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OPTIMIZATION OF SURFACE ROUGHNESS IN MILLING ALUMINUM 7075-T6 USING THE TAGUCHI METHOD

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Abstract
Machining processes, particularly milling, play a critical role in achieving high-precision components in subtractive manufacturing. Surface roughness is a key indicator of surface quality, influencing mechanical performance, fatigue life, and assembly fit in industrial applications. This study utilizes the Taguchi method to optimize machining parameters—cutting speed, feed rate, and depth of cut—for minimizing surface roughness (Ra) during the milling of Aluminum 7075-T6 alloy, a material extensively employed in aerospace, automotive, and military sectors due to its high strength-to-weight ratio. Experimental trials were conducted using an L9 orthogonal array, with results analyzed through signal-to-noise (S/N) ratios, analysis of variance (ANOVA), and regression modeling. The findings reveal that feed rate exerts the most significant influence on Ra (50.75% contribution), followed by cutting speed (28.34%) and depth of cut (12.75%). Optimal parameters identified are a cutting speed of 430 m/min, feed rate of 500 mm/min, and depth of cut of 0.3 mm, yielding a predicted Ra of 0.08967 µm. These optimizations enhance manufacturing efficiency and component durability, providing practical insights for precision engineering.
Keywords: Surface roughness, Cutting speed, Feed rate, Depth of cut, Taguchi method, Aluminum 7075-T6

INTRODUCTION

Surface roughness is a pivotal quality metric in machined components, directly impacting functional attributes such as wear resistance, corrosion susceptibility, and frictional behavior. In the context of high-performance materials like Aluminum 7075-T6, optimizing roughness is essential for industries demanding lightweight yet robust parts, where suboptimal parameters can lead to defects like built-up edges or excessive tool wear. This section reviews prior research on milling parameters' effects on surface quality, establishing the foundation for applying the Taguchi method to identify optimal conditions.

Numerous investigations have explored the interplay between milling parameters and microstructural alterations in Aluminum 7075-T6. For instance, milling speed significantly elevates chip temperatures, with levels up to 36°C at higher speeds, while depth of cut influences grain recrystallization, reducing dynamic recrystallization by 45.8% at greater depths [1]. Grain refinement is also depth-dependent, with larger grains decreasing in volume but increasing in quantity as depth rises. At the tool's leading face (P1), elevated speeds refine grains to approximately 1 µm, boosting recrystallization by 80.7%, whereas at the trailing face (P3), grain size initially decreases before enlarging at 416 mm/min. Feed rate predominantly affects recrystallized grain quantity at the tool tip (P2), with a 60.4% increase and a shift toward smaller grains, alongside a 20% reduction in grain growth at P1 and P2 [1].

Comparative studies on milling strategies highlight the advantages of trochoidal over conventional methods for AA 7075-T6, reducing surface roughness (Ra), improving

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circularity, and stabilizing cutting forces. Feed rate dominates Ra by 57.28%, while milling method influences circularity (73.73%) and forces (68.97%) [2]. Cryogenic tool treatments further enhance predictions, with Taguchi optimization and artificial neural networks yielding accurate Ra forecasts [3]. Tool wear analysis on Aluminum 7075 underscores the benefits of optimized parameters for smoother surfaces and extended tool life [4].

Ball-end milling strategies for AA 7075-T6 validate statistical models for roughness prediction [5], while micro-milling with Taguchi-based grey relational analysis optimizes parameters [6]. Turning operations on AA 7050 reveal machining length's impact on roughness [7], and coated tools improve surface quality in AA 6061-T6511 [8]. Response surface methodology provides predictive models for minimum roughness in AA 6061-T6 [9], with optimized parameters like 884 RPM spindle speed and 243 mm/min feed yielding superior finishes [10].

Multi-parameter optimization in AA 6013 using uncoated carbide tools and L16 arrays identifies ideal conditions [11], while pocket machining in AA 5083 via L27 arrays and ANOVA minimizes Ra [12]. For harder materials, Taguchi optimizes roughness and wear in Hadfield steel [13] and Waspaloy under minimal lubrication [14]. Turning DIN 1.2344 tool steel with L9 arrays and regression yields predictive equations [15], and comparisons of PVD/CVD coatings on DIN 1.2738 optimize for minimum roughness [16]. Finish milling of AISI P20+S with L8 arrays confirms wet cooling and low feeds for best Ra [17].

