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Surface roughness analysis in turning titanium alloy under MQL and cryogenic coolants

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KEYWORDS

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ABSTRACT

Titanium alloys are valued for their high strength-to-weight ratio and thermal stability, making them essential in aerospace and medical applications. However, their poor thermal conductivity and rapid tool wear pose significant challenges to machinability. This study investigates the effects of minimum quantity lubrication (MQL) and cryogenic CO_2 cooling on surface roughness during the turning of titanium alloy (Ti-6Al-4V ELI). Turning operational were conducted on a CNC lathe using uncoated carbide inserts. The cutting parameters were set as follows: cutting speeds of 120, 170, and 220 m/min; feed rates of 0.10, 0.15, and 0.20 mm/rev; and depths of cut of 0.4, 0.5, and 0.6 mm. Surface roughness was measured with a portable Mitutoyo SJ-301 tester over a 20 mm cutting length at three different locations along the machined surface. Response surface methodology (RSM) was applied to analyze the data, assess model accuracy, and identify significant factors. Results showed that MQL consistently produced better surface quality, with feed rate identified as the most influential factor; lower feed rates yielded smoother finishes. These findings emphasize the role of advanced cooling techniques in enhancing machining performance, particularly for aerospace and biomedical applications where high precision is critical.

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1.0 INTRODUCTION

Titanium alloys, due to their unique combination of high strength-to-weight ratio, corrosion resistance, and ability to withstand high temperatures, are essential materials for various applications, including aerospace and biomedical devices. These alloys are characterized by a low density, about half that of steel, making them ideal for industries where reducing weight is crucial (Peters et al., 2003). However, their machinability presents significant challenges, such as poor thermal conductivity, rapid tool wear, and susceptibility to galling during processing. Recent studies have focused on improving the machinability of titanium alloys through advanced cooling methods. Among these, cryogenic cooling techniques, such as liquid nitrogen and CO_2, have shown potential for enhancing tool life and minimizing thermal effects during high-speed cutting (Aramcharoen, 2016). Additionally, Minimum Quantity Lubrication (MQL) strategies have gained attention due to their environmental benefits, including reduced coolant consumption and enhanced heat dissipation (Pervaiz et al., 2017). MQL has a longer tool life (25%) and leads to reduce surface roughness of machined surface (30%) compared with that turned under the conventional coolant condition (Che Haron et al., 2016). These advanced cooling methods contribute to better machining outcomes, enhancing both operational performance and environmental sustainability.

In machining titanium alloys, surface roughness is a critical parameter that affects the performance and longevity of the final product, particularly in demanding fields like aerospace and biomedical implants. Studies have demonstrated that feed rate is the most influential factor on surface roughness in turning operations. Higher feed rates generally lead to increased roughness, while greater cutting speeds and depths of cut tend to improve the surface finish. To optimize these parameters, researchers have used Response Surface Methodology (RSM) to create predictive models that link cutting parameters to surface roughness outcomes, leading to improved process efficiency (Ramesh et al., 2012). Additionally, the choice of tool material and coatings plays a role in determining surface quality. Uncoated tools typically perform better at lower cutting speeds, while PVD-coated tools are better suited for high-speed conditions, as they help minimize roughness while maintaining efficiency (Ramana and Aditya, 2017). Moreover, the application of coolants, including high-pressure, MQL, and cryogenic methods, has been shown to influence the machinability of titanium alloys, with each method offering distinct advantages in terms of tool life, heat dissipation, and surface finish.

Minimum Quantity Lubrication (MQL) is a modern technique designed to reduce the environmental and health impacts of traditional flood coolant systems while improving machining performance. By using a much smaller amount of coolant, typically in the form of an aerosol or mist, MQL precisely targets the cutting zone, providing adequate lubrication and cooling with minimal waste (Boubekri and Shaikh, 2014). Initially, MQL used oil-based fluids, but recent advancements have introduced more eco-friendly lubricants, such as vegetable oils and nanofluids, which improve thermal conductivity and further reduce environmental impact (Lv et al., 2018; Fernando et al., 2019). MQL is particularly useful in industries such as automotive and aerospace, where precision and environmental concerns are paramount (Filipovic and Stephenson, 2006). This method helps reduce coolant usage, decreasing chemical waste and exposure, thereby contributing to a cleaner and safer work environment. MQL also reduces operational costs related to coolant purchase, maintenance, and disposal. By effectively managing heat at the tool-workpiece interface, MQL improves tool life and surface finish (Lv et al., 2018).

