



Influence of MQL parameters on surface roughness and temperature in end milling of titanium alloy

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KEYWORDS	ABSTRACT
Minimum Quantity Lubrication (MQL) Titanium alloy Silicon dioxide End milling Taguchi method.	This paper addresses the challenge of optimizing Minimum Quantity Lubrication (MQL) parameters in the end milling of titanium alloys, where improper lubrication can lead to increased friction, elevated temperatures, and poor surface quality. The study aims to enhance machining performance by systematically investigating the effects of lubrication flow rate, nozzle distance, and nozzle angle on key performance metrics such as surface roughness and cutting temperature. The Taguchi method was employed to design experiments and analyse the influence of these parameters, enabling the identification of optimal conditions. Results revealed that a flow rate of 10 m ³ /s, nozzle distance of 20 mm, and nozzle angle of 60° minimized surface roughness to 0.66 µm and a flow rate of 10 m ³ /s, nozzle distance of 10 mm, and nozzle angle of 30° reduced cutting temperature to 58°C, significantly improving machining efficiency. This research highlights the importance of precise MQL parameter control and contributes to advancing sustainable manufacturing practices by reducing environmental impact and enhancing process efficiency.

Received 10 July 2025; received in revised form 13 August 2025; accepted 21 August 2025.

To cite this article: Ismail et al. (2025). Influence of MQL parameters on surface roughness and temperature in end milling of titanium alloy. *Jurnal Tribologi* 47, pp.121-137.

1.0 INTRODUCTION

Titanium alloy, such as Ti-6Al-4V, are widely used in various industries due to their high strength-to-density ratio, corrosion resistance, and resistance to dynamic loads (Matuszak et al. 2023). Titanium alloys are well-known for their unique properties, offering an excellent strength-to-weight ratio, making them ideal for applications where weight reduction is essential, such as aerospace, automotive, and medical industries. They also exhibit outstanding resistance to corrosion, even in harsh environments, making them suitable for marine and chemical processing applications. However, these desirable properties also create challenges in machining. Ti-6Al-4V high chemical reactivity at elevated temperatures can cause “galling”, where the tool and workpiece weld together. Proper cooling while milling Ti-6Al-4V is crucial since titanium has poor thermal conductivity, which means that it has a low ability to dissipate heat generated during machining (Qin et al. ,2016). Additionally, Ti-6Al-4V hardens quickly during machining, requiring greater force to minimize tool breakage risk. In more severe cases, Ti-6Al-4V low thermal conductivity causes high temperatures at the cutting zone, accelerating tool wear and worsening galling.

Ti-6Al-4V known to be harder than many other materials and their respective alloys (Hasan et al. 2023). This very strength, meanwhile, can also provide difficulties when milling. Because of their high work hardening tendencies and low thermal conductivity, Ti-6Al-4V can be challenging to machine. A notable feature of Ti-6Al-4V is their exceptional strength-to-weight ratio. They are also recognized for being harder than various other materials and their alloys (Tatar et al. 2020). Ti-6Al-4V belong to a group of hard to-cut materials (S group by ISO 513:2012) due to their high strength, toughness, oxidise ability, low E modulus, and low thermal conductivity. Machining these materials is accompanied by a build-up formation on the tool and release of a large amount of heat (Vereschaka et al. 2019). Additionally, employing Ti-6Al-4V in MQL research projects provides insightful information on how well this lubricating technique works for difficult-to-machine due to materials. Broadly speaking, the outcomes can be applied to other materials with comparable machining complexity. Titanium and its alloys are known to be particularly difficult to machine, primarily because some of the properties which contribute to their excellent in-service performance, such as their ability to retain high strength at elevated temperatures, also pose significant challenges for the cutting tool (Conger et al. 2025), Ti-6Al-4V is generally referred to as “difficult-to-machine materials” most especially at high temperature and speed because of its low thermal conductivity (Ilesanmi et al, 2020).

Minimum Quantity Lubrication (MQL) offers a compelling alternative to traditional flood cooling in machining by delivering an optimum amount of lubricant to the cutting zone, which contributes to lubrication and cooling benefits. However, achieving optimal performance with MQL requires a precise consideration of several critical parameters which include the nozzle distance, flow rate of the lubricant, and the nozzle angle. A poorly distanced nozzle can lead to several challenges. The nozzle that is too far from the cutting zone will lead to lower lubrication and cooling as the lubricant stream will not reach the cutting zone effectively. On the other hand, if the nozzle positioned too close, it could cause the lubricant to pool or deflect off the workpiece, again failing to reach the critical areas. This can lead to increased friction, heat generation which lead to higher surface roughness and temperature. The amount of lubricant to be delivered also plays a significant role in cutting process. An insufficient flow rate may not provide sufficient lubrication and cooling which may lead to unpleasant issues mainly on its surface roughness and temperature. Nozzle angle is important in directing the lubricant stream to the critical areas. An improper angle can lead to lubricant being wasted or failing to reach the cutting zone. An angled

approach can make the lubricant penetrate the machining area and coat the necessary surfaces to cool the cutting areas.