This literature synthesis underscores the Taguchi method's efficacy in parameter optimization, addressing gaps in comprehensive studies on Aluminum 7075-T6 milling. By focusing on cutting speed, feed rate, and depth of cut, this research contributes to sustainable manufacturing practices, reducing waste and enhancing precision in high-stakes applications.

MATERIAL AND METHOD

The selection of appropriate materials and methodologies is crucial in experimental machining studies to ensure reproducibility and industrial relevance. Aluminum 7075-T6, known for its exceptional mechanical properties, requires precise control of machining variables to minimize surface defects. This section details the experimental setup, including workpiece material, equipment, and the Taguchi-based design, providing a robust framework for analyzing parameter effects on surface roughness.

Material

Experiments were conducted on a DMG MORI CMX 70U 5-axis CNC vertical machining center, equipped with a 12,000 RPM inline spindle, 30 m/min axis speeds, and Heidenhain linear scales offering 0.002 µm precision (Figure 1). The workpiece was secured using a SCHUNK KONTEC KSC vise with a 3 mm deep serrated clamping groove for enhanced rigidity (Figure 1).

Fig. 1. *CNC vertical machining center and vice used in experiments*

Nine test samples of certified Aluminum 7075-T6, dimensions 32 × 24 × 20 mm, were prepared from plate stock (Figure 2). This alloy, widely used in aerospace, automotive,

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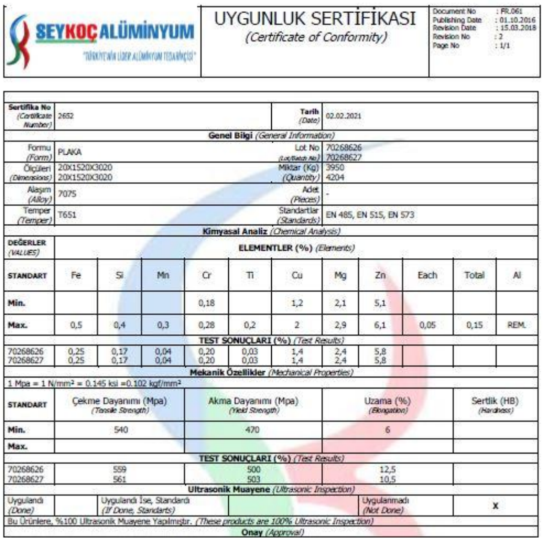
and military applications, exhibits high strength, machinability, and fatigue resistance. Its chemical composition and certification are detailed in Figure 2.



SEYKOÇ ALÜMİNYUM

UYGUNLUK SERTİFİKASI
(Certificate of Conformity)

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Revision No : 2
Page No : 1/1

Sertifika No (Certificate Number)	2652	Tarih (Date)	02.02.2021
Genel Bilgi (General Information)			
Formu (Form)	PLAKA	Lot No (Lot/Batch No)	70268626 70268627
Ölçüleri (Dimensions)	20X1520X3020 20X1520X3020	Miktar (Kg) (Quantity)	3950 4204
Alaşım (Alloy)	7075	Adet (Pieces)	-
Temper (Temper)	T651	Standartlar (Standards)	EN 485, EN 515, EN 573

Kimyasal Analiz (Chemical Analysis)

DEĞERLER (VALUES)	ELEMENTLER (%) (Elements)										
STANDART	Fe	Si	Mn	Cr	Ti	Cu	Mg	Zn	Each	Total	Al
Min.				0,18		1,2	2,1	5,1			
Max.	0,5	0,4	0,3	0,28	0,2	2	2,9	6,1	0,05	0,15	REM.
TEST SONUÇLARI (%) (Test Results)											
70268626 70268627	0,25 0,25	0,17 0,17	0,04 0,04	0,20 0,20	0,03 0,03	1,4 1,4	2,4 2,4	5,8 5,8			

