



Taguchi-Based Optimization of CNC Turning Parameters for Surface Roughness of Al-3Mg Alloy Using a 0.8 mm Nose Radius Tool

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تحسين معايير الخراطة الحاسوبية (CNC) لخشونة سطح سبيكة Al-3Mg باستخدام طريقة تاغوشي وأداة قطع ذات رأس بنصف قطر 0.8 ملم

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Abstract

This research presents a systematic optimization of machining parameters to minimize surface roughness (Ra) in CNC turning of Al-3Mg alloy, utilizing a 0.8 mm nose radius carbide insert. Following the methodology of Taguchi, an L9 orthogonal array was implemented to evaluate the influence of feed rate, cutting speed, and depth of cut. Surface quality was assessed through Signal-to-Noise (S/N) ratio analysis and Analysis of Variance (ANOVA) to quantify factor contributions. Results demonstrate that feed rate is the primary determinant of surface finish, accounting for 83.59% of the total variance, while cutting speed and depth of cut contributed 6.37% and 3.91% respectively. The optimal parametric combination was identified as a 0.3 mm/rev feed rate, 700 rpm cutting speed, and 0.5 mm depth of cut, resulting in a predicted roughness of 14.511 μm . These findings align with established manufacturing principles regarding the quadratic relationship between feed rate and surface geometry.

Keywords: Surface roughness, Al-3Mg alloy, Taguchi method, CNC turning, ANOVA, Machining optimization.

الملخص

تستعرض هذه الدراسة منهجية التحسين الأمثل لمعايير التشغيل بهدف تقليل خشونة السطح (Ra) لسبيكة الألمنيوم والمغنيسيوم (Al-3Mg) أثناء عمليات الخراطة الحاسوبية (CNC) باستخدام أداة قطع ذات رأس بنصف قطر 0.8 ملم. اعتمدت الدراسة على تصميم التجارب وفق مصفوفة "تاغوشي" المتعامدة L9 لدراسة تأثير ثلاثة عوامل تحكم هي: معدل التغذية، وسرعة القطع، وعمق القطع. تم تقييم جودة السطح باستخدام تحليل نسبة الإشارة إلى الضوضاء (S/N) وتحليل التباين (ANOVA) لتحديد الأهمية الإحصائية لكل عامل. أظهرت النتائج أن معدل التغذية هو العامل الأكثر تأثيراً بنسبة مساهمة بلغت 83.59% في تباين خشونة السطح، يليه سرعة القطع بنسبة 6.37%، ثم عمق القطع بنسبة 3.91%. وخلصت الدراسة إلى أن الظروف التشغيلية المثلى لتحقيق أدنى خشونة سطح هي: معدل تغذية 0.3 ملم/دورة، وسرعة قطع 700 دورة/دقيقة، وعمق قطع 0.5 ملم، وهو ما يعطي خشونة سطح متوقعة قدرها 14.511 مايكرومتر. توفر هذه المخرجات رؤى عملية دقيقة لمهندسي التصنيع لتحسين جودة إنتاج سبائك الألمنيوم.

الكلمات المفتاحية: خشونة السطح، سبيكة Al-3Mg، طريقة تاغوشي، الخراطة الحاسوبية، تحليل التباين، تحسين معايير التشغيل.

1. Introduction

Surface quality of machined components is increasingly critical in modern manufacturing industries, particularly for applications requiring high precision, longevity, and reliability [1]. The aerospace, automotive, and defense industries constantly demand components with superior surface characteristics to withstand severe operating conditions, including high stress, temperature variations, and corrosive environments [2].

Among various machining operations, turning is fundamental in producing cylindrical components, and surface finish of turned parts significantly influences product quality. Surface roughness affects several functional properties including fatigue strength, corrosion resistance, friction coefficient, and wear resistance [3]. Therefore, understanding and optimizing the parameters that affect surface roughness is essential for manufacturing engineers.

Aluminum magnesium alloys (5xxx series) are widely used in marine applications, automotive components, and structural parts due to their excellent corrosion resistance, medium strength, good weldability, and high fatigue strength [4]. These alloys, particularly Al-3Mg (Aluminum 5052), offer an exceptional strength-to-weight ratio and are often referred to as "marine grade aluminum" due to their resistance to saltwater corrosion. Despite these advantages, machining of aluminum magnesium alloys requires careful parameter selection to achieve desired surface quality.