MQL is a micro-lubrication technique that delivers only 50-150 ml/hr of cutting fluid to the machining zone, reducing lubricant costs and significantly minimizing the environmental impact of conventional cutting fluids and coolants. (Kharka et al. 2023). The MQL system consists of basic components such as fluid containers, air compressors, pipelines, control valves, and nozzles. A dial flow regulator controls the delivery of cutting fluid from the reservoir to the nozzle at a set flow rate. The nozzle's other open-end releases high-pressure compressed air to atomize the cutting fluid (Mehmood et al. 2022). Through a nozzle system, it applies an exact, minuscule amount of lubrication straight to the cutting zone. MQL is believed to offer better machining performance and efficiency. The main goal of MQL is to achieve a better cutting performance (Sedamkar et al. 2020). To ensure the effectiveness of MQL, the parameters also has been studied by Siregar et al. (2025) in their experimental investigation where they used nozzle angle of 30°, 45°, and 60°, nozzle distance of 30 mm, 40 mm, and 50 mm and flowrate of 0.66 ml/min, 1.32 ml/min and 1.98 ml/min. More significantly, MQL lowers friction and heat generation by efficiently delivering lubrication to the cutting zone. MQL promotes lower heat generation, which helps prevent workpiece materials and chips from welding to the cutting edge.

Surface roughness is a crucial aspect of machined parts because it will directly impact their functionality, performance, and aesthetics. According to Ali et al. (2023) surface roughness is a crucial outcome of the machining process for determining whether a material is machinable. It is a term used to describe the minuscule imperfections on the machined surface, like multiple nodes on the surface. This kind of surface will cause a big impact on the workpiece's performance, functionality, and aesthetic. The key factor in achieving a high-quality surface finish is the selection of appropriate cutting parameters, including cutting speed, feed rate, and depth of cut. In the end milling process of Ti-6Al-4V, the primary factors influencing surface roughness are the machine's cutting speed, the type of end mill used, the adopted feed rate, and the chosen depth of cut (Samsudeensadham et al. 2015). On the other hand, Van-Canh et al. (2024) has undergone the study of the effect of depth of cut on surface roughness and conclude that the higher value of depth of cut gives better finish than lower depth of cut. Higher cutting speed can result to a smoother surface finish as it creates a more frequency of the continuous chip removal process.

The heat generated in cutting process is one of the most important issues in the metalworking industry (Lin et al. 2013). The friction between the cutting tool and workpiece during the cutting process will generates heat which this heat can cause both good and side effects for the final workpiece. One of the primary risks associated with increased temperature is thermal shock, which leads to poor surface quality, heat buildup in the cutting zone, the appearance of sparks, and the formation of chip burrs. This occurs due to higher thermal stress in the cutting area, which is caused by reduced heat dissipation from both the chips and the workpiece (Ali et al. 2023). The study of Krishnaraj et al. (2014) of cutting speed to temperature has successfully proved that higher cutting speed has higher effect of temperature and lower depth of cut can also contribute to higher temperature. On the other hand, cutting fluids can act as double agent, which cool the process and lubricating the cut for smoother chip formation.

The other factor to be considered is the lubrication during the machining process, which where the role of MQL takes place. The surface roughness of the workpiece under the condition of nano-fluid MQL was much smaller than the case of dry air (Lee et al. 2010). The MQL system provides some lubrication and reduces friction on the machined surface (Ozbek et al. 2020). The shear force occurs when the microscopic asperities on the tool and workpiece surfaces rub against each

other hence MQL lubricant can fill the asperities which can create smoother surface as it reduces the amount of the direct contact between the tool and workpiece. In a previous study, Safiei et al. (2018) conducted an experimental investigation to determine the optimum MQL parameters and concluded that the best combination for minimizing surface roughness was a nozzle distance of 30 mm, a nozzle angle of 30°, and an MQL flow rate of 1.98 ml/min. In another study, Kieren et al. (2018) explored oil flow rates of 1.88 ml/h, 3.75 ml/h, and 7.5 ml/h, alongside air flow rates of 25 ml/min and 40 ml/min. The optimal performance was achieved with the lowest oil flow rate of 1.88 ml/h and an air flow rate of 40 ml/min.

The objective of this experiment is to analyse the effect of MQL parameters which are nozzle distance, flow rate and nozzle angle on surface roughness and temperature of titanium alloy in end milling process. This experiment will be conducted using Taguchi Method L9 condition using CNC milling machine. The reading of surface roughness and temperature will be recorded for further analysis.

2.0 EXPERIMENTAL PROCEDURE

The experiment of end milling Ti-6Al-4V was conducted under Taguchi Method L9 condition using nanoparticle MQL technique. The cutting parameters were constant throughout the whole experiments with cutting speed of 40 m/s, feed rate of 0.2 mm/tooth and depth of cut 0.25 mm. Table 1 showed the parameter of the end milling Ti-6Al-4V by using a vertical CNC milling machine.

Table 1: MQL flowrate and nozzle setup.

Exp	Flowrate (m³/s)	Distance (mm)	Angle (°)
1	10	10	30
2	10	15	45
3	10	20	60
4	15	10	45
5	15	15	60
6	15	20	30
7	20	10	60
8	20	15	30
9	20	20	45

Figure 1 showed the setup of the experiment with the nozzle distance of 10 mm and the angle of 90°. Figure 2 (a) showed the nozzle angle of 45° and (b) of 30°.