Mekanik Özellikler (Mechanical Properties)

1 Mpa = 1 N/mm² = 0.145 ksi =0.102 kgf/mm²

STANDART	Çekme Dayanımı (Mpa) (Tensile Strength)	Akma Dayanımı (Mpa) (Yield Strength)	Uzama (%) (Elongation)	Sertlik (HB) (Hardness)
Min.	540	470	6	
Max.				
TEST SONUÇLARI (%) (Test Results)				
70268626 70268627	559 561	500 503	12,5 10,5	

Ultrasonik Muayene (Ultrasonic Inspection)

Uygulandı (Done)		Uygulandı İse, Standardı (If Done, Standarts)		Uygulanmadı (Not Done)	X

Bu Ürünlere, %100 Ultrasonik Muayene Yapılmıştır. (These products are 100% Ultrasonic Inspection)

Onay (Approval)

Fig. 2. *Aluminum 7075-T6 chemical composition and manufacturer's certificate of conformity*

The cutting tool was interfaced via a Haimer ER-25 DIN ISO 7388-1 SK40 collet holder, balanced to G2.5 at 25,000 RPM (Figure 3). A 12 × 12 × 26(36) × 83 mm ALU-POWER carbide end mill with three flutes and 45° helix angle was selected for its suitability in aluminum machining, promoting efficient chip evacuation and longevity (Figure 3).

Fig. 3. *Cutting tool and tool holder*

Method

The Taguchi method streamlines experimental design by minimizing trials while maximizing information on parameter effects, thus saving time and resources. In this study, an L9 orthogonal array was employed to evaluate three levels each of cutting speed (A), feed rate (B), and depth of cut (C), facilitating the identification of optimal conditions for minimal surface roughness in Aluminum 7075-T6 milling.

Machining parameters and levels are outlined in Table 1. The L9 experimental design is presented in Table 2, ensuring orthogonal combinations for unbiased assessment.

Table 1. *Machining parameters and their levels*

Parameters	Symbol	Level		
		1	**2**	**3**
Cutting Speed (m/min)	**A**	170	300	430
Feed rate, (mm/min)	**B**	500	1500	2500
Depth of cut (mm)	**C**	0,3	1,3	2,3

Table 2. *Taguchi orthogonal array (L 9 OA) experimental design*

Experiment no.	A	B	C
1	170	500	0,3
2	170	1500	1,3
3	170	2500	2,3
4	300	500	1,3
5	300	1500	2,3
6	300	2500	0,3
7	430	500	2,3
8	430	1500	0,3
9	430	2500	1,3

The "smaller-is-better" signal-to-noise (S/N) ratio was used to evaluate Ra, as minimizing surface roughness is the objective.
The S/N ratio is calculated as:

$$S/_N = -10\log\frac{1}{n}\sum_{i=1}^{n} y_i^2 \quad (1)$$

where y_i is the measured Ra value, and n is the number of repetitions. This metric prioritizes low variability and low mean Ra values, aligning with quality optimization goals.

In summary, this methodological approach integrates high-precision equipment with statistical design to yield

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reliable insights, paving the way for practical optimizations in aluminum machining processes.

RESULTS AND DISCUSSION

Analyzing experimental outcomes is vital for translating raw data into actionable engineering knowledge, particularly in optimizing surface quality for enhanced component performance. The results from Taguchi trials on Aluminum 7075-T6 milling reveal parameter influences on Ra, supported by S/N ratios, ANOVA, and regression. This section interprets these findings, correlating them with physical mechanisms like chip formation and heat generation.

Samples were machined at 45 Nm torque clamping, maintaining consistent conditions across trials (Figure 4). Each experiment was replicated thrice for accuracy. Surface roughness (Ra) was measured using a Mitutoyo SJ-210 device at 21°C, averaging four readings per sample. The experimental Ra values, predicted Ra, and corresponding S/N ratios are listed in Table 3.