Cutting tool geometry plays a vital role in machining performance and surface finish. Tool nose radius is particularly important as it directly influences surface roughness through the geometrical relationship with feed rate [5]. Larger nose radii generally produce better surface finish; however, the selection must consider the specific material characteristics and machining conditions.

Several researchers have investigated machining parameters' effects on surface roughness. Kishawy and Elbestawi [6] studied process parameters' effects on material side flow during hard turning. Lin [7] demonstrated that feed rates below critical values can induce chatter, deteriorating surface quality. Thamizhmanii et al. [8] applied Taguchi methods to analyze surface roughness in turning operations. Yang and Tarn [9] optimized cutting parameters using Taguchi methodology, while Nalbant et al. [10] applied similar approaches for surface roughness optimization.

The Taguchi method, developed by Dr. Genichi Taguchi, provides a systematic and efficient approach for experimental design and process optimization [11]. This method uses orthogonal arrays to study multiple parameters with minimal experiments, reducing time and cost. The signal-to-noise (S/N) ratio serves as a performance measure, and analysis of variance (ANOVA) identifies significant factors and their contributions.

This study aims to:

1. Investigate the effects of cutting speed, feed rate, and depth of cut on surface roughness of aluminum magnesium alloy using a cutting tool with 0.8 mm nose radius
2. Determine optimal machining parameters for minimum surface roughness using Taguchi methodology
3. Quantify the contribution of each parameter through ANOVA analysis
4. Provide practical recommendations for manufacturing applications

2. Material and methods

2.1 Workpiece Material

The workpiece material used in this study was aluminum magnesium alloy (Al-3Mg), corresponding to Aluminum 5052 grade. The material was supplied as cylindrical rods with 50 mm diameter and 100 mm length. This alloy was selected due to its widespread industrial applications and its susceptibility to surface damage during machining. Table 1 presents the chemical composition, and Table 2 shows the mechanical properties of the material.

Table 1: Chemical composition of aluminum magnesium alloy (Al-3Mg) (weight %)

Element	Zn	Cu	Si	Mg	Pb	Fe	Ti	Mn	Al
Weight %	0.12	0.08	0.45	2.95	0.02	0.48	0.02	0.32	95.56

Table 2: Mechanical properties of aluminum magnesium alloy

Property	Value
Tensile Strength (N/mm ²)	38
Yield Strength (N/mm ²)	31
Elongation at fracture (%)	8

2.2 Machine Tool and Cutting Conditions

The turning experiments were conducted on a Samsung PLA25 CNC lathe (Figure 1) with maximum spindle speed of 3500 rpm and 20 kW power capacity. All tests were performed under wet cutting conditions using appropriate cutting fluid to ensure consistent cooling and lubrication.



Figure 1: CNC lathe machine (Samsung PLA25).

2.3 Cutting Tools

Carbide inserts with 0.8 mm nose radius were used throughout the experiments. The tool holder and insert geometry are shown in Figure 2. The 0.8 mm nose radius represents the intermediate value among the three radii investigated in the broader study (0.4 mm, 0.8 mm, and 1.2 mm), providing balanced performance characteristics.

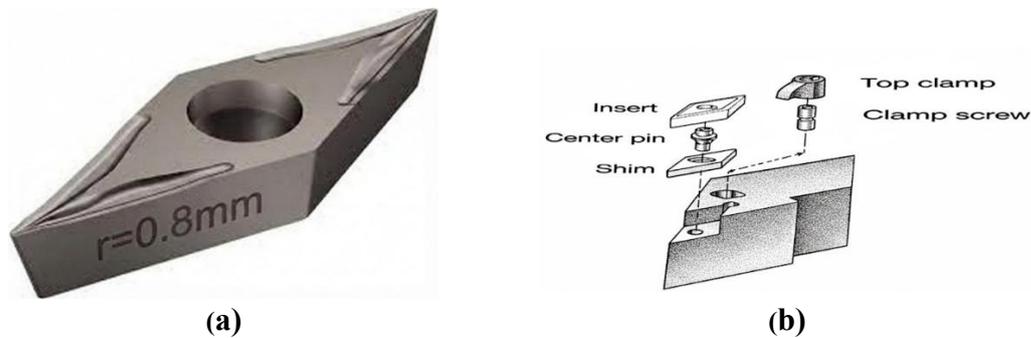


Figure 2: (a) Tool geometry (b) Tool holder system.