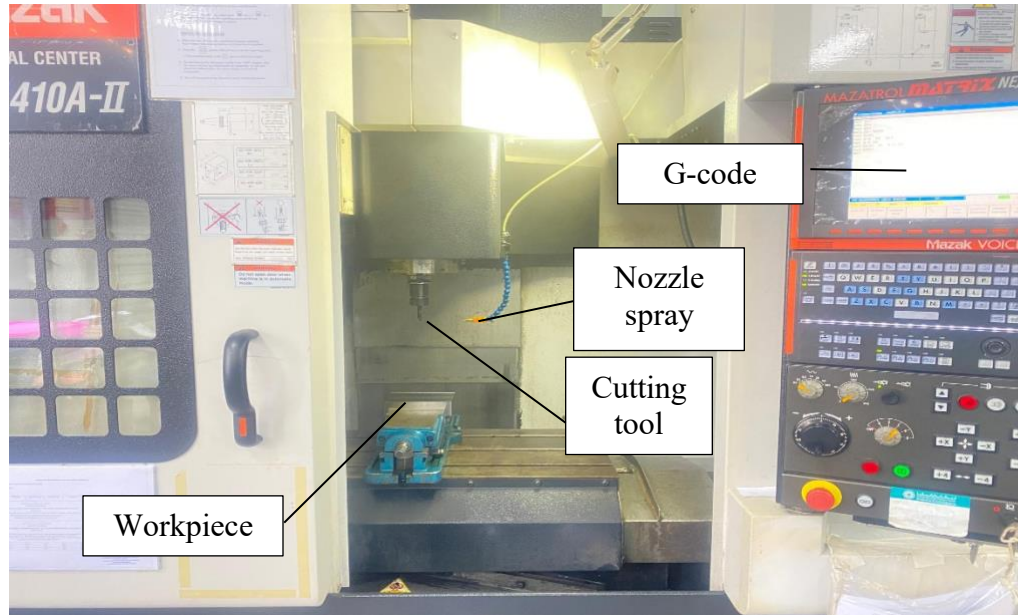


Figure 1: Experimental setup.



Figure 2: Show one of the nozzle angles, 45°.

Coolant that was used as basic coolant in this research is semi-synthetic type. This coolant is water-based as it is mixed with water and usually used in many types of machining. The ratio of the coolant mixed with distilled water is 1:9 (C: DW). This coolant is a premier grade heavy duty machining coolant, highly stable with extended life and suitable for hard alloys. This coolant plus 1% (by weight) of silicon dioxide (SiO_2) is used and sprayed out using MQL system. Figure 3 showed the MQL system.

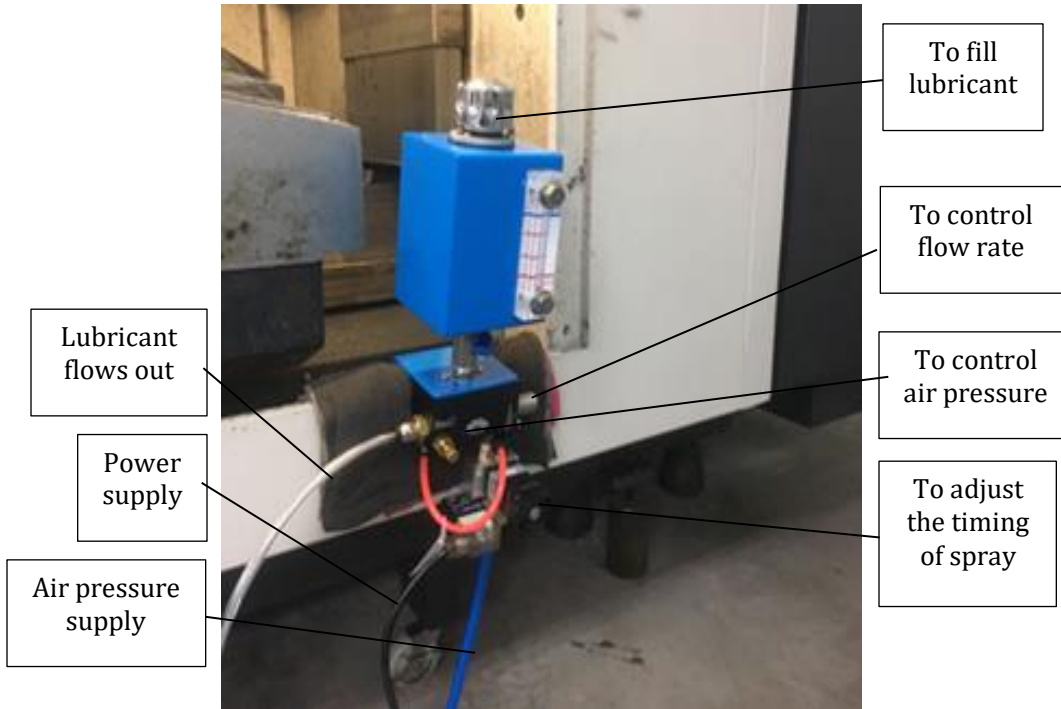


Figure 3: The MQL system.

The material used for the workpiece is the titanium alloy (Ti-6Al-4V). Table 2 and Table 3 illustrates the composition (wt%) of titanium alloy and mechanical properties of titanium alloy at room temperature. Figure 4 shows the workpiece dimension of the titanium alloy (length x width x height) in mm. The titanium alloy is sourced from Metal Chain Supply Expert Company, the supplier.

Table 2: The composition (wt%) of titanium alloy.

Content	O	H	N	C	Fe	V	Al	Ti
wt%	-	0.005	0.01	0.05	0.09	4.40	6.15	4.295

Table 3: The mechanical properties of titanium alloy at room temperature.

