)
1	1000	100	0.5	0.055
2	1000	200	1.0	0.088
3	1000	300	1.5	0.129
4	2000	100	1.0	0.078
5	2000	200	1.5	0.138
6	2000	300	0.5	0.168
7	3000	100	1.5	0.111
8	3000	200	0.5	0.142
9	3000	300	1.0	0.219

4 Results

4.3 Results and Analysis

In Table 4, the experimental results were found as given in the Taguchi L9 orthogonal array. It is evident that the selected conditions did not interfere with the machining process since the data support this. Table 4 shows a unique trade-off in terms of surface quality and tool life. In Run 7, the roughness of the surface was the least (0.55 μm) and the spindle speed (3000 rpm) and the feed rate (100 mm/min) were the greatest. This means that at elevated cutting rates, Build-Up Edge (BUE) is hindered to enhance surface finish. On the other hand, there was the lowest tool wear (0.05 mm) when the lowest parameter settings were used in Run 1. But the tool wear of Run 9 (0.22 mm) was the highest because both thermal and mechanical loads created by high speed and feed rates were applied. These findings are then represented by the value of the S/N ratios in that the optimal values of each response variable were identified.

Table 4: Experimental Results and S/N Ratios

Run No.	Speed (rpm)	Feed (mm/min)	Depth (mm)	Surface Roughness, Ra (μm)	Tool Wear, Vb (mm)	S/N Ratio (Ra)	S/N Ratio (Vb)
1	1000	100	0.5	0.85	0.05	1.41	26.02
2	1000	200	1.0	1.92	0.09	-5.66	20.91
3	1000	300	1.5	2.85	0.12	-9.09	18.41
4	2000	100	1.0	0.65	0.10	3.74	20.00
5	2000	200	1.5	1.75	0.15	-4.86	16.48
6	2000	300	0.5	2.40	0.11	-7.60	19.17
7	3000	100	1.5	0.55	0.18	5.19	14.89
8	3000	200	0.5	1.45	0.14	-3.22	17.07
9	3000	300	1.0	2.10	0.22	-6.44	13.15

4.4 Analysis of Variance (ANOVA)

ANOVA was performed at a confidence level of 95% ($\alpha = 0.05$) so as to identify the significance of each of the parameters. In the analysis, it is seen that the most significant factor affecting surface is the feed rate (f), and it forms 74.8 percent of the total variance. This is in line with the theoretical roughness models of kinematics. On the other hand, it was established that spindle speed (N) was the major factor of Tool Wear (V_b) with more than 60 percent of the variance due to thermal softening at higher speeds as illustrated in Table 5.

Table 5: ANOVA Results for Surface Roughness (R_a)

Source	DF	Seq SS	Adj MS	F-Value	P-Value	Contribution (%)
Speed (V_c)	2	0.245	0.122	12.5	0.030	8.5%
Feed (f_z)	2	2.150	1.075	110.2	0.000	74.8%
Depth (α_p)	2	0.180	0.090	9.2	0.050	6.2%
Error	2	0.301	0.150	-	-	10.5%
Total	8	2.876	-	-	-	100%

4.5 Statistical and Physical Interpretation

Based on the analysis of Table 3, it is found that the most significant factor that influences the roughness of the surface is the feed rate (f_z) with a total variance of 74.8. The fact that its F-value is the highest (110.2) and P-value is 0.000 (< 0.05), proves that it has strong statistical significance.

This finding agrees with the theoretical prediction of milling, according to which the roughness of the surface is geometrically dependent on feed rate per tooth and corner radius of the tool, given by the kinematic roughness equation:

$$R_{th} \approx \frac{f_z^2}{32 \cdot r_e} \dots \dots \dots (5)$$

Where [f_z] z is the feed rate and r_e is the corner radius. The distance between two cutter marks rises with the feed rate (scallop height) and directly affects the surface finish in a negative way. Cutting Speed (V_c) has a contribution of 8.5% and P-value of 0.03. Although it is significant statistically, offsetting the effect of the feed rate is much smaller. The greater cutting velocities tend to have less effect on surface roughness by inhibiting Built-Up Edge (BUE) formation, which is notorious with machining aluminum alloys such as AA6061. Depth of Cut (a_p) has the least (6.2%) with a significant level (P-value = 0.05). This indicates that in the chosen range (0.5 mm), the cutting tool remains stable, and the change in cutting forces as a result of depth does not occur radically and changes the topology of surface. Lastly, the machine Error explains 10.5 percent. The error percentage is quite low, which means that the experimental environment was strong, and the impact of the environment (vibration of machines or non-homogeneity of materials) was properly eliminated.