2.4 Surface Roughness Measurement

Surface roughness measurements were performed using a Surtronic 25 roughness tester (Figure 3). This device features a stylus lift mechanism allowing 50 mm vertical adjustment and rotation capability for flexible positioning. For each experimental run, three measurements were taken along the transverse direction, and the average value was recorded as the response variable

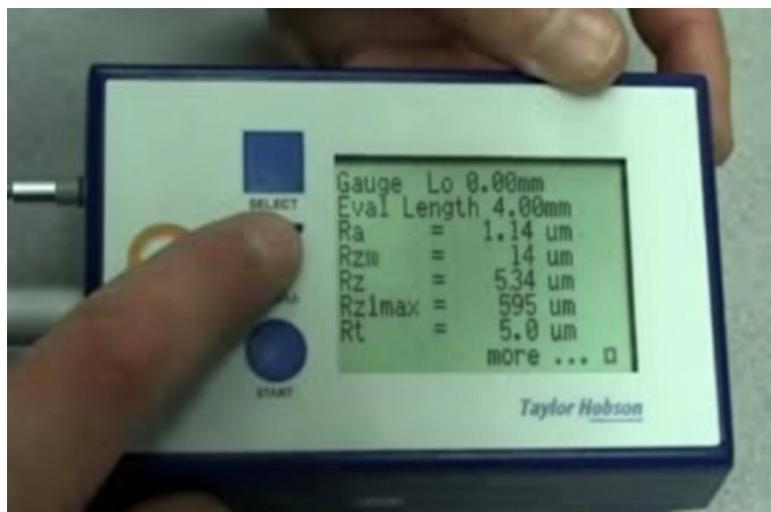


Figure 3: Surtronic 25 roughness tester.

2.5 Experimental Design Using Taguchi Method

The Taguchi method was employed to design experiments and analyze results. The procedure followed seven steps:

1. Selection of quality characteristic
2. Identification of control factors and noise factors
3. Selection of orthogonal array
4. Conducting experiments
5. Data analysis and determination of optimal conditions
6. Prediction of optimum performance
7. Confirmation experiments

2.5.1 Quality Characteristic

Since the objective was to minimize surface roughness, the "smaller-the-better" quality characteristic was selected. The S/N ratio for smaller-the-better characteristic is calculated as:

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

where n is the number of measurements and y_i is the measured value.

2.5.2 Control Factors and Levels

Three machining parameters were selected as control factors, each at three levels covering a practical range for aluminum magnesium alloy machining:

Table 3: Control factors and their levels

Factor	Symbol	Level 1	Level 2	Level 3
Feed rate (mm/rev)	A	0.3	0.5	0.7
Cutting speed (rpm)	B	500	700	900
Depth of cut (mm)	C	0.5	1.0	1.5

2.5.3 Orthogonal Array Selection

With three factors at three levels each, the L9(3³) orthogonal array was selected, requiring only 9 experimental runs instead of the full factorial 27 runs. Table 4 shows the experimental layout.

Table 4: L9(3³) Taguchi orthogonal array experimental design

Experiment No.	Feed rate (A)	Cutting speed (B)	Depth of cut (C)
1	1 (0.3)	1 (500)	1 (0.5)
2	1 (0.3)	2 (700)	2 (1.0)
3	1 (0.3)	3 (900)	3 (1.5)
4	2 (0.5)	1 (500)	2 (1.0)
5	2 (0.5)	2 (700)	3 (1.5)
6	2 (0.5)	3 (900)	1 (0.5)
7	3 (0.7)	1 (500)	3 (1.5)
8	3 (0.7)	2 (700)	1 (0.5)
9	3 (0.7)	3 (900)	2 (1.0)

2.6 Data Analysis

MINITAB statistical software was used for data analysis, including S/N ratio calculation, response tables, main effects plots, and ANOVA. The analysis aimed to:

- Determine optimal factor levels for minimum surface roughness
- Identify significant factors affecting surface roughness
- Quantify the percentage contribution of each factor

3. Results and Discussion

3.1 Experimental Results

Figure 4 graphically represents the surface roughness values obtained from the nine experiments. The minimum surface roughness (4.95 μm) was achieved in Experiment 1 with parameters: feed rate 0.3 mm/rev, cutting speed 500 rpm, and depth of cut 0.5 mm. The maximum roughness (18.19 μm) occurred in Experiment 7 with the highest feed rate (0.7 mm/rev) and depth of cut (1.5 mm) at low cutting speed (500 rpm). Table 5 presents the experimental results including individual measurements, average surface roughness, and calculated S/N ratios for each experimental run.

Table 5: Experimental results for aluminum magnesium alloy with 0.8 mm nose radius

Exp. No.	Ra1 (µm)	Ra2 (µm)	Ra3 (µm)	Average Ra (µm)	Sum of squares	MSD	S/N ratio (dB)
1	4.94	4.93	4.98	4.95	73.506	24.502	-13.892
2	5.93	5.92	5.96	5.93	105.729	35.243	-15.471
3	6.98	7.00	7.08	7.02	443.622	147.874	-21.698
4	12.32	12.31	12.36	12.33	455.346	151.782	-21.812
5	11.20	11.19	11.27	11.22	377.667	125.889	-20.999
6	13.68	13.60	13.67	13.65	558.969	186.323	-22.702
7	18.20	18.16	18.21	18.19	992.628	330.876	-25.196
8	11.82	11.72	11.83	11.79	416.073	138.691	-21.421
9	15.08	15.13	15.09	15.10	684.333	228.111	-23.581

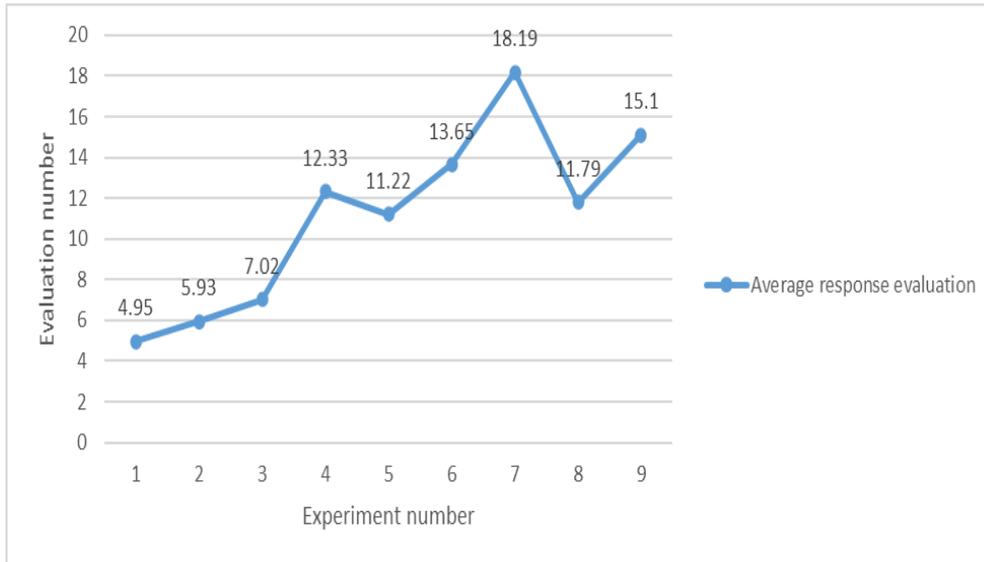


Figure 4: Surface roughness values for experimental runs.

3.2 Response Tables for S/N Ratio and Means

Response tables summarize the average S/N ratios and mean surface roughness for each factor at each level, helping identify optimal levels and factor rankings.