Tensile strength (MPa)	Yield strength (MPa)	Density (kg/m ³)	Modulus of elasticity (GPa)	Hardness (HRC)
993	830	4540	114	36

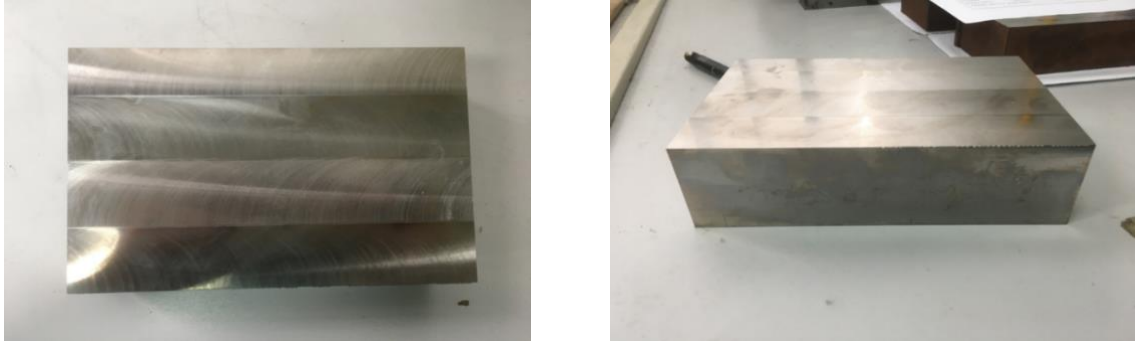


Figure 4: The workpiece dimension (160 mm × 110 mm × 42 mm).

Coated carbide cutting tool that had been used in this research was milling insert: EDPT070308PDSRGE KCSM30, coated carbide TiAlN, 0.1102 inch thick, 0.1850 inch wide. Titanium aluminium nitride (TiAlN) or aluminium titanium nitride (AlTiN; for aluminium contents higher than 50%). TiAlN is a group of metastable hard coatings consisting of nitrogen and the metallic elements aluminium and titanium. Figure 5 showed the dimension of insert using Dino-lite with magnification of 45x with the height of 3 mm and the length of 7 mm. The insert of coated carbide cutting tool must be attached to the cutting tool body by using screw. Figure 6 shows the insert before attached to the insert holder body, during attached to the body tool and after attached to the machine.

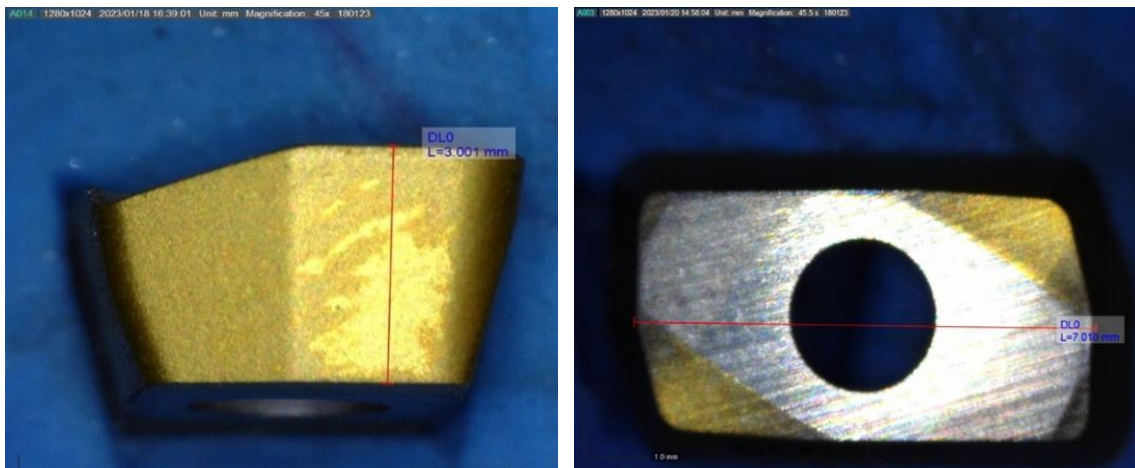


Figure 5: The dimension of coated carbide cutting tool (insert).