Cryogenic cooling is another promising technique that uses liquefied gases like liquid nitrogen (LN_2) or carbon dioxide (CO_2) to reduce temperatures in the cutting zone. This method has gained interest in its ability to enhance machining performance, especially in reducing tool wear and improving surface finishes. Cryogenic CO_2 cooling, which involves the use of solid or gaseous CO_2, is particularly effective because CO_2 sublimates from solid to gas, absorbing substantial amounts of heat, thereby cooling the tool and workpiece efficiently (Proud et al., 2022; Pereira et al., 2022). This cooling technique has proven to be especially useful in machining heat-resistant alloys, where traditional coolants may not be sufficient (Tapoglou et al., 2017). CO_2's non-toxic nature makes it an environmentally friendly alternative to oil-based coolants, aligning with sustainability goals in manufacturing. Moreover, the use of cryogenic cooling can lead to significant cost savings by extending tool life and reducing the frequency of tool changes. Additionally, the reduced need for hazardous waste disposal further enhances its economic and environmental advantages (Jerold and Kumar, 2012).

Both MQL and cryogenic cooling methods represent advancements in machining technologies that improve titanium alloys' machinability, tool life, and surface finish. MQL offers an environmentally conscious approach to reducing coolant usage and improving machining performance, while cryogenic cooling helps lower cutting zone temperatures, minimizing tool wear and improving surface quality. These methods contribute to more sustainable and efficient machining processes, particularly in industries that require high precision and superior surface integrity, such as aerospace and biomedical fields.

Together, these cooling technologies offer promising solutions for overcoming the challenges associated with machining titanium alloys, ensuring that they continue to meet the high-performance demands of various industries. Further research and development into these methods will likely continue to enhance their effectiveness, providing more sustainable and cost-effective approaches to machining titanium alloys while improving the overall performance and longevity of the final products. This study aims to provide an in-depth comparison between minimum quantity lubrication (MQL) and cryogenic CO_2 cooling techniques, evaluating their respective impacts on surface roughness during the machining of titanium alloys, with an emphasis on understanding how each cooling method influences machining efficiency, tool life, and final surface quality in precision manufacturing

2.0 EXPERIMENTAL PROCEDURE

The experimental workpiece was a cylindrical Ti-6Al-4V ELI titanium alloy bar, characterized by an alpha phase surrounded by beta at the grain boundary (Figure 1). The alloy's nominal composition is detailed in Table 1. The microstructure features an extended alpha phase within a fine, dark-etched beta matrix. Known for its exceptional strength and high hardness (317 HV), a minimum of 3 mm was removed from the surface to eliminate flaws and residual stress. The cylindrical titanium, with a 100 mm diameter and 150 mm length (Figure 2), was center drilled at the base to reduce vibration and securely mounted on the chuck with the tailstock.

Table 1: Chemical composition of Ti-6Al-4V ELI (% wt).

Element	C	Si	Fe	Ti	Al	N	V	S	O	H	Y
Wt %	0.11	<0.03	0.18	Bal.	6.1	0.007	4.0	<0.003	0.11	0.0031	<0.005

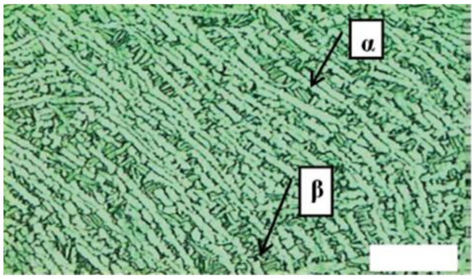

Figure 1: Microstructure of Ti-6Al-4V ELI.

Figure 2: Workpiece of Ti-6Al-4V ELI.