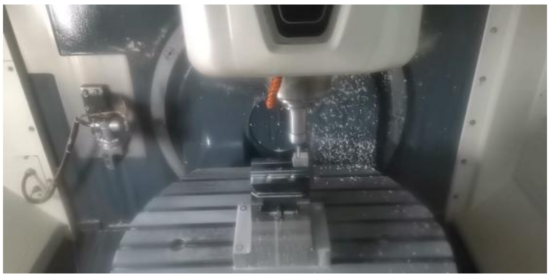

Fig. 4. *Milling of test pieces*

Table 3. *Experimental surface roughness results with calculated s/n ratio*

Experiment No.	Ra (µm)	Predicted Ra (µm)	S/N Ratio (dB)
1	0,153	0,29333	16,3062
2	0,528	0,51867	5,5473
3	1,388	1,25700	-2,8478
4	0,135	0,00400	17,3933
5	0,366	0,50633	8,7304
6	0,666	0,65667	3,5305
7	0,099	0,08967	20,0873
8	0,135	0,00400	17,3933
9	0,325	0,46533	9,7623

The response table for S/N ratios (Table 4) indicates feed rate (B) as the most influential (rank 1, delta 14.447), followed by cutting speed (A, rank 2, delta 9.412) and depth of cut (C, rank 3, delta 3.753). The main effects plot (Figure 5) visualizes optimal levels: A3 (430 m/min), B1 (500 mm/min), C1 (0.3 mm).

The lowest Ra (0.099 µm) occurs in Experiment 7 (A3, B1, C3: 430 m/min, 500 mm/min, 2.3 mm), though the optimal combination from S/N analysis is A3, B1, C1 (430 m/min, 500 mm/min, 0.3 mm), predicting an Ra of approximately 0.08967 µm. This discrepancy suggests depth of cut's lesser influence allows flexibility at lower levels for minimal Ra.

Table 4. *Response Table for Signal to Noise Ratios and significance for surface roughness*

Level	A	B	C
1	6,335	**17,929**	**12,410**
2	9,885	10,557	10,901
3	**15,748**	3,482	8,657
Delta	9,412	14,447	3,753
Rank	2	1	3

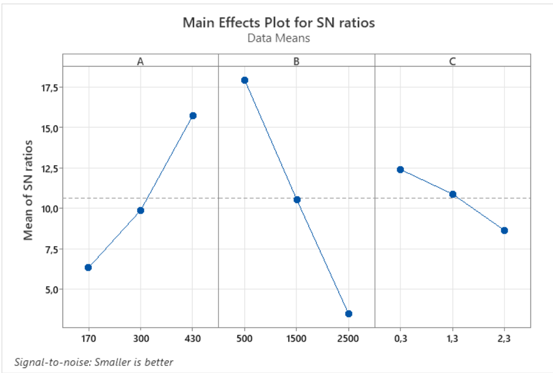

Fig. 5. *Main Effect Plot for Signal to Noise Ratios (A: Cutting speed B: Feed rate C: Depth of cut)*

Figure 6 illustrates the effects of primary factors on Ra, showing reduced roughness at higher speeds and lower feeds, attributable to decreased vibration and built-up edge formation.

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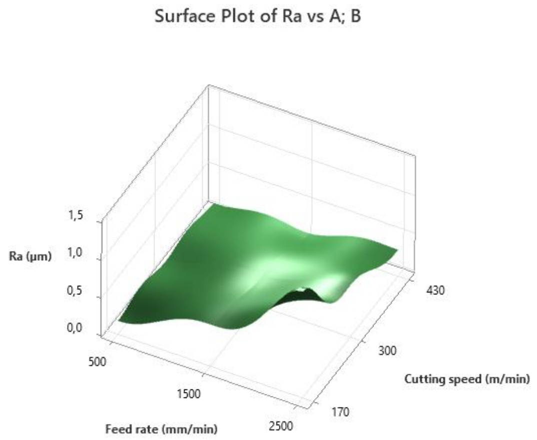

Figure 6. *Effect of Cutting Factors on Ra*

Analysis of Variance (ANOVA)

ANOVA quantifies parameter contributions at 95% confidence, with p-values assessing significance. Table 5 shows feed rate contributing 50.75% to Ra variance, cutting speed 28.34%, and depth of cut 12.75%, with 8.16% error. The error term accounts for 8.16%, indicating a reliable model with minimal unaccounted variability.