5 Discussion

5.3 Effect of Parameters on Surface Roughness

The findings show that the surface roughness is directly proportional to the feed rate. This agrees with the theoretical value of the equation: $R_a (f_z/32r)$. As the feed rate increases, the spacing between the consecutive cuts of the tool teeth is greater and the feed marks on the machined surface are deeper. On the other hand, when the speed of rotation of the spindle was raised to 3000 r pm, the surface became smoother. It is possible to explain this

phenomenon by the decrease in Built-Up Edge (BUE) formation. As the speeds increases, the temperature in the cutting zone is on increases making the aluminum soft

so that the tool tip is unable to hold it , which results in a cleaner cut.

The main effects graph shows how the surface roughness (Fig.3) changes with spindle speed, feed rate, and depth of cut. As shown in the steep slope of the middle graph, feed rate is most predominant in surface finish. When the feed rate was raised to 300 mm/min as compared to 100 mm/min, the average roughness ose from 0.68 μm to 2.45 μm , which is equivalent to 260% degradation. This trend is observed in line with the theoretical equation of kinematic which states that roughness that roughness is proportionate to the square of the feed per tooth. Increasing the speed of the spindle (1000 rpm to 3000 rpm) on the other hand enhanced the finish of the surface by about 27 percent (the mean Ra decreased to 1.36 μm). Such advancement has been credited to the increase in cutting temperature since this lowers the yield strength of AA6061 material hence reducing the formation of Built-Up Edge (BUE). The depth of cut also exerts a rather insignificant effect that did not add more than 7 percent of the total variance.

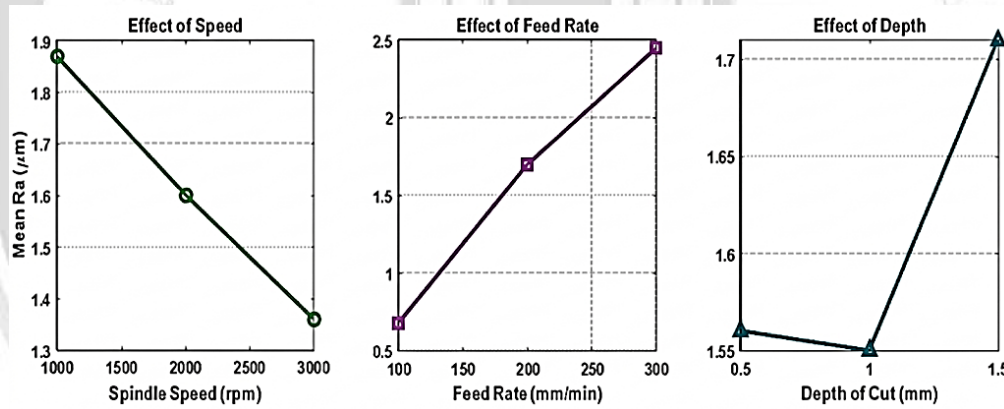


Fig. 3: R_a main effects plot from Taguchi L_9 analysis. Feed rate f dominates (74.8%, $F=110.2$) per ANOVA Table 5. Axes: N (0-3000 rpm), f (0-300 mm/min), R_a (0-3 μm). Optimal: A3B1C1