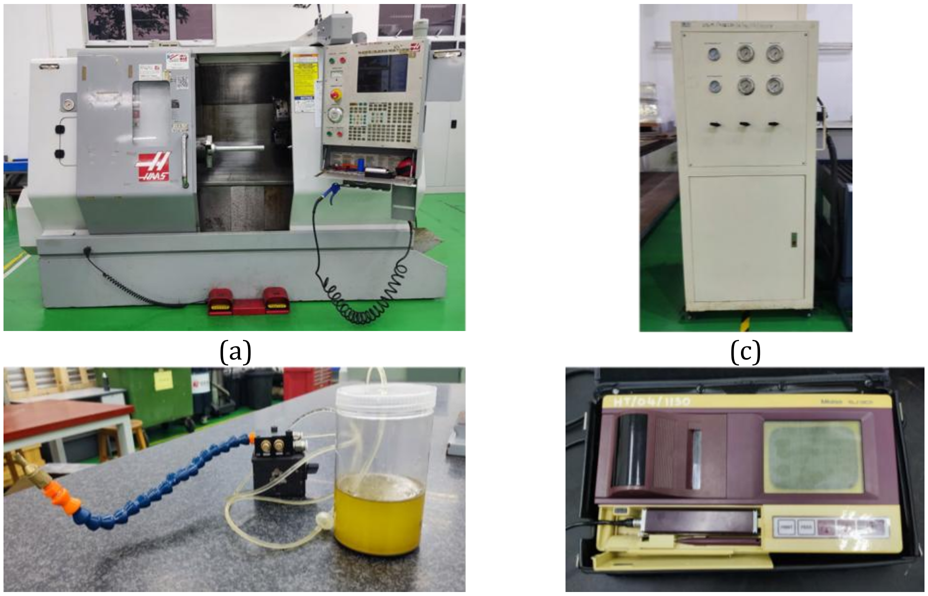

Figure 3: (a) Haas SL-20 lathe machine, (b) MQL systems, (c) Cryogenic electrical control system, and(d) Surface roughness tester Mitutoyo SJ 301.

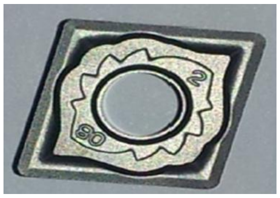

Figure 4: Uncoated carbide inserts CNGG 120408H13A.

The machining experiments for both minimal quantity lubrication (MQL) and cryogenic carbon dioxide (CO_2) cutting conditions were conducted on a Haas SL-20 lathe, as shown in Figure 3(a). MQL systems example can be seen in Figure 3(b) while the cryogenic electrical control system can be seen in Figure 3(c). The surface roughness value of the workpiece will be measured using the Mitutoyo SJ 301 model, as shown in Figure 3(d).

The machining experiment will use a carbide insert (ISO number CNGG 120408H13A) for turning operations, as shown in Figure 4. The uncoated, rhombic-shaped insert features a chip breaker and is made of 82.6% tungsten carbide (WC) and 16.4% cobalt (Co) binder. Designed with positive rake angles, the insert efficiently controls chip formation, reduces force, and improves the environmental sustainability of the cutting process. Tungsten carbide inserts offer exceptional accuracy and effectiveness in cutting processes, enabling accurate and seamless cuts while minimizing material waste and optimizing productivity (Siju and Waigaonkar, 2021).

The cutting parameters used in the experiments are shown in Table 2. The cutting speeds were set at 120, 170 and 220 m/min, while the feed rates were 0.1, 0.15 and 0.2 mm/rev. The depths of cut were set 0.4, 0.5 and 0.6 mm during the machining process. The combinations of cutting parameters were determined using the Box–Behnken design of experiments, resulting in seventeen experimental runs.

Table 2: Cutting parameters.

Cutting speed, *V* (m/min)	**Feed rate, *F* (mm/rev)**	**Depth of cut, *doc* (mm)**
120	0.1	0.4
170	0.15	0.5
220	0.2	0.6

3.0 RESULTS AND DISCUSSION

This study investigated the influence of Minimum Quantity Lubrication (MQL) and cryogenic cooling on the surface roughness of Ti-6Al-4V ELI titanium alloy through separate experimental trials. The comparison highlights how coolant selection significantly affects surface quality and providing machining strategies for hard-to-cut materials. The surface roughness data obtained from the experiments are presented in Table 3. A total of 17 experiments were conducted for each coolant types. Meanwhile, the 3D surface interactions between factors and surface roughness values for MQL and cryogenic coolants are shown in Figures 5 and 6, respectively.

Table 3: Surface roughness *Ra* value under MQL and Cryogenic condition.