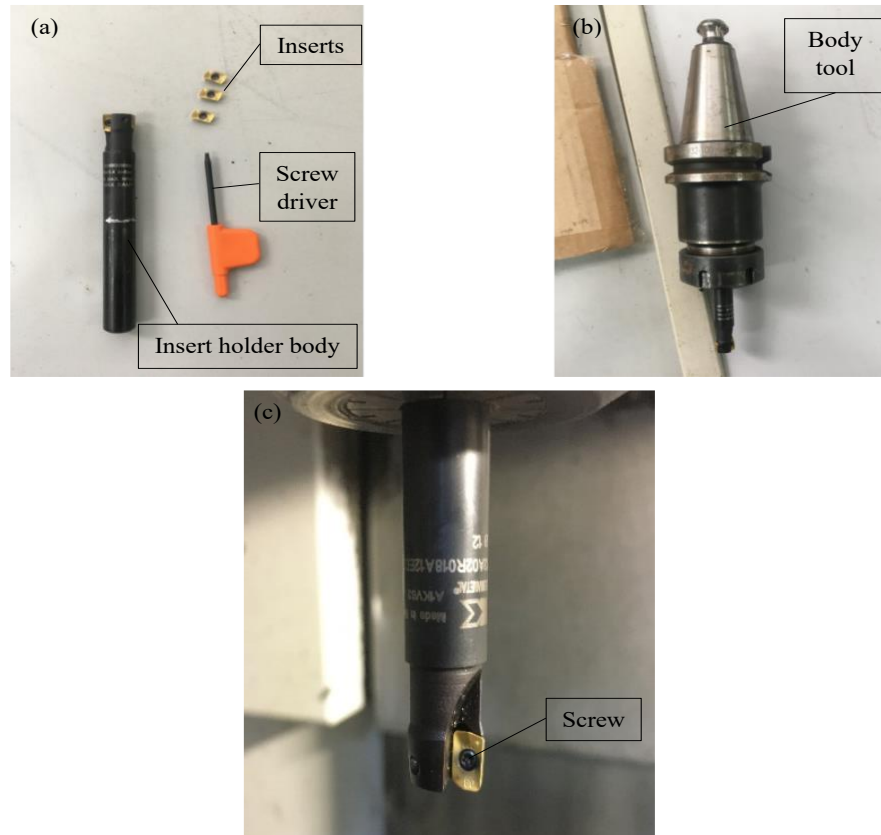


Figure 6: The inserts of coated carbide cutting tool; (a) before attached to the insert holder body, (b) during attached to the body tool and (c) after attached to the machine.

Figure 7 showed the position of thermal camera directly to cutting zone to measure the temperature during the end milling of Ti-6Al-4V. A portable thermal camera was employed to capture temperature data, with its emissivity calibrated to 0.31 to ensure accurate readings specific to Ti-6Al-4V. Surface roughness was measured along the feed direction (parallel to the tool path) on the machined surface. The measurements were taken at three equally spaced locations along the central region of the cutting path to avoid edge effects and obtain representative values of the machined surface. At each location, the measurement was repeated three times and the average value was recorded to minimize the effect of random measurement errors or surface irregularities. This repetition improves statistical reliability and accounts for local variation on the surface. Figure 8 showed the portable surface roughness tester (Mitutoyo Surftest SJ series) to measure the roughness of the machined material after the machining.



Figure 7: The position of thermal camera.

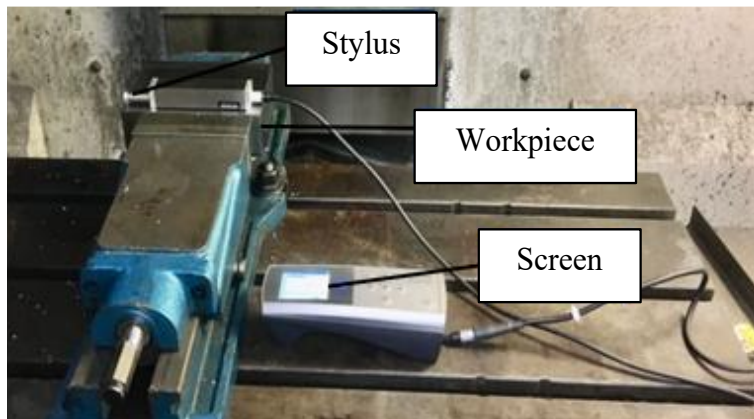


Figure 8: The portable surface roughness tester.

The Taguchi Method (TM) is a statistical approach to experimental design developed by Genichi Taguchi, which aims to improve product quality and process performance by minimizing the effects of uncontrollable variables (noise) through robust design. It simplifies the Design of Experiments (DOE) by using a specially structured orthogonal array (OA) to study a large number of variables with a minimal number of experiments. Titanium alloys are costly and difficult to machine. TM drastically reduces the number of trials, saving time, cost, and resources. TM emphasizes making the process insensitive to noise factors, which is particularly important in machining operations involving MQL. TM offers straightforward analysis using Signal-to-Noise (S/N) ratios, making it suitable even for complex systems when integrated with response aggregation techniques. Although Taguchi Method is traditionally suited for single-response optimization, it remains a practical and efficient tool for this study by integrating it with multi-response decision-making techniques. Its use is justified due to its efficiency, simplicity, cost-effectiveness, and ability to provide robust process parameter combinations, especially when dealing with expensive materials and complex lubrication strategies.

3.0 RESULTS AND DISCUSSION

Table 4 provides experimental results of average surface roughness and temperature analysing the effects of MQL parameters—flowrate, nozzle distance, and nozzle angle—on surface roughness and temperature during the end milling of Ti-6Al-4V using SiO₂ nanoparticles.

Table 4: The experimental results of average surface roughness and temperature.

Exp	Flowrate (m ³ /s)	Distance (mm)	Angle (°)	Surface roughness (µm)	Temperature (°C)
1	10	10	30	0.93	58.75
2	10	15	45	0.99	71.90
3	10	20	60	0.66	95.30
4	15	10	45	0.99	91.70
5	15	15	60	0.76	101.80
6	15	20	30	0.84	108.50
7	20	10	60	1.04	84.60
8	20	15	30	0.92	105.20
9	20	20	45	1.00	110.80

The flowrate was varied at three levels: 10, 15, and 20 m³/s. At the lowest flowrate (10 m³/s), surface roughness results were moderate, with Exp 3 achieving the best surface finish of 0.66 µm. The temperatures for this flowrate ranged between 58.75°C in Exp 1 and 95.30°C in Exp 3, showcasing effective cooling. The nozzle distance was also varied at three levels: 10 mm, 15 mm, and 20 mm. shorter nozzle distances, such as 10 mm, demonstrated better cooling performance, as seen in Exp 1 with the lowest temperature of 58.75°C and a surface roughness of 0.93 µm. The nozzle angle, tested at 30°, 45°, and 60°, also played a critical role in the distribution of the MQL. At 30°, surface roughness values were consistent, ranging from 0.84 µm in Exp 6 to 0.93 µm in Exp 1, with temperatures spanning from 58.75°C to 108.50°C.