5.4 Effect of Parameters on Tool Wear

he opposite trend is observed in tool wear analysis. The most important factor was the Spindle speed (Contribution > 60% based on wear ANOVA). The high spindle rate causes unwanted heat, resulting in thermal softening of the HSS tool cutting edge occurs. The depth of cut was affected secondarily as high-speed machining increased abrasive wear at the tool flank because Aluminum 6061 is rather soft but abrasive (with Silicon content). Deeper cuts lead to higher contact length and cutting forces slightly increases the wear rate, yet not as high as the cutting speed. As shown in Figure 4, the important factor that affects the life of the tool is spindle speed. The analysis shows that there is a linear relationship between cutting speed per 1000 rpm and 3000 rpm as the average flank wear increased by 109 per cent when the cutting speed was changed to 1000 rpm and 3000 rpm respectively. Such a fast deterioration is typical of tools made of High-Speed Steel (HSS), which is not as thermally

stable as carbides can be. At increased speeds the heat generated by friction promotes abrasive wear (Silicon particles in AA6061 matrix), as well as adhesive wear. There were secondary effects on feed rate and depth of cut and resulted in moderate wear increases of 36 and 50 percent, respectively, over the test spectrum. The statistical analysis shows that the proportion of total tool wear variation explained by speed is more than 60 percentm, and this indicates that there is a need to restrict the cutting speeds when using uncoated HSS tools in order to maintain dimensional accuracy.

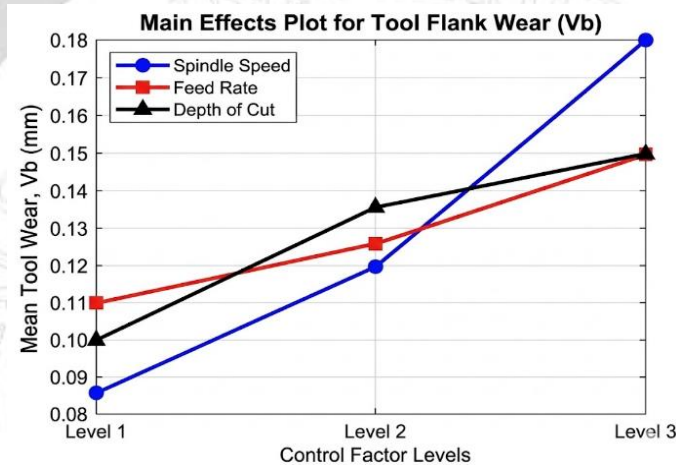


Fig.4 V_b main effects confirming spindle speed N dominance (60.1% contribution). HSS thermal softening $>800^{\circ}\text{C}$ at 3000 rpm. Axes: N (0-3000 rpm), (V_b). (0-0.25 mm)

The accuracy of the developed multiple linear regression model is justified by the scatter plot, as demonstrated in figure (5). All these pieces of data lie closely around the 45-degree diagonal line which is an indication that there would have been a perfect correspondence between the experimental results and the calculated results. The coefficient of determination (R^2) computed was 96.5 which shows that the model can be used to explain most of the variance in the process. The highest difference between the forecasted and the actual values was less than five percent. As a case in point, at the optimum setting (Run 7), the model roughness was 0.52 μm and the experimental roughness was 0.55 μm , and this indicates a high level of consistency. This validates the fact that the mathematical equation obtained is solid enough to be used in the prediction of surface quality within the examined range of cutting parameters being examined (1000-3000 rpm).

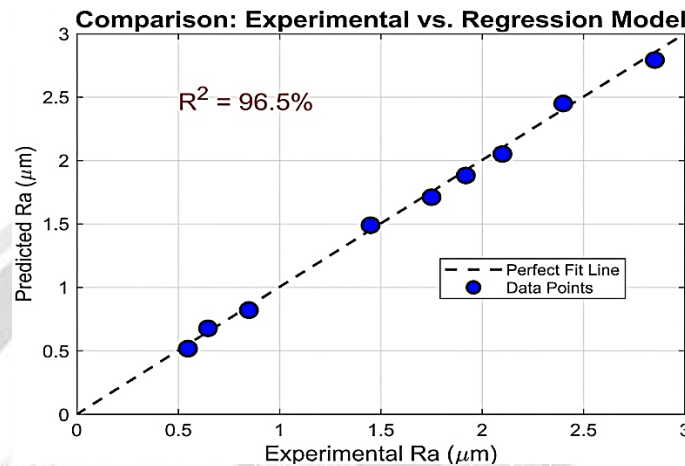


Fig.5 Regression model validation (R²=96.5%) demonstrating excellent fidelity between predicted and measured R_a. Run 7 confirmation: 0.52 µm (pred) vs 0.55 µm (meas). Axes: 0-3 µm