Run	**Cutting speed (m/min)**	**Feed rate (mm/rev)**	**Depth of cut (mm)**	**Surface roughness *Ra* (MQL) (μm)**	**Surface roughness *Ra* (Cryogenic) (μm)**
1	220	0.15	0.4	0.56	1.49
2	220	0.15	0.60	0.59	1.21
3	170	0.15	0.50	0.80	1.27
4	170	0.15	0.50	0.77	1.44
5	120	0.15	0.60	1.07	1.12
6	170	0.20	0.40	1.01	2.08
7	120	0.10	0.50	0.66	0.76
8	220	0.10	0.50	0.37	0.82
9	170	0.10	0.40	0.47	0.88
10	120	0.20	0.50	1.31	2.10
11	170	0.15	0.50	0.87	1.38
12	170	0.15	0.50	0.71	1.33
13	120	0.15	0.40	1.03	1.25
14	170	0.15	0.50	1.00	1.21
15	170	0.20	0.60	1.24	1.92
16	220	0.20	0.50	1.12	1.98
17	170	0.10	0.6	0.54	0.77

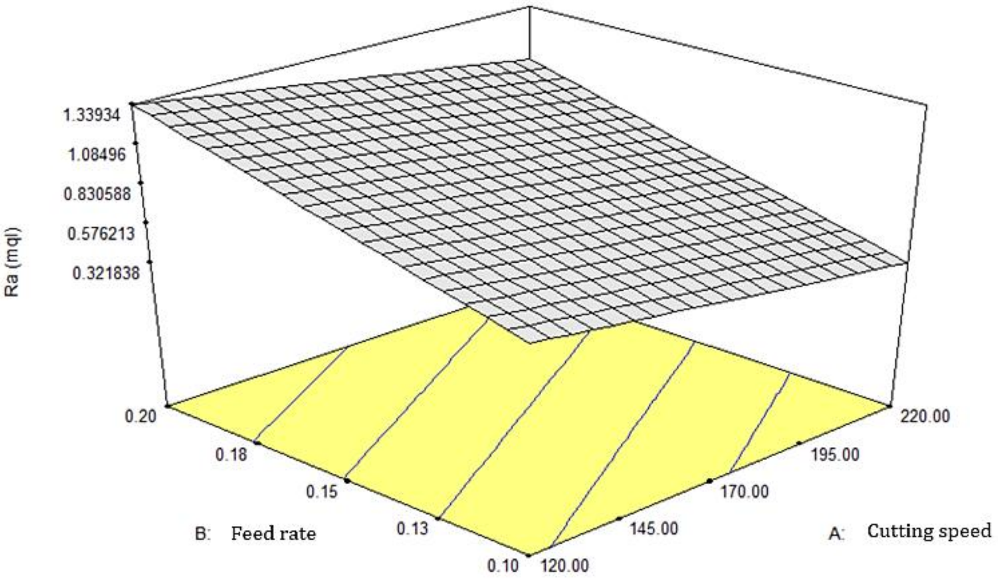

Figure 5: 3D surface interaction between factors and surface roughness under MQL cooling.

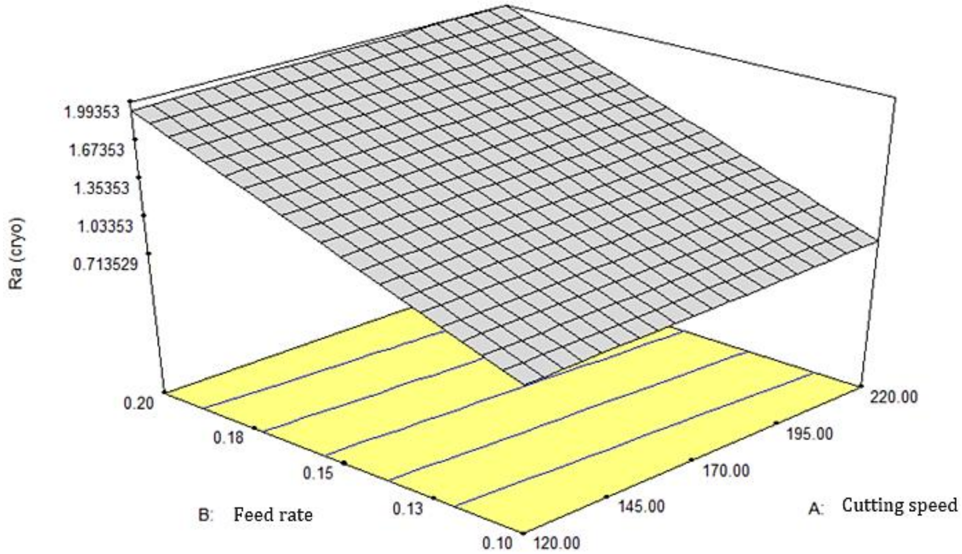

Figure 6: 3D surface interaction between factors and surface roughness under cryogenic cooling.