The response table for signal-to-noise (S/N) ratios provides insights into the influence of flowrate, nozzle distance, and nozzle angle on surface roughness and temperature during machining, ranked based on their Delta values. Table 5 shows the response table for signal-to-noise on (a) surface roughness and (b) temperature.

Table 5: The response table for signal-to-noise on (a) surface roughness, and (b) temperature.

(a)				
Level	Flowrate (m ³ /s)	Distance (mm)	Angle (°)	
1	1.4423	0.1257	0.9563	
2	1.3285	1.0651	0.2067	
3	0.2764	1.8564	1.8841	
Delta	1.1659	1.7307	1.6774	
Rank	3	1	2	

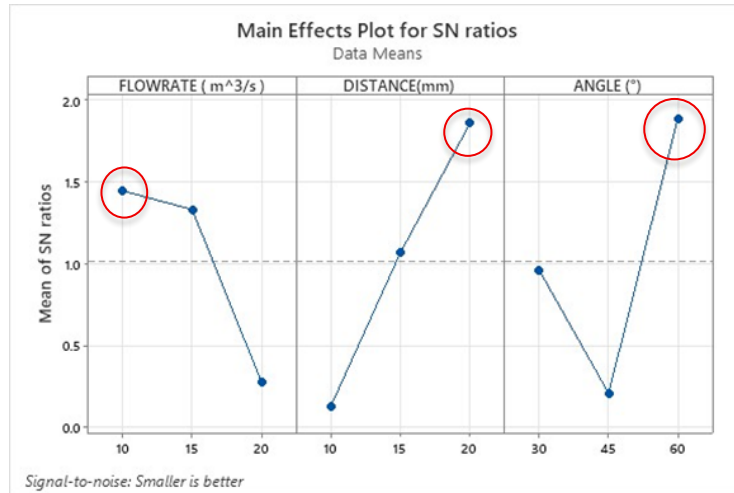
(b)

Level	Flowrate (m ³ /s)	Distance (mm)	Angle (°)
1	-37.37	-37.37	-38.84
2	-40.04	-39.24	-39.09
3	-39.96	-40.39	-39.43
Delta	2.67	2.67	0.59
Rank	1	2	3

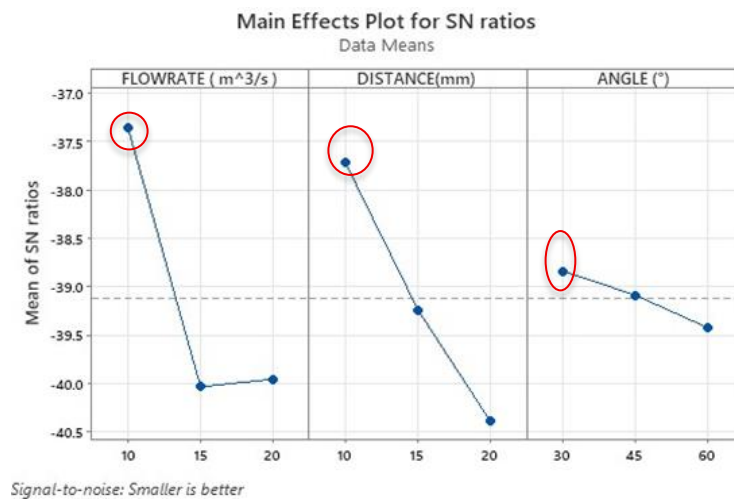
The response table for signal-to-noise on surface roughness, the nozzle distance emerged as the most significant parameter, with the largest Delta value of 1.7307. This finding highlights that variations in nozzle distance greatly impact surface roughness. The second most influential parameter is nozzle angle, with a Delta value of 1.6774. A nozzle angle of 60° (Level 3) resulted in the highest S/N ratio, emphasizing the importance of directing the lubricant stream accurately to reduce friction and dissipate heat during machining. Flowrate was ranked as the least significant parameter, with the smallest Delta value of 1.1659. Although higher flowrates (Level 3: 20 m³/s) were more effective in reducing surface roughness, the relatively low Delta value indicates that its overall contribution is less pronounced compared to the other two parameters.

The response table for signal-to-noise on temperature, the flowrate is identified as the most significant parameter, with the highest Delta value of 2.67. This result indicates that variations in flowrate have the greatest impact on reducing temperature. Among the tested levels, a flowrate of 15 m³/s achieves the lowest S/N ratio (-40.04), making it the most effective for minimizing thermal effects. Nozzle distance is ranked as the second most influential parameter, also with a Delta value of 2.67. While the Delta value for nozzle distance matches that of flowrate, its overall contribution to temperature reduction is considered slightly less impactful based on the consistency of the S/N ratios. In contrast, nozzle angle has the least influence on temperature, as reflected by its smaller Delta value of 0.59. This indicates that changes in nozzle angle have a relatively minor effect compared to the other parameters.

The S/N ratios are calculated using the "smaller-is-better" criterion, as lower temperatures are desirable for enhanced machining performance and tool life (Zhujani et al. 2024). The plot shows the mean S/N ratios for each level of the three MQL parameters: flowrate, nozzle distance, and nozzle angle. Figure 9 shows the graph presents the main effects plot for signal-to-noise (S/N) ratios based on the Taguchi analysis of (a) surface roughness and (b) temperature during the machining process.