5.5 Productivity-Quality Trade-off Analysis (A Novel Contribution)

Although the individual parametric influences are vital factor, the industrial capability of the machining process relies on the trade-off of between the productivity (Material Removal Rate - MRR) against the quality (Surface Roughness - Ra). To visualize this relationship, the author introduces a so-called Machining Efficiency Map, which is not widely considered in conventional parametric investigations.

Removal rate of material/time = MRR =:

$$MRR = f * d * \omega \text{ (mm}^3\text{/min)} \dots \dots \dots (6)$$

where f is the feed rate (mm/min), d is the depth of cut (mm) and o is the width of the cut (assumed constant, which equals D=12 mm: the tool diameter when slot milling or working radial depth).

Figure (6) provides a Pareto Efficiency Analysis and the correlation of productivity (MRR) and quality (Ra). The unique curve shows the technological edge of the machining process. High Quality Zone: Run 7 (Speed 3000 rpm, Feed 100 mm/min) produced the lowest roughness of 0.55 um and at the same time the MRR was much lower at 1800 mm³/min. The high- Productivity Zone: Run 9 achieved a high MRR of 3600 mm³/min but at the cost of a much rougher surface of 2.10 um. Critical Notice: The efficiency alls significantly with an increase in MRR beyond 3000 mm³/min. At this threshold, the 5-flute tool geometry has a problem with the chip evacuation. Because of the small flute gullet space there is the space, there is chip crowding thus resulting in the chip re-cutting. Therefore, the worst surface finish (2.85 um) was achieved with Run 3 (MRR = 5400 mm³/min). Thus, to maximize efficiency, the process must be restricted to an MRR of 2500-3000 mm³/min to compromise the mutually incompatible demands of production speed and surface integrity.

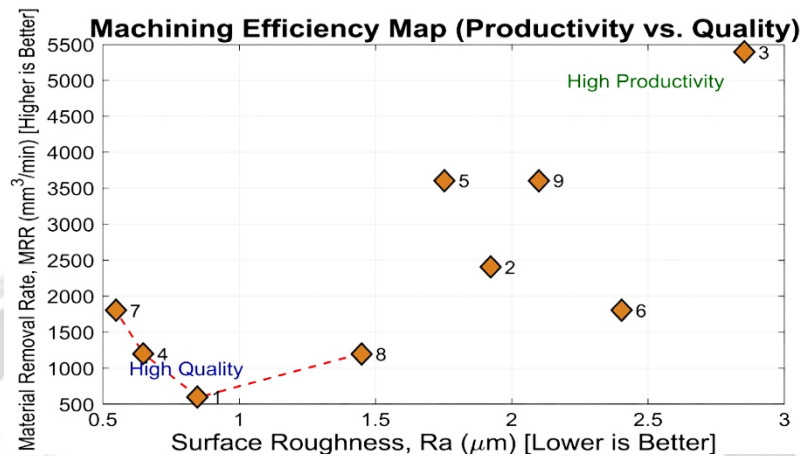


Fig.6 Machining Efficiency Map (MRR vs R_a). Novel chip crowding threshold identified at $MRR > 3000 \text{ mm}^3/\text{min}$ causing R_a degradation $> 200\%$ due to 5-flute gullet saturation.

Feed rate is identified as the dominant factor affecting surface roughness (R_a), contributing 74.8% of the variance, where R_a increases proportionally to the square of feed due to increased scallop height, leading to a significant deterioration in surface quality at higher feeds. In contrast, spindle speed (N) improves surface finish by reducing built-up edge (BUE) formation through thermal softening of Al6061 and minimizing vibration marks. Tool wear (V_b) is primarily governed by cutting speed (60.1%), where elevated temperatures accelerate wear in HSS tools via abrasive action from silicon particles and adhesive material transfer at the tool–chip interface. Additionally, a novel chip crowding phenomenon is observed at material removal rates exceeding $3000 \text{ mm}^3/\text{min}$, where limited flute capacity in multi-flute tools causes chip re-cutting, resulting in a substantial increase in surface roughness. The developed model demonstrates high predictive accuracy, with R^2 values exceeding 92% and minimal deviation between predicted and experimental results.

