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Effect of lubrication strategies and cutting parameters on surface roughness in turning of Ti6Al4V alloy using Taguchi method

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Abstract
This study investigates the effects of cutting parameters and lubrication strategies on surface roughness during the turning of Ti6Al4V titanium alloy. Due to its low thermal conductivity and high chemical reactivity, Ti6Al4V is considered a difficult-to-machine material, requiring effective lubrication and cooling techniques to enhance machining performance. In this work, three lubrication conditions, including dry machining, minimum quantity lubrication (MQL), and nanofluid minimum quantity lubrication (NFMQL) using Al_2O_3 nanoparticles, were evaluated. A Taguchi L9 orthogonal array was employed to systematically analyze the influence of cutting speed, feed rate, depth of cut, and lubrication method on surface roughness. The results indicated that feed rate is the most significant factor affecting surface roughness, followed by depth of cut, lubrication method, and cutting speed. Among the investigated conditions, NFMQL demonstrated superior performance, significantly improving surface finish compared to MQL and dry machining. This improvement is attributed to enhanced lubrication and heat transfer, as well as the formation of a protective tribo-film at the tool–chip interface.
Keywords: *Titanium alloy; Ti-6Al-4V; Turning; MQL; NF MQL*

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I. INTRODUCTION

Titanium alloys, particularly Ti6Al4V, are widely used in aerospace, biomedical, and automotive industries due to their excellent strength-to-weight ratio, high corrosion resistance, and superior mechanical properties [1–3]. However, these advantageous properties also make Ti6Al4V a typical difficult-to-machine material. Its low thermal conductivity, high chemical reactivity, and strong affinity to cutting tools result in excessive heat generation, rapid tool wear, and poor surface quality during machining operations . In particular, the concentration of heat in the cutting zone significantly accelerates tool degradation and deteriorates surface integrity [4–6].Traditionally, flood cooling has been employed to mitigate these issues by providing effective lubrication and heat dissipation. However, the use of large volumes of cutting fluids raises serious environmental and health concerns, including fluid disposal, operator exposure, and increased production costs [7,8]. Consequently, sustainable and eco-friendly machining techniques have attracted increasing attention in recent years.

Minimum Quantity Lubrication (MQL) has emerged as a promising alternative to conventional flood cooling. This technique utilizes a small amount of lubricant delivered in aerosol form, significantly reducing fluid consumption while maintaining adequate lubrication performance. Previous studies have demonstrated that MQL can effectively reduce cutting forces, tool wear, and surface roughness compared to dry machining . However, due to its limited cooling capacity, MQL may not be sufficient for machining difficult-to-cut materials such as titanium alloys under severe cutting conditions.

To overcome these limitations, researchers have increasingly focused on nanofluid-based MQL (NFMQL), where nanoparticles are added to the base lubricant to enhance its thermal and tribological properties. Nanoparticles such as Al_2O_3, CuO, graphene, and carbon nanotubes have been reported to significantly improve heat transfer and reduce friction at the tool–chip interface [9–11]. The enhanced performance of NFMQL is mainly attributed to mechanisms such as nano-rolling, tribo-film formation, and improved thermal conductivity.

Recent studies have reported substantial improvements in machining performance when using NFMQL. For instance, the incorporation of Al_2O_3 nanoparticles in MQL has been shown to reduce surface roughness, cutting temperature, and tool wear, while simultaneously increasing tool life and productivity . Similarly, hybrid nanofluid MQL systems have demonstrated superior tribological performance and lower friction coefficients compared to conventional MQL . Moreover, recent review studies highlight that NFMQL is becoming a key enabling technology for sustainable machining of titanium alloys .

In addition to lubrication conditions, machining parameters such as cutting speed, feed rate, and depth of cut play a crucial role in determining surface roughness and overall machining performance. Among these parameters, feed rate is often reported as the most influential factor affecting surface finish, followed by cutting speed and depth of cut . Therefore, the combined optimization of cutting parameters and lubrication strategies is essential to achieve high-quality machining performance.