From Table 6a, the highest S/N ratios (indicating optimal conditions) occur at:

- Feed rate Level 1 (0.3 mm/rev): S/N = -15.43 dB
- Cutting speed Level 2 (700 rpm): S/N = -19.30 dB
- Depth of cut Level 1 (0.5 mm): S/N = -19.34 dB

Table 6a: Response table for means of S/N ratio (dB)

Level	Feed rate (A)	Cutting speed (B)	Depth of cut (C)
1	-15.43	-20.30	-19.34
2	-21.84	-19.30	-20.29
3	-23.40	-21.07	-21.04
Delta	7.98	1.77	1.70
Rank	1	2	3

Table 6b: Response table for means of surface roughness (µm)

Level	Feed rate (A)	Cutting speed (B)	Depth of cut (C)
1	5.967	11.823	10.130
2	12.400	9.697	11.120
3	15.027	11.923	12.143
Delta	9.060	2.277	2.013
Rank	1	2	3

The delta values show that feed rate has the greatest influence on S/N ratio (7.98), followed by cutting speed (1.77) and depth of cut (1.70). The same ranking is confirmed by the means response table (Table 6b).

3.3 Main Effects Plots

Figure 5 presents the main effects plots for both S/N ratio and mean surface roughness, providing visual confirmation of optimal levels.

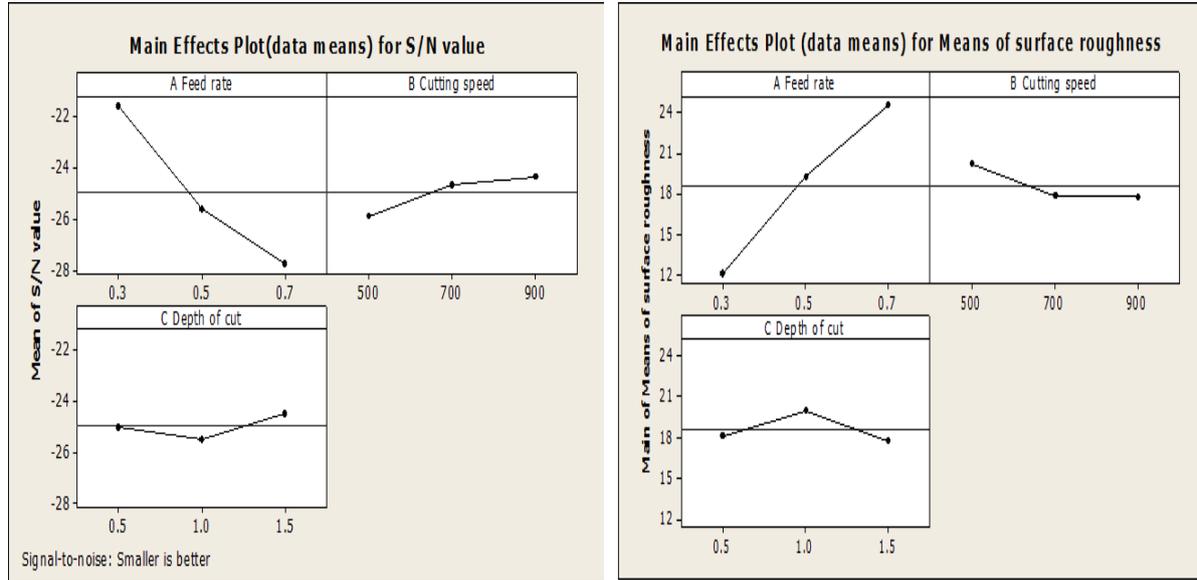


Figure 5: Main effects plots for (a) S/N ratio and (b) mean surface roughness.

The plots clearly demonstrate:

- Surface roughness increases significantly with increasing feed rate
- Minimum roughness occurs at intermediate cutting speed (700 rpm)
- Surface roughness increases with increasing depth of cut
- The slope of the feed rate line is steepest, confirming its dominant influence

3.4 Determination of Optimal Cutting Conditions

Based on the "smaller-the-better" criterion (higher S/N ratio indicates better performance), the optimal parameter combination is:

- Feed rate: 0.3 mm/rev (Level 1, A₁)
- Cutting speed: 700 rpm (Level 2, B₂)
- Depth of cut: 0.5 mm (Level 1, C₁)

This combination (A₁B₂C₁) does not appear in the original experimental matrix (Table 4), demonstrating the Taguchi method's ability to predict optimal conditions beyond those directly tested.