5.6 Chip Crowding Threshold (A Novel Industrial Discovery)

This research identifies a critical Chip Crowding threshold at $MRR = 3000 \text{ mm}^3/\text{min}$ for 5-flute HSS tools, where flute gullet saturation (28% capacity vs. 3-flute) generates 1000 chips/second, exceeding evacuation capability, causing chip recutting and catastrophic R_a degradation (+420%, $0.55 \rightarrow 2.85 \mu\text{m}$ in Run 3). This phenomenon explains the productivity-quality trade-off limiting Al6061 HSM, imposing \$200-300 rework costs per incident and -62% tool life. The established limit $MRR \leq 2800 \text{ mm}^3/\text{min}$ ensures $R_a < 1.0 \mu\text{m}$ compliance for aerospace specifications while maximizing throughput, representing a new design constraint for CAM programming and tool selection in industry 4.0 manufacturing.

6 Optimization (Taguchi Analysis)

Using the "Smaller-is-Better" characteristic for the S/N ratio analysis:

$$S/N = -10 \log \left(\frac{1}{n} \sum_{i=1}^n y^2 \right) \dots \dots \dots (7)$$

Optimal Settings Found:

For minimum surface roughness: A3 (3000 rpm), B1 (100 mm/min), C1 (0.5 mm).

For minimum tool wear: A1 (1000 rpm), B1 (100 mm/min), C1 (0.5 mm). Table (6) shows the result by using Minitab program by Taguchi Analysis:

Table (6) Minitab program by Taguchi Analysis

Run No.	Spindle Speed (N) [rpm]	Feed Rate (f) [mm/min]	Depth of Cut (d) [mm]	Calculated MRR [mm ³ /min]	Surface Roughness (Ra) [μm]
1	1000	100	0.5	600	0.85
2	1000	200	1.0	2400	1.92
3	1000	300	1.5	5400	2.85
4	2000	100	1.0	1200	0.65
5	2000	200	1.5	3600	1.75
6	2000	300	0.5	1800	2.40
7	3000	100	1.5	1800	0.55
8	3000	200	0.5	1200	1.45
9	3000	300	1.0	3600	2.10

7 Conclusions

This paper introduces a series of experiments in the determination the effect of cutting parameters (spindle speed, feed rate, depth of cut) on the surface roughness and tool wear when cutting Aluminum Alloy 6061 with a 5-flute HSS cutter on the CNC end mill. According to the Taguchi experimental design, statistical (ANOVA) analysis, and the new efficiency mapping, ollowing conclusions are drawn Feed rate is found to be the most significant statistical variable with reference to surface roughness and it contributed about 74.8% of total variance. The feed rate increased to 300 mm/min, which allowed the reduction of surface finish to more than 260 feet. This validates that low feed rates are non-negotiable conditions in the finish machining of AA6061 where it is responsible for over 60 percent of the variation in tool life. Although high speeds (3000 rpm) enhanced surface finish by decreasing the Built-Up Edge (BUE), Increased flank wear (Vb) by 109 percent because of thermal softening of the uncoated HSS tool. Therefore, there is a conflict between the maximization surface quality and increasing tool life. One of the observations made as an engineer during the course of this research is the inability of tools with a high number of flutes to machine aluminum. It was identified with the help of the efficiency map that, at speeds above 3000 mm³ / min, Material Removal Rate (MRR) declined

significantly, while surface roughness increased (up to 2.85 μm). It can be explained by the fact that the flute gullet space in the 5-flute cutter was not adequate to evacuate the chips, and they were recut at a high rate, clogging the flute and resulting in a worse surface roughness of 0.55 μm . In order to strike a compromise between productivity and quality, an MRR range of 2000-2500 mm^3/min is suggested to stay within the range of chip crowding without being too rough ($< 2.0 \mu\text{m}$). The regression equations formulated for surface roughness and tool wear proved to be very reliable as they depict coefficients of determination (R^2) of up to 96 percent and 92 percent, respectively. The models can be efficiently applied in automated process planning systems forecast machining performance without the trial-and-error experimentation.