The data presented in Table 3 provides insights into how these factors interact to impact surface roughness during the turning process. The three machining parameters include cutting speed, feed rate, and depth of cut have a distinct impact on surface roughness. Cutting speed, for instance, shows a clear trend of reducing surface roughness as it increases. At lower cutting speeds, such as 120 m/min, the surface roughness values under MQL are higher, ranging from 0.66 µm to 1.31 µm. In contrast, at a higher cutting speed of 220 m/min, the roughness improves significantly, with the lowest value of 0.37 µm observed under MQL at a feed rate of 0.1 mm/rev and depth of cut of 0.5 mm. This improvement is likely due to the reduced heat generation and more stable cutting conditions at higher cutting speeds (Singh et al., 2021).

Feed rate, on the other hand, has the most substantial influence on surface roughness. As the feed rate increases, surface roughness also increases. For example, at a cutting speed of 120 m/min and depth of cut of 0.5 mm, surface roughness under MQL increases from 0.66 µm at a feed rate of 0.1 mm/rev to 1.31 µm at 0.2 mm/rev. A similar trend is observed under cryogenic cooling, where surface roughness rises from 0.76 µm to 2.10 µm across the same feed rate range. This behavior can be attributed to the higher material removal rate and more pronounced tool marks left on the surface at higher feed rates (Shah & Bhavsar, 2019). The depth of cut has a relatively smaller but noticeable impact on surface roughness. Increasing the depth of cut generally results in higher surface roughness values, although the effect is less pronounced compared to feed rate and cutting speed. For example, at a cutting speed of 170 m/min and feed rate of 0.15 mm/rev, surface roughness under MQL increases from 0.71 µm at a depth of cut of 0.5 mm to 1.24 µm at 0.6 mm. The increased cutting forces and heat generation at higher depths of cut likely contribute to this trend (Mishra et al., 2020).

Based on Figure 7, the histogram pattern shown that MQL consistently provides better surface finish (less values) than cryogenic cooling across most machining conditions. For instance, in a run number 7, at a cutting speed of 120 m/min and feed rate of 0.1 mm/rev, surface roughness under MQL is 0.66 μm, compared to 0.76 μm under cryogenic cooling. Similarly, in run number 10, at a feed rate of 0.2 mm/rev, MQL achieves a roughness of 1.31 μm, while cryogenic cooling results in a significantly higher roughness of 2.10 μm.

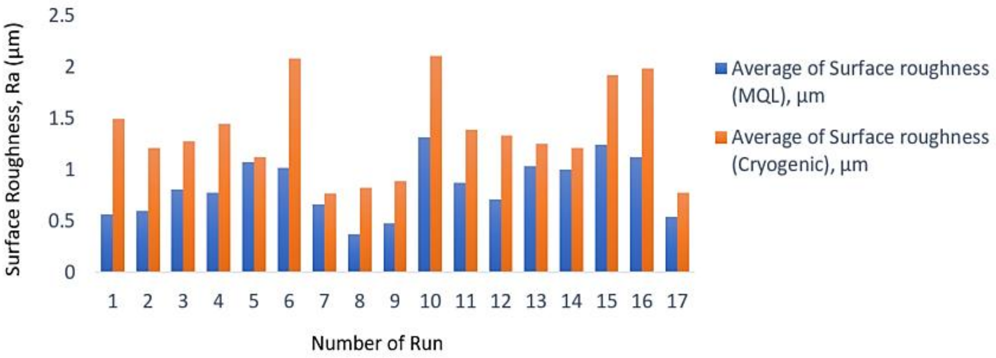

Figure 7: Surface roughness values comparison using MQL and cryogenic cooling.

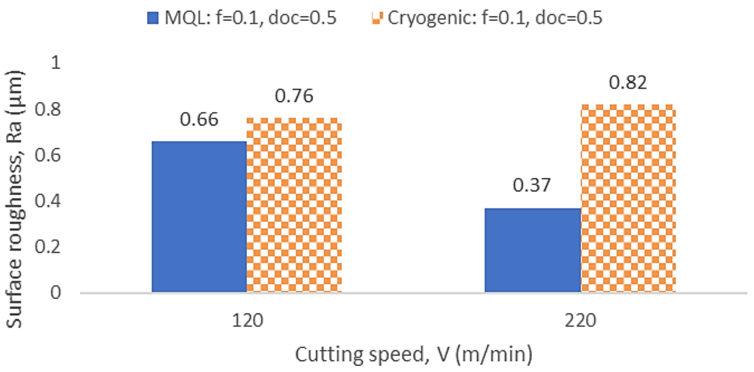

Figure 8: Chart comparison between surface roughness, Ra under MQL and cryogenic cooling using different cutting speed, v.