(a)



(b)

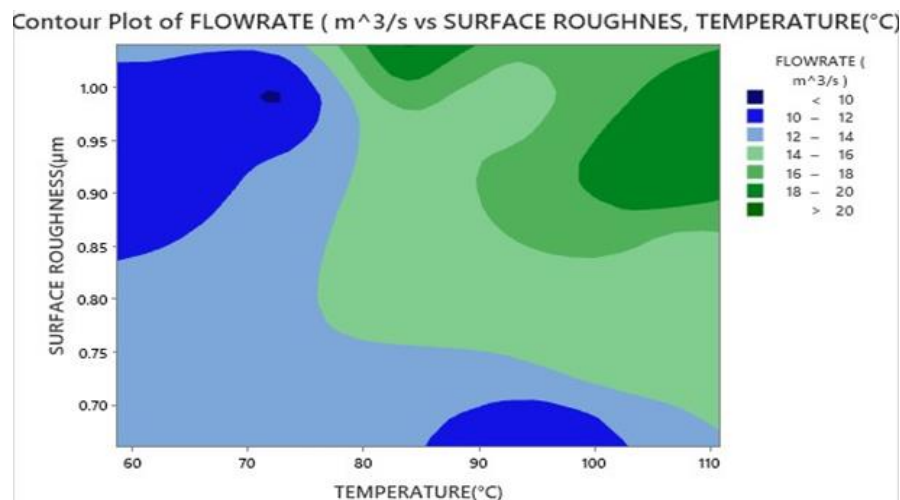
Figure 9: The main effects plot for S/N ratios of (a) surface roughness, and (b) temperature.

The main effects plot for S/N ratios of surface roughness indicates that the plot for flowrate shows a steady decline in S/N ratios as the flowrate increases from 10 m³/s to 20 m³/s, indicating that higher flowrates may result in lower surface quality. A larger nozzle distance (20 mm) effectively reduces surface roughness, achieving smoother surfaces. The sharp rise in S/N ratios confirms the significant impact of nozzle distance, aligning with its highest Delta value and ranking as the most critical parameter in the analysis (Srivabut et al. 2024). For nozzle angle shows a non-linear relationship, with the lowest S/N ratio observed at 60° (Level 3). This suggests that the intermediate angle is less effective in minimizing surface roughness, while the higher angle (60°) and lower angle (30°) are more optimal.

The main effects plot for S/N ratios of temperature for flowrate, the S/N ratio is highest at 10 m³/s, indicating that this flowrate results in the lowest temperatures and is therefore the most

favourable. As the flowrate increases to 15 m³/s and 20 m³/s, the S/N ratio decreases significantly, suggesting higher temperatures. This trend indicates that increasing the flowrate beyond 10 m³/s may lead to excessive lubrication or cooling inefficiency, possibly due to the reduced effectiveness of the lubricant in maintaining optimal thermal conditions. For nozzle distance, the plot shows a clear decrease in the S/N ratio as the distance increases from 10 mm to 20 mm. The highest S/N ratio is observed at 10 mm, suggesting that the nozzle is most effective when positioned close to the cutting zone. At greater distances, the effectiveness of the lubricant spray diminishes, likely due to dispersion or reduced impact on the tool-workpiece interface. For nozzle angle, the S/N ratio gradually decreases as the angle increases from 30° to 60°. The highest S/N ratio at 30° suggests that this angle provides the most effective cooling and temperature reduction. As the angle becomes steeper, the lubricant may be less effectively directed toward the cutting zone, resulting in higher temperatures.

The contour plots presented illustrate the combined effects of MQL flowrate (m³/s), nozzle distance (mm), and nozzle angle (°) on key machining responses, namely surface roughness (µm) and temperature (°C), during the end milling of titanium alloy. These plots provide visual insights into the optimal interaction between MQL parameters and their influence on surface integrity and thermal behavior. Figure 10 show the contour plot of flowrate (m³/s), nozzle distance (mm), and nozzle angle (°) on surface roughness (µm) and temperature (°C).



(a)