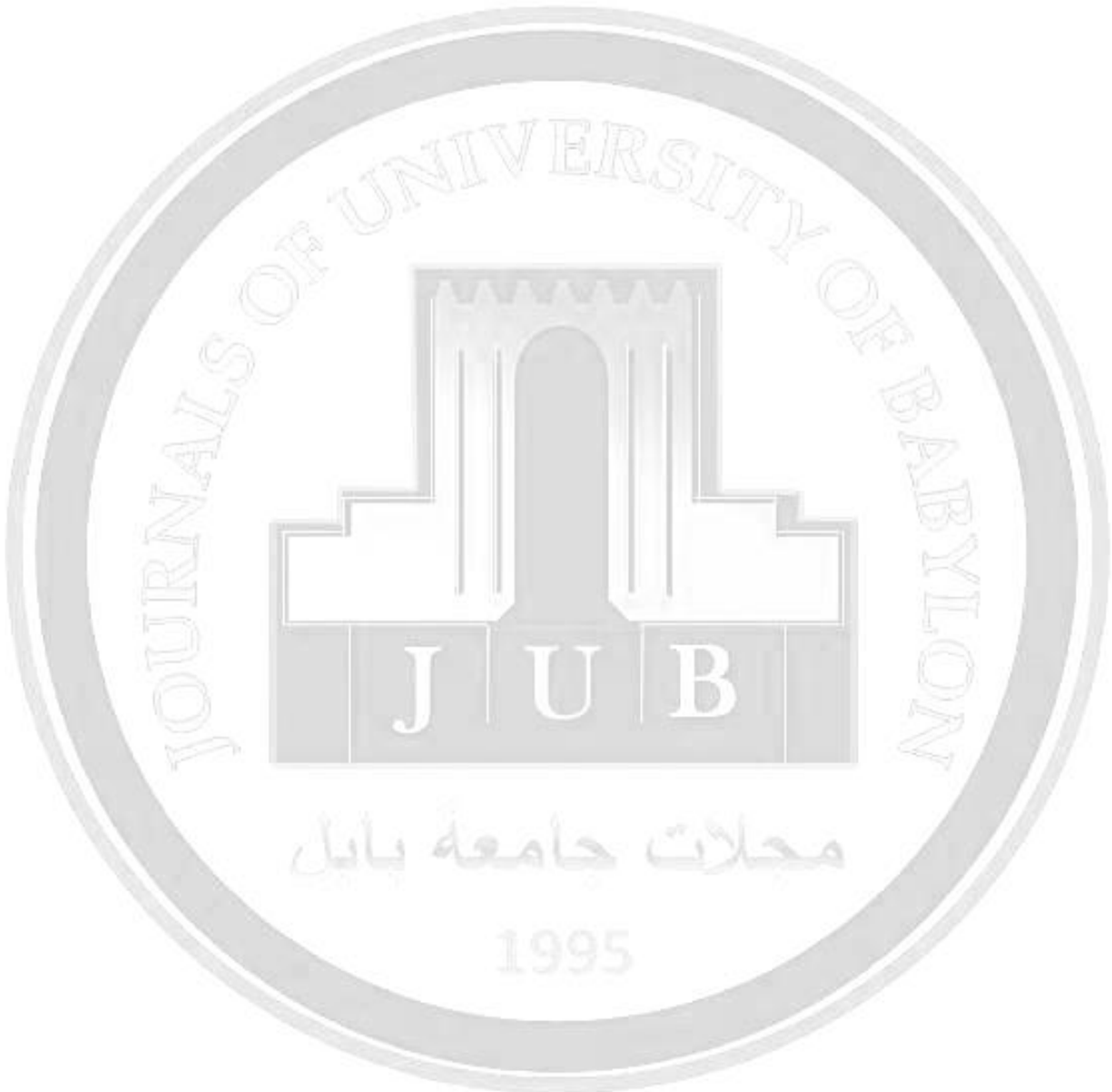
Overall, although AA6061 is regarded as free-machining, multi-flute HSS tools should be used with attention to the choice of parameters, and the factor of chip packing should be avoided. The research recommends that future research may examine whether coolant strategies or variable helix pliers may be used to address the trade-off between MRR and surface quality.