Despite the growing interest in NFMQL, there are still several research gaps. Firstly, many previous studies have focused on either lubrication strategies or cutting parameters independently, without systematically evaluating their combined effects. Secondly, the application of statistical design methods such as Taguchi for optimizing NFMQL conditions in turning Ti6Al4V remains limited. Thirdly, the influence of Al_2O_3-based nanofluids under different machining conditions requires further investigation to better understand their effectiveness.

Therefore, the present study aims to investigate the influence of cutting parameters and lubrication strategies, including Dry, MQL, and Al_2O_3-based NFMQL, on surface roughness during the turning of Ti6Al4V alloy. A Taguchi L9 orthogonal array is employed to systematically analyze the effects of machining parameters and determine the optimal conditions. The outcomes of this study are expected to contribute to the development of sustainable and high-performance machining processes for titanium alloys.

II. MATERIAL AND METHOD

The machining experiments were performed on a CNC lathe manufactured by Takang Machine Tools under controlled conditions to ensure the repeatability of the results. A commercial external turning tool equipped with a CNMG 120408 insert (grade PR1535) supplied by Kyocera Corporation was used throughout the experiments. This insert grade is suitable for machining titanium alloys due to its high wear resistance and thermal stability. The workpiece material was Ti6Al4V titanium alloy, which is widely used in aerospace and biomedical applications but is considered difficult-to-machine due to its low thermal conductivity and high chemical reactivity.

The main objective of this study is to investigate the influence of cutting parameters and lubrication strategies on surface roughness (Ra) in turning operations. Three lubrication conditions were considered, including dry machining (Dry), minimum quantity lubrication (MQL), and nanofluid minimum quantity lubrication (NFMQL). In the MQL condition, vegetable oil was used as the base lubricant and supplied in aerosol form using compressed air. For the NFMQL technique, Al_2O_3 nanoparticles with an average size of 30 nm were dispersed into the vegetable oil to enhance both thermal and tribological properties. The addition of nanoparticles is expected to improve heat dissipation and reduce friction at the tool–chip interface. The experimental system is set up as shown in Figure 1.

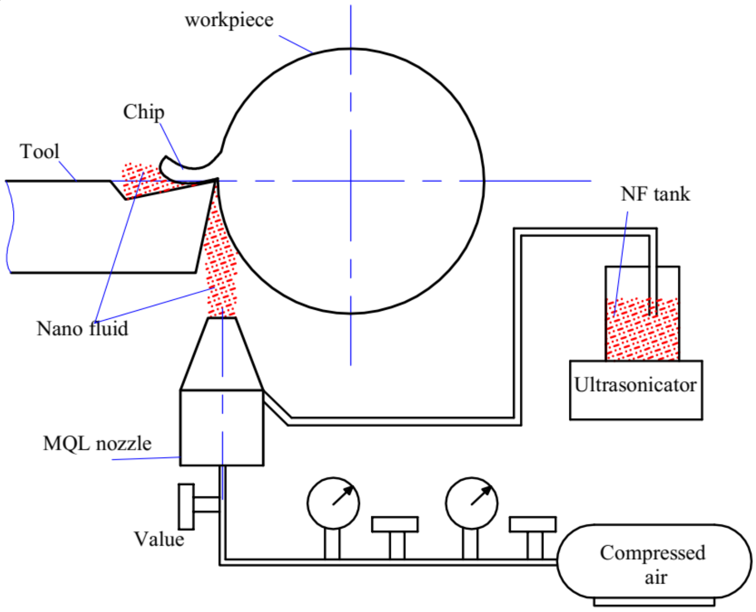

Figure 1. Experimental set up

The experimental design was based on a Taguchi L9 orthogonal array to efficiently evaluate the effects of multiple input factors. Four machining parameters were considered, namely lubrication method (LM), cutting speed (V), feed rate (f), and depth of cut (d), each at three levels. The detailed levels of these factors are presented in **Table 1**.

Table 1. Cutting parameters and level

	Input parameters	Symbol	Level		
			1	**2**	**3**
1	**Lubrication method – LM**	**LM**	Dry	MQL	NFMQL
2	**Cutting speed (m/min) -V**	**V**	30	60	90
3	**Feed per tooth - f (mm/rev)**	**f**	0.08	0.12	0.16
4	**depth of cut – d (mm)**	**d**	0.2	0.8	1.4

Surface roughness (Ra) was selected as the primary response and measured using a portable surface roughness tester SJ-210 manufactured by Mitutoyo Corporation. For each experiment, measurements were taken at multiple locations along the machined surface, and the average value was used to ensure measurement reliability.