Figure 8 presents the influence of cooling methods on surface roughness at varying cutting speeds. At 120 m/min, minimum quantity lubrication (MQL) results in lower surface roughness (0.66 μm) compared to cryogenic cooling (0.76 μm). As the cutting speed increases to 220 m/min, MQL's effectiveness improves significantly, reducing surface roughness to 0.37 μm, whereas cryogenic cooling leads to a marginal increase in roughness (0.82 μm). These findings indicate that MQL offers superior performance in reducing surface roughness, particularly at higher cutting speeds. Existing literature supports these observations. Pimenov et al., 2021 highlight the environmental and machining benefits of MQL over cryogenic cooling, particularly for titanium alloys, attributing its superior performance to enhanced lubrication and cooling properties. Gajrani, 2020 similarly reported that MQL outperforms both dry and cryogenic cooling by effectively reducing friction and thermal effects. Jamil et al., 2019 further demonstrated that while cryogenic cooling reduces cutting temperatures, it is less efficient in minimizing surface roughness compared to MQL, which offers better tribological performance and surface quality.

These findings reinforce MQL's advantages in achieving lower surface roughness and improving machining efficiency across various conditions.

Figure 9 illustrates the impact of feed rate on surface roughness when employing MQL and cryogenic cooling. At a lower feed rate of 0.1 mm/rev, MQL exhibits superior performance, achieving a surface roughness of 0.47 μm compared to 0.88 μm for cryogenic cooling. This suggests that MQL's effective lubrication properties at low feed rates reduce friction and tool wear, resulting in a smoother machined surface. These findings align with Jamil et al., 2019 who reported that although cryogenic cooling efficiently lowers cutting temperatures, it lacks sufficient lubrication at higher feed rates, leading to increased surface roughness. As the feed rate increases to 0.2 mm/rev, surface roughness rises for both cooling methods. However, MQL maintains its advantage with a roughness of 1.01 μm, significantly outperforming cryogenic cooling, which reaches 2.08 μm. The substantial roughness increase under cryogenic cooling at higher feed rates highlights its limitations in sustaining lubrication efficiency under elevated machining parameters. This observation is further supported by Gupta et al., 2021 who found that cryogenic cooling becomes less effective in reducing surface roughness at higher feed rates due to its diminished lubrication performance. Surface roughness raised by a mean of 32.8% when feed rate increased from 0.1mm/rev to 0.2 mm/rev. Meanwhile a maximum increase in cutting speed is reflected negatively on surface roughness by an average of 18.7%. These results reinforce the effectiveness of MQL in minimizing surface roughness across different feed rates, particularly under higher machining conditions where cryogenic cooling struggles to maintain lubrication efficiency.

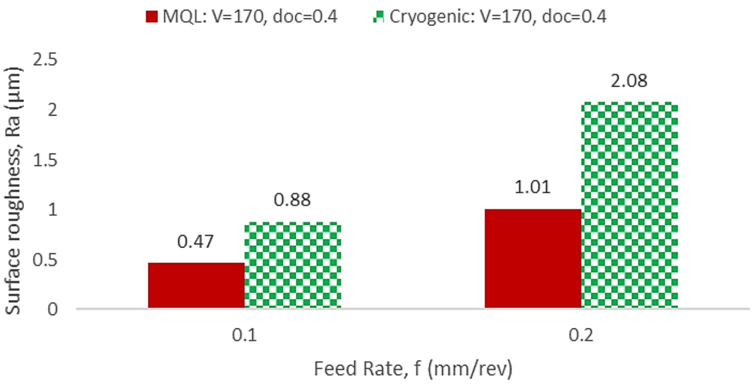

Figure 9: Chart comparison between surface roughness *Ra* under MQL and cryogenic cooling using different feed rate *f*.