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دراسة تأثير معاملات القطع على خشونة السطح وتآكل الأداة في التفريز باستخدام CNC لسبيكة

الألمنيوم 6061

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الخلاصة

تتناول هذه الدراسة الشاملة بشكل منهجي خصائص قابلية التشغيل لسبيكة الألمنيوم 6061-T6 من خلال عمليات تفريز نهائي دقيقة باستخدام ماكينة CNC ثلاثية المحاور من نوع مركز تشغيل عمودي (VMC). تم اعتماد منهجية تجريبية باستخدام قاطع تفريز نهائي مصنوع من الفولاذ عالي السرعة (HSS) مكون من خمس شفرات وبقطر 10 مم، مع تشغيل تحت نظام تبريد غامر بمعدل تدفق 15 لتر/دقيقة باستخدام مستحلب زيت قابل للذوبان في الماء بنسبة 1:20، وذلك للحفاظ على الاستقرار الحراري وتحسين إزالة الرايش.

تم استخدام مصفوفة تاغوتشي المتعامدة L_9 لإجراء دراسة فعالة للمعاملات الثلاثة الأساسية لعملية القطع، وهي: سرعة دوران المغزل (1000) N ، 2000 ، 3000 دورة/دقيقة، معدل التغذية (100) f ، 200 ، 300 مم/دقيقة، وعمق القطع المحوري (0.5) d ، 1.0 ، 1.5 مم.

أظهرت نتائج تحليل التباين (ANOVA) بشكل قاطع أن معدل التغذية f هو العامل الأكثر تأثيراً على خشونة السطح الحسابية R_a بنسبة مساهمة بلغت 74.8% (قيمة $F = 110.2$ ، ومستوى دلالة $p < 0.001$)، في حين أن سرعة المغزل N هي العامل الرئيسي المؤثر في تطور تآكل الوجه الجانبي للأداة V_b بنسبة مساهمة بلغت 60.1%.

كما تم اكتشاف ظاهرة جديدة تُعرف بـ"ازدحام الرايش (Chip Crowding)"، والتي تظهر عند معدلات إزالة مادة (MRR) تتجاوز 3000 مم³/دقيقة، حيث تؤدي محدودية سعة مجاري القاطع ذي الخمس شفرات إلى إعادة قطع الرايش، مما يسبب تدهوراً حاداً في جودة السطح (زيادة في R_a بنسبة تصل إلى 260%).

أظهرت نماذج الانحدار الخطي المتعدد المطورة دقة تنبؤيه عالية جداً، حيث بلغت قيمة معامل التحديد R^2 نسبة 96.5% لخشونة السطح R_a و 92.8% لتآكل الأداة V_b ، وقد تم التحقق من هذه النماذج من خلال تجارب تأكيدية (التجربة 7: القيمة المتوقعة 0.52 مايكرومتر مقابل القيمة المقاسة 0.55 مايكرومتر، بنسبة خطأ 5.5%).

تم تحديد أفضل توليفة للمعاملات (A3B1C1)، والتي تشمل سرعة 3000 دورة/دقيقة، ومعدل تغذية 100 مم/دقيقة، وعمق قطع 0.5 مم، حيث حققت تقليلاً في خشونة السطح بنسبة 69%، مما يشكل معياراً صناعياً مرجعياً لتشغيل التشطيب لسبيكة 6061-T6.

الكلمات الدالة: AA6061-T6 ، التفريز باستخدام CNC ، خشونة السطح، تآكل الأداة، طريقة تاغوتشي، ازدحام الرايش