The experimental matrix and corresponding surface roughness results obtained from the Taguchi L9 design are summarized in **Table 2**. These results form the basis for subsequent analysis, including the evaluation of parameter significance and optimization of machining performance.

Table 2. Experiment matrix and Ra measurement results

Trial nuber	LM	V (m/min)	f (mm/rev)	d (mm)	Ra (µm)
1	Dry	30	0.08	0.2	1.282
2	Dry	60	0.12	0.8	0.919
3	Dry	90	0.16	1.4	1.184
4	MQL	30	0.12	1.4	0.96
5	MQL	60	0.16	0.2	1.48
6	MQL	90	0.08	0.8	0.675
7	NFMQL	30	0.16	0.8	1.045
8	NFMQL	60	0.08	1.4	0.354
9	NFMQL	90	0.12	0.2	0.652

III. RESULTS AND DISCUSION

3.1 Analysis of signal-to-noise (S/N) ratio

The influence of machining parameters on surface roughness was evaluated using the Taguchi signal-to-noise (S/N) ratio with the “smaller-is-better” criterion. The corresponding response values are presented in Table 4 .

Table 4. Response Table for Means

Level	LM	V (m/min)	f (mm/rev)	d (mm)
1	1.1283	1.0957	0.8703	1.2047
2	1.0383	1.0177	0.9103	0.8797
3	0.8503	0.9037	1.2363	0.9327
Delta	0.2780	0.1920	0.3660	0.3250
Rank	3	4	1	2

Based on the delta values of the S/N ratios, the feed rate (f) was identified as the most dominant factor affecting surface roughness, followed by depth of cut (d), lubrication method (LM), and cutting speed (V). The significantly higher delta value of feed rate indicates that it has the strongest contribution to the variation of surface roughness.

This result is consistent with machining theory, where feed rate directly governs the geometrical formation of the machined surface. Higher feed rates increase the uncut chip thickness and surface scallop height, leading to a deterioration in surface finish.

The depth of cut ranked as the second most influential parameter, suggesting that its effect on cutting forces and process stability plays a considerable role in surface generation, as figure 2. Meanwhile, the lubrication method showed a noticeable but less dominant influence compared to mechanical parameters. Cutting speed exhibited the lowest effect, indicating that within the investigated range, its impact on surface roughness is relatively limited.

he Main Effects Plot for S/N ratios (smaller-is-better) highlights the optimal levels of machining parameters that minimize the response. For the lubrication method (LM), the S/N ratio increases significantly from Dry to MQL and reaches the highest value at NFMQL, indicating that NFMQL provides the best performance in reducing the response (e.g., surface roughness or cutting force). Similarly, the cutting speed (V) shows a positive trend, with the highest S/N ratio observed at 90 m/min, suggesting that higher cutting speeds improve machining quality.

In contrast, the feed rate (f) exhibits a strong negative effect on the S/N ratio. The highest value occurs at 0.08 mm/rev, while a sharp decrease is observed at 0.16 mm/rev, indicating that increasing feed rate significantly deteriorates the response. This confirms that feed rate is the most sensitive parameter. For the depth of cut (d), the S/N ratio increases from 0.2 to 0.8 mm and then slightly decreases at 1.4 mm, implying that 0.8 mm is the optimal level for this factor.

Overall, the optimal parameter combination based on the S/N ratio analysis is **NFMQL (LM3), V = 90 m/min, f = 0.08 mm/rev, and d = 0.8 mm**, which corresponds to the maximum S/N ratios and thus the best machining performance under the “smaller-is-better” criterion.