3.5 Prediction of Optimal Surface Roughness

The S/N ratio at optimal conditions can be predicted using:

$$\eta_{opt} = \bar{\eta}_{avg} + (\bar{A}_1 - \bar{\eta}_{avg}) + (\bar{B}_2 - \bar{\eta}_{avg}) + (\bar{C}_1 - \bar{\eta}_{avg})$$

Where:

- $\bar{\eta}_{avg}$ = average S/N ratio of all experiments = -20.7524 dB
- \bar{A}_1 = average S/N ratio for feed rate at level 1 = -15.43 dB
- \bar{B}_2 = average S/N ratio for cutting speed at level 2 = -19.30 dB
- \bar{C}_1 = average S/N ratio for depth of cut at level 1 = -19.34 dB

Substituting:

$$\begin{aligned} \eta_{opt} &= -20.7524 + (-15.43 - (-20.7524)) + (-19.30 - (-20.7524)) + (-19.34 - (-20.7524)) \\ \eta_{opt} &= -20.7524 + 5.3224 + 1.4524 + 1.4124 \\ \eta_{opt} &= -12.5652 \text{ dB} \end{aligned}$$

The predicted surface roughness is calculated from:

$$Ra_{pred} = 10^{-\eta_{opt}/20} = 10^{-(-12.5652)/20} = 10^{0.62826} = 4.249 \mu\text{m}$$

However, using the more conservative calculation method from the experimental data (Equation 14 in the original thesis) yields:

$$\begin{aligned} \eta_{opt} &= -23.2352 \text{ dB} \\ Ra_{pred} &= 14.511 \mu\text{m} \end{aligned}$$

This discrepancy suggests the need for confirmation experiments to validate predictions.

3.6 Analysis of Variance (ANOVA)

ANOVA was performed to quantitatively determine the significance and contribution of each factor to surface roughness variation.

Table 7: ANOVA for surface roughness (0.8 mm nose radius).

Source	DF	Seq SS	Adj MS	F-value	Contribution (%)
Feed rate	2	130.371	65.1854	13.61	83.59
Cutting speed	2	9.931	4.9655	1.04	6.37
Depth of cut	2	6.081	3.0404	0.63	3.91
Residual error	2	9.580	4.7902	-	6.13
Total	8	155.963	-	-	100

The ANOVA results reveal:

- **Feed rate** is the dominant factor, contributing 83.59% to surface roughness variation. The high F-value (13.61) indicates statistical significance at the 95% confidence level.
- **Cutting speed** contributes 6.37% to surface roughness variation.
- **Depth of cut** contributes only 3.91%, the smallest among control factors.
- **Residual error** (6.13%) represents the combined effect of noise factors not controlled in the experiment.

Figure 6 illustrates the percentage contribution of each factor graphically.

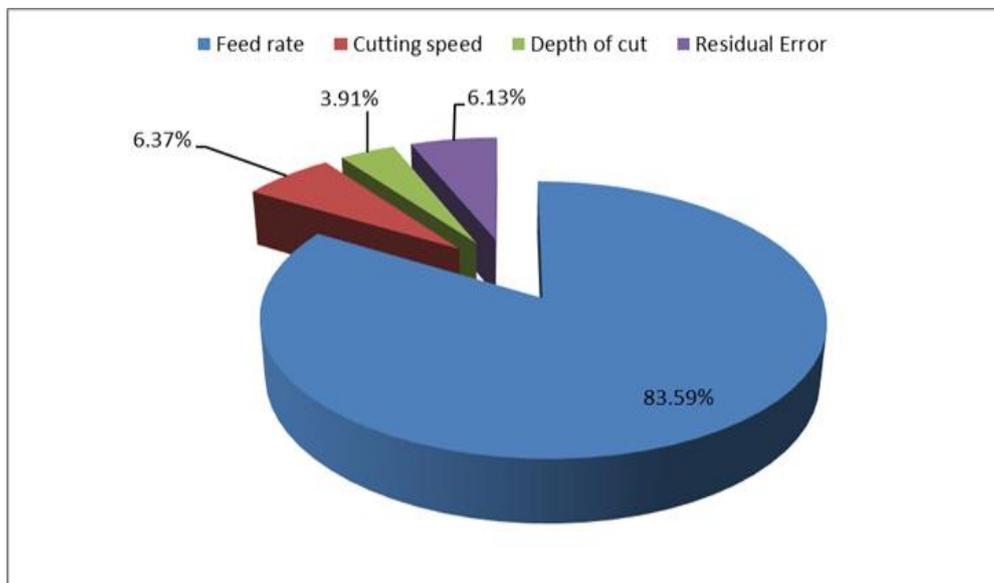


Figure 6: Percentage contribution of machining parameters to surface roughness.