The p-values (0.224 for A, 0.139 for B, 0.390 for C) indicate that none of the parameters are statistically significant at the 5% level ($p < 0.05$). This may result from the limited degrees of freedom (DF = 2 for each factor) in the L9 design, which reduces statistical power. However, the high contribution percentages suggest practical significance, particularly for feed rate.

Table 5. *Analysis of Variance (Ra)*

Source	DF	Contribution	Adj MS	P-Value
A (m/min)	2	28,34%	0,19241	0,224
B (mm/min)	2	50,75%	0,34460	0,139
C (mm)	2	12,75%	0,08653	0,390
Error	2	8,16%	0,05541	
Total	8	100,00%		

The ANOVA results align with the S/N ratio response table (Table 4), which ranks factors by their delta values (difference between maximum and minimum S/N ratios).

The delta values confirm feed rate as the most impactful (14.447), followed by cutting speed (9.412) and depth of cut (3.753). The main effects plot (Figure 5) visually supports this, showing that Ra decreases significantly at lower feed rates (B1: 500 mm/min) and higher cutting speeds (A3: 430 m/min), with depth of cut having a milder effect.

Regression Analysis

Regression modeling predicts Ra based on parameters. The model summary (Table 6) yields R^2 of 86.61% (adjusted 78.57%), indicating a good fit. Equation (2) highlights the feed rate's positive and cutting speed's negative coefficients.

Table 6. *Model summary and regression equation for Ra*

S	R-sq	R-sq(adj)	R-sq(pred)
0,190704	86,61%	78,57%	46,08%

$$Ra\ (\mu m) = 0{,}310 - 0{,}001936\ A + 0{,}000332\ B \quad (2)$$

Fitted Plots Assessment

Figure 7 compares predicted and experimental Ra, showing close alignment, particularly for lower Ra values, validating the model's applicability. Predicted versus experimental Ra plots confirm model accuracy, with close alignment suggesting reliable predictions for industrial use.

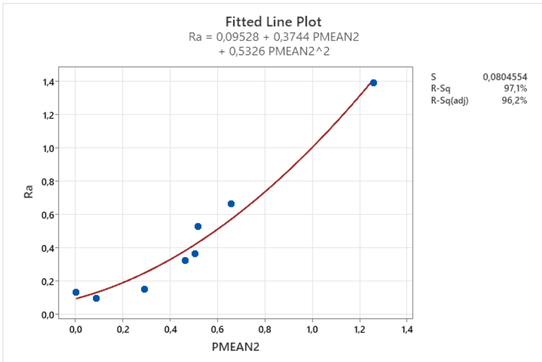

Fig. 7. *Comparison of the predicted values with the experimental results for Ra output parameters*

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Overall, these discussions affirm the Taguchi method's utility in pinpointing feed rate as the dominant factor, offering guidelines for minimizing Ra and improving machinability in Aluminum 7075-T6 applications.

CONCLUSION

Optimizing surface roughness in milling is imperative for advancing manufacturing precision and sustainability, reducing defects and extending tool life in critical industries. This study demonstrates the Taguchi method's effectiveness in achieving superior surface finishes for Aluminum 7075-T6.

Taguchi L9 analysis identifies feed rate as the primary influencer, followed by cutting speed and depth of cut. Optimal parameters—430 m/min cutting speed, 500 mm/min feed rate, 0.3 mm depth of cut—yield minimal Ra, as evidenced by S/N plots and ANOVA. While p-values indicate no statistical significance at the 5% level, the high contribution percentages and S/N ratios confirm practical significance. These findings offer actionable insights for improving manufacturing efficiency and component performance, with future studies planned to incorporate additional parameters for comprehensive optimization.

Future work will incorporate additional parameters in thesis extensions for broader optimizations.

In essence, these findings enhance efficiency and performance, contributing to innovative practices in precision engineering.

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