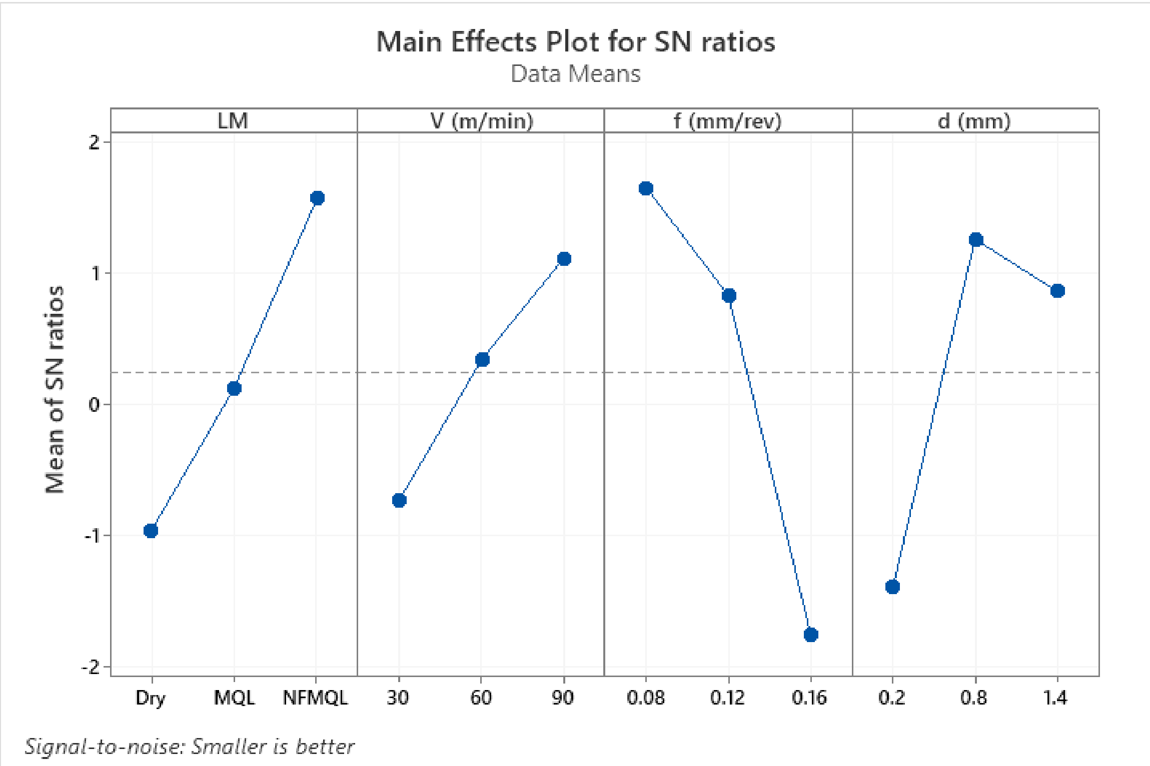

Figure 2. Main effects plot for SN ratios

3.2 Effect of machining parameters based on mean response

The response table for means (Table 3) further confirms the trends observed in the S/N analysis. Among all factors, feed rate exhibited the largest variation range, reaffirming its critical role in determining surface quality.

Table 3. Response Table for Signal to Noise Ratios
Smaller is better

Level	LM	V (m/min)	f (mm/rev)	d (mm)
1	-0.9637	-0.7285	1.6482	-1.3906
2	0.1211	0.3390	0.8265	1.2551
3	1.5658	1.1127	-1.7515	0.8587
Delta	2.5295	1.8412	3.3997	2.6457
Rank	3	4	1	2

Lower feed rates resulted in improved surface finish due to reduced feed marks and smoother material removal. As the feed increased, the material deformation became more severe, leading to higher roughness values.

The lubrication method also showed a clear influence on surface roughness. The NFMQL condition provided the lowest average roughness values, followed by MQL and dry machining. This confirms the beneficial role of lubrication, particularly when enhanced with nanoparticles.

Depth of cut demonstrated a moderate influence. Increasing depth of cut tends to increase cutting forces and vibration, which can negatively affect surface integrity. However, its effect remains secondary compared to feed rate.

Cutting speed again showed the least variation in mean surface roughness. Although higher cutting speeds can improve surface finish by reducing built-up edge formation, its influence is less significant compared to feed and depth of cut in this study.