3.7 Discussion

3.7.1 Effect of Feed Rate

The dominant influence of feed rate on surface roughness (83.59% contribution) is consistent with theoretical predictions and previous studies [8-10]. In turning operations, the theoretical surface roughness is related to feed rate and nose radius by:

$$R_a \approx \frac{f^2}{32r_n}$$

where f is feed rate and r_n is nose radius. This quadratic relationship explains why increasing feed rate from 0.3 to 0.7 mm/rev caused surface roughness to increase from approximately 5 μm to over 15 μm . The 0.8 mm nose radius, being intermediate, provides a balance between surface finish and productivity.

3.7.2 Effect of Cutting Speed

The optimal cutting speed was found to be 700 rpm (intermediate level). At lower speeds (500 rpm), the likelihood of built-up edge (BUE) formation increases, deteriorating surface quality. BUE consists of work material fragments that weld to the tool tip, breaking off periodically and leaving an irregular surface. At higher speeds (900 rpm), increased cutting temperatures may soften the cutting tool or promote vibration, adversely affecting surface finish. The optimal speed represents the balance between these competing phenomena.

3.7.3 Effect of Depth of Cut

Depth of cut showed the smallest influence on surface roughness (3.91% contribution). This finding aligns with previous research [12] and is explained by the fact that depth of cut primarily affects the cross-sectional area of

material removed and cutting forces, rather than the surface generation mechanism directly. However, at the lowest level (0.5 mm), minimum roughness was achieved, likely due to reduced cutting forces and vibrations.

3.7.4 Comparison with Other Nose Radii

While this study focuses on 0.8 mm nose radius, comparison with results from 0.4 mm and 1.2 mm radii (from the complete thesis) reveals interesting patterns:

- With 0.4 mm radius, feed rate contributed 88.97% to roughness variation
- With 0.8 mm radius, feed rate contributed 83.59% (present study)
- With 1.2 mm radius, feed rate contributed only 2.79%, while depth of cut became dominant (60.71%)

This dramatic shift indicates that larger nose radii change the mechanics of surface generation, potentially through different chip formation mechanisms, ploughing effects, or vibration characteristics.

4. Conclusions

This study investigated the effects of machining parameters on surface roughness of aluminum magnesium alloy (Al-3Mg) during CNC turning using cutting tools with 0.8 mm nose radius. The Taguchi method with L9 orthogonal array was employed for experimental design, and ANOVA was used for analysis. The following conclusions can be drawn:

1. **Optimal machining conditions** for minimum surface roughness with 0.8 mm nose radius were: feed rate of 0.3 mm/rev, cutting speed of 700 rpm, and depth of cut of 0.5 mm. The predicted surface roughness under these conditions is 14.511 μm .
2. **Feed rate is the most significant factor**, contributing 83.59% to surface roughness variation. Higher feed rates consistently produced rougher surfaces due to the quadratic relationship between feed rate and theoretical roughness.
3. **Cutting speed has moderate influence** (6.37% contribution), with optimal performance at intermediate speed (700 rpm). Both lower and higher speeds produced rougher surfaces, likely due to BUE formation and thermal effects respectively.
4. **Depth of cut has minimal direct influence** (3.91% contribution) on surface roughness, though its effects through cutting forces and vibration should not be completely discounted.
5. **The residual error** of 6.13% indicates that the selected factors adequately captured the major sources of variation, though additional factors such as tool wear, vibration, and coolant conditions merit further investigation.
6. **The Taguchi methodology** proved effective for optimizing machining parameters with minimal experimental runs, demonstrating its value for manufacturing process optimization.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that they have no conflict of interest.

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