Figure 10 illustrates the influence of depth of cut on surface roughness for MQL and cryogenic cooling. At a lower depth of cut (0.4 mm), MQL demonstrates superior performance, achieving a surface roughness of 0.47 μm compared to 0.88 μm for cryogenic cooling. This suggests that MQL's enhanced lubrication properties effectively reduce surface roughness under moderate cutting loads, where the improvement of approximately 30-50%. As the depth of cut increases to 0.6 mm, both cooling techniques exhibit a slight increase in surface roughness. However, MQL continues to outperform cryogenic cooling, maintaining a lower surface roughness of 0.54 μm compared to 0.77 μm. These findings indicate that while both methods are influenced by higher cutting loads, MQL provides superior lubrication and thermal management, resulting in smoother surface finishes. This trend aligns with the findings of Zhao et al., 2020 who reported that cryogenic cooling primarily excels in thermal management but is less effective in lubrication, often leading to suboptimal surface roughness in titanium machining. The results further reinforce MQL's advantages in maintaining surface quality across varying depths of cut due to its superior tribological performance.

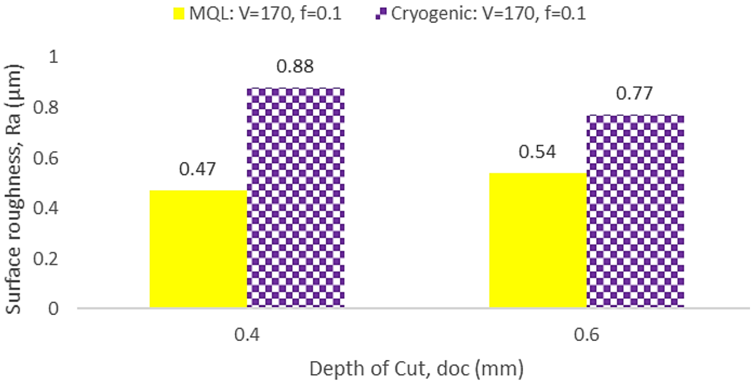

Figure 10: Chart comparison between surface roughness *Ra* under MQL and cryogenic cooling using different depths of cut *doc*.

The comparative analysis of the charts and supporting research indicates that MQL is consistently more effective in achieving lower surface roughness compared to cryogenic cooling during titanium alloy turning with various changes of parameters. This highlights MQL's superior lubrication capabilities, which enable better performance under both moderate and high machining loads. Cryogenic cooling primarily focuses on reducing the temperature in the cutting zone by using liquid nitrogen or other cold gases. This thermal management is beneficial because it helps prevent excessive heat generation, which can lead to tool wear and material deformation. However, cryogenic cooling lacks effective lubrication properties, which are critical for reducing friction between the cutting tool and the workpiece. According to Wang and Rajurkar, 2000 on cryogenic cooling as a coolant in machining of difficult to machine with the same cutting length, they found that the surface quality of all materials including titanium alloys with LN_2 cooling is better than without LN_2 cooling.

In contrast, MQL provides both cooling and lubrication by applying a fine mist of lubricant directly to the cutting zone. The lubrication reduces friction and wear, resulting in smoother surface finishes. These findings suggest that MQL is a preferable cooling method for applications requiring enhanced surface finish. Gupta et al., 2021 concluded that dry cutting environment has increased flank wear higher in comparison with CO_2- and LN_2-assisted cutting. When CO_2 and LN_2 cooling systems were included in the cutting process, the decrease in flank wear was up to 44.2% and up to 62.3%, respectively in comparison with dry cutting. The significant reduction of tool failure modes such as flank wear, chipping, BUE and BUL formations by cryogenic cooling assisted machining contributed directly to the improvement of surface roughness. Cutting fluids are most fundamental and important part in the metalworking industries. It is widely employed due to their ability to reduce friction, cutting temperature, thus enhance the workpiece surface quality (Dearnley et al. 2015).

4.0 CONCLUSION

MQL consistently delivered superior surface quality, achieving up to 50% improvement in surface roughness compared to cryogenic cooling. Its effectiveness was linked to precise lubrication and efficient heat dissipation, while also providing environmental benefits through reduced coolant consumption and disposal. These findings highlight MQL as a sustainable and high-performance cooling strategy for machining titanium alloys. Therefore, it was emphasized that using coolant when machining hardened materials such as titanium alloys enhances cutting tool performance and leads to smoother surface finishes. In this experiment, MQL was applied as the cutting fluid, providing effective cooling that reduced heat generation at the tool–workpiece interface. As a result, tool wear was minimized and the machined surface quality was improved.

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