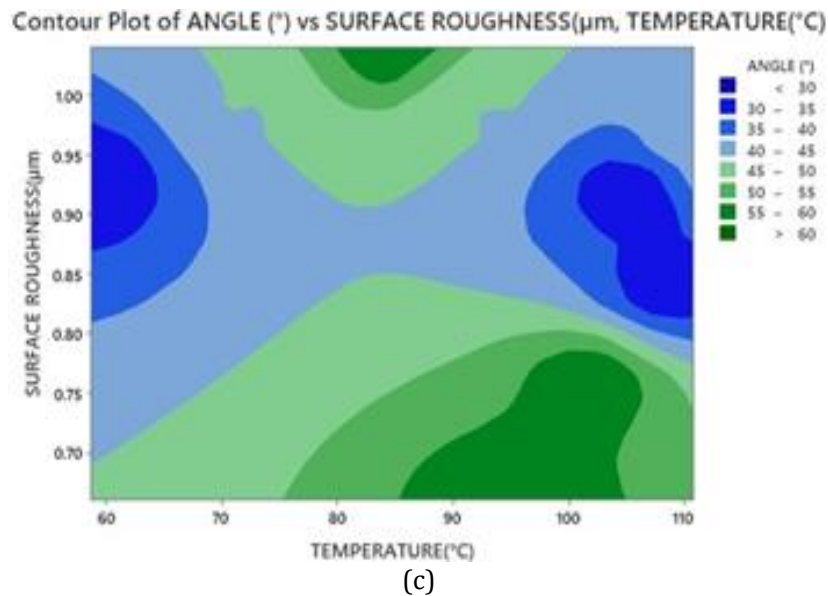
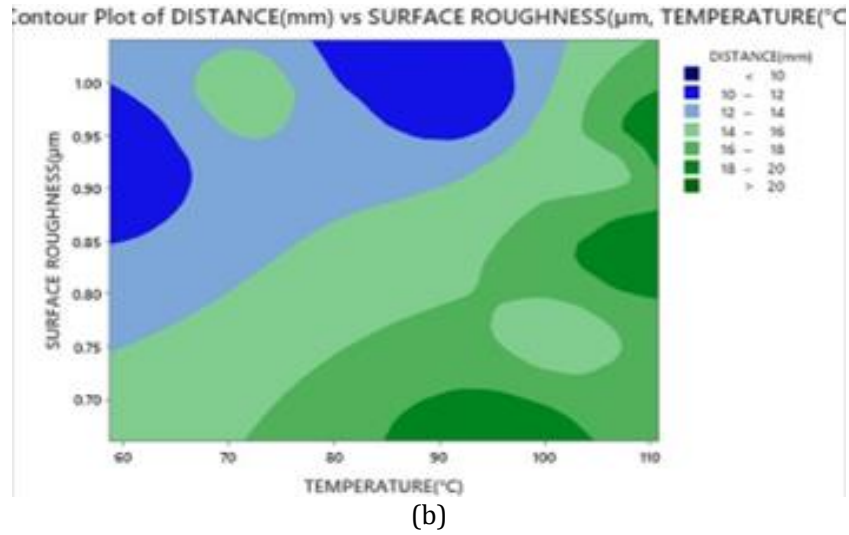


Figure 10: Contour plot of (a) flowrate (m^3/s); (b) distance (mm); and (c) angle ($^{\circ}$), on surface roughness (μm) and temperature ($^{\circ}\text{C}$).

The contour plot highlights the relationship between flowrate, surface roughness, and temperature during machining. Lower flowrates ($<10 \text{ m}^3/\text{s}$) and moderate temperatures (80°C – 90°C) consistently result in smoother surfaces, with surface roughness values approaching $0.70 \mu\text{m}$. This suggests that within these conditions, lubrication and cooling are effectively balanced, reducing cutting resistance and enhancing surface quality. The plot emphasizes that achieving optimal machining performance requires careful balancing of flowrate and temperature. Moderate temperatures appear to facilitate effective lubrication and stable cutting, while

excessive flowrates or thermal effects can lead to suboptimal outcomes, such as material oxidation or disruptions in the lubrication film (Al-Saraireh et al. 2024).

The contour plot that illustrates the relationship between nozzle distance, surface roughness, and temperature during the machining process. At shorter distances (10–12 mm) and moderate temperatures (around 80°C–90°C), the surface roughness tends to be lower, with values approaching 0.75 μm . This indicates that the nozzle's proximity facilitates effective lubrication and cooling, resulting in an improved surface finish. The plot emphasizes the importance of maintaining a suitable nozzle distance to optimize surface finish. Shorter distances allow for more focused delivery of the lubricant, enhancing its effectiveness in reducing surface imperfections (Fadzil et al. 2023). Conversely, larger nozzle distances or high temperatures may compromise machining efficiency, leading to poorer surface quality due to inadequate lubrication or thermal effects on the material (Zan et al. 2021).

The contour plot of angle on surface roughness and temperature where the contour plot illustrates the relationship between nozzle angle, surface roughness, and temperature during the machining process. At lower nozzle angle (30°–35°) and moderate temperatures (around 60°C–90°C), the surface roughness tends to be higher, with values approaching 0.95 μm . This suggests that the nozzle's proximity facilitates effective lubrication and cooling, leading to an improved surface finish. The plot emphasizes the importance of maintaining a suitable nozzle angle to optimize surface finish. Steeper angle allows for more focused dispersal of lubricant to the cutting tool, enhancing its effectiveness in reducing surface imperfections (Zein et al. 2024). Conversely, less steep nozzle angle or high temperatures may compromise machining efficiency, leading to poorer surface quality due to inadequate lubrication or thermal effects on the material (Conger et al. 2024).

CONCLUSIONS

In conclusion, this study investigated the influence of MQL parameters—flowrate, nozzle distance, and nozzle angle—on surface roughness and temperature during the end milling of Ti-6Al-4V. The results demonstrated that nozzle distance had the most significant impact on surface roughness, while flowrate greatly influenced the cutting temperature.

Based on the Signal-to-Noise (S/N) ratio analysis using the Taguchi method:

- (a) The highest S/N ratio for surface roughness was observed at a nozzle distance of 20 mm, indicating the most stable and lowest roughness under this setting.
- (b) The optimum flowrate for minimizing temperature was identified at 10 m^3/s , which produced the highest S/N ratio for cutting temperature, reflecting effective cooling and lubrication.

In contrast, nozzle angle showed a relatively minor effect on both output responses within the selected range, suggesting that distance and flowrate should be prioritized in MQL optimization. Overall, the application of optimized MQL parameters not only improved the surface quality of the machined titanium alloy but also contributed to thermal control, enhancing tool life and promoting environmentally responsible machining.

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