The Main Effects Plot for Means clearly illustrates the influence of machining parameters on the response, as figure 3. Regarding the lubrication method (LM), the mean value decreases significantly from Dry to MQL and reaches the lowest level at NFMQL, indicating that nanofluid MQL provides the most effective improvement in machining performance. Similarly, as the cutting speed (V) increases from 30 to 90 m/min, the mean value gradually decreases, suggesting that higher cutting speeds contribute to better outcomes. In contrast, the feed rate (f) shows a strong increasing trend, with the mean value rising sharply from 0.08 to 0.16 mm/rev, reaching the highest level at 0.16 mm/rev, confirming that this parameter is the most sensitive. For the depth of cut (d), the mean value decreases notably from 0.2 to 0.8 mm and then slightly increases at 1.4 mm, indicating the existence of an optimal intermediate level. Overall, the trends observed in the plot are consistent with the S/N ratio analysis, confirming that feed rate and depth of cut are the most influential factors affecting the machining response.

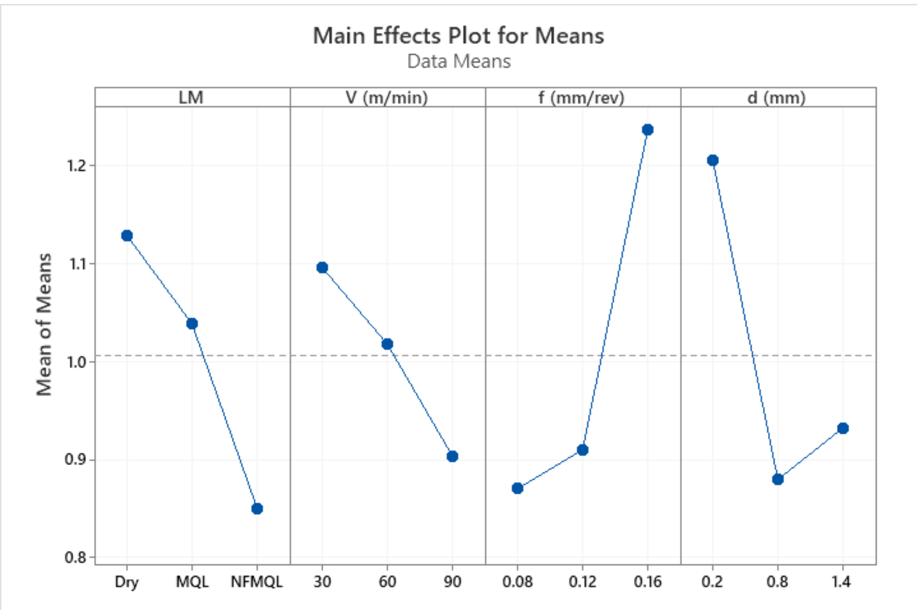

Figure 3. Main effects plot for means of the surface roughness

IV. CONCLUSION

This study investigated the effects of cutting parameters and lubrication strategies on surface roughness during the turning of Ti6Al4V alloy using a Taguchi L9 experimental design. Based on the obtained results, the following conclusions can be drawn:

Firstly, among the investigated parameters, feed rate was identified as the most influential factor affecting surface roughness, followed by depth of cut, lubrication method, and cutting speed. This confirms that the geometrical mechanism of surface formation plays a dominant role in determining surface quality during turning operations.

Secondly, lubrication strategy significantly affected machining performance. The NFMQL technique demonstrated superior performance compared to conventional MQL and dry machining. The incorporation of Al_2O_3 nanoparticles enhanced both lubrication and heat transfer, leading to reduced friction at the tool–chip interface and improved surface finish. This highlights the effectiveness of nanofluid-assisted MQL as a sustainable and high-performance cooling/lubrication approach for machining titanium alloys.

Finally, the findings of this study provide valuable insights into the application of advanced lubrication techniques in machining difficult-to-cut materials. Future work should focus on integrating advanced modeling and optimization approaches, such as artificial neural networks (ANN) and multi-objective optimization algorithms (e.g., NSGA-II), to further enhance prediction accuracy and process optimization. Additionally, tool wear and cutting temperature should be investigated to provide a more comprehensive understanding of the machining performance under NFMQL conditions.

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