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Machinability and tribological investigation of nano-hybrid cryogenic-MQL during milling Ti-6Al-4V alloy

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KEYWORDS

Nano-Hybrid
Cryogenic
MQL
Surface Roughness
Tribology
Ti-4Al-6V

ABSTRACT

This paper examines the end milling of Ti-6Al-4V alloy using a nano-hybrid cryogenic-minimum quantity lubricant (MQL) cooling system, focusing on tribology, tool wear, tool life, and surface roughness. Experiments were conducted at cutting speeds of 130 and 150 m/min, feed rates of 0.2 and 0.5 mm/rev, and a constant depth of cut of 0.5 mm using a single insert carbide tool. The nano-hybrid cryogenic-MQL system was the primary cooling method, and a four-ball tribometer was used for tribology studies. Tribology experiments showed that incorporating nanoparticles in MQL resulted in a lower coefficient of friction (0.131) compared to MQL without nanoparticles (0.146) at 3500 seconds. The results also highlighted the importance of cooling systems and cutting parameters in optimizing tool wear, tool life, and surface roughness. It was found that a cutting speed of 130 m/min and a feed rate of 0.2 mm/rev significantly improved tool life by approximately 50% and a cutting speed of 130 m/min and a feed rate of 0.2 mm/rev produced better surface roughness compared to other parameters. In conclusion, the nano-hybrid cryogenic-MQL system enhances machinability and meets industry requirements, proving to be a viable, environmentally friendly, and sustainable cooling alternative.

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1.0 INTRODUCTION

Titanium alloys, such as Ti-6Al-4V, are well-known for their outstanding characteristics like a high strength-to-weight ratio, superior resistance to corrosion, and compatibility with biological systems, making them widely desired in aerospace, medical, and automotive sectors (Abraham and Venkatesan, 2023). Despite the advantages, machining Ti-6Al-4V is difficult because of its poor thermal conductivity and high chemical reactivity, resulting in rapid tool wear, elevated cutting temperatures, and subpar surface finishes. These problems necessitate the development of new cooling and lubrication methods to enhance machinability and improve tribological performance during milling operations.

Conventional cooling techniques like flood cooling are commonly employed to reduce the high temperatures created while machining Ti-6Al-4V. However, these techniques are limited due to issues such as ineffective dissipation of heat, high levels of coolant usage, and environmental worries. Inadequate flood cooling does not efficiently reach the cutting area, causing poor cooling and lubrication, which speeds up tool deterioration and surface quality decline (Yuan et al., 2011; Pereira et al., 2016; Musfirah et al., 2017). Moreover, according to Anderson and Meade (Anderson and Meade; 2014), certain components in various cutting fluids, along with the potential growth of harmful microorganisms, can be harmful to the workers. Skin contact, inhalation, or ingestion can lead to exposure. This level of contact may result in skin and respiratory conditions, including chronic sickness. Given the shortcomings of the flood cooling technique, researchers have explored alternative methods that can provide better performance and additional benefits.

To overcome the limitations of traditional approaches, alternative cooling and lubrication methods such as minimum quantity lubrication (MQL) and cryogenic cooling have become more popular. MQL is the process of applying a small amount of lubricant combined with compressed air to the cutting area, which reduces coolant usage, minimizes environmental impact, and provides sufficient lubrication (Dhar et al., 2006; Boubekri and Shaikh, 2015). The study conducted by Anandan et al. (2020) and Pal et al. (2020) have demonstrated that the MQL technique provides sufficient lubrication to the cutting zone without the need for excessive coolant. The flow rate range in MQL typically falls between 2 and 8 ml/min, which is much lower than the flow rate of up to 12 l/min seen in conventional cooling technique. Therefore, MQL cut lubrication costs and fluid volume by 40 to 60% and increased pressure on the fine coolant spray to effectively reach the cutting zone (Yıldırım et al., 2017). The study done by Zan et al. (2021) found that the primary influence in MQL machining is the angle of nozzle elevation, determining that milling force increases in relation to acceleration and oil flow rate has a significant influence on the cutting temperature. On the other hand, Padmini et al. (2016) demonstrated that the MQL technique employing nanofluids with vegetable oils can have a beneficial impact on the surface roughness of a machined surface. In their research, they found that the presence of 0.5% MoS_2 nanoparticles in coconut oil decreased the R_a surface roughness parameter more than using pure oils, regular cutting fluid, dry machining, and nanofluids made from sesame and rapeseed oil. However, Jamil et al. (2022) found that the effectiveness of MQL decreases significantly when cutting Ti-6Al-4V because of the large amount of heat produced. Then, because of the low thermal conductivity, heat builds up in the main cutting zone, making it easier for reactions to occur with the cutting tool material, leading to chip adhesion and accelerated tool wear due to build-up edge (BUE) formation. This issue is more noticeable in milling than in turning processes (Leyens and Peter, 2010). Therefore, various alternative cooling systems that are more effective for machining titanium alloys should be studied to obtain optimal machining results.

In the past few years, cryogenic machining with liquid nitrogen (LN_2) and carbon dioxide (CO_2) in liquid form to cool the cutting tool and workpiece, has become popular because of their effective lubri-cooling effects, environmentally friendly features, and practicality for use (Hong et al., 2001; Shokrani et al., 2012). The employment of very low temperatures (-196°C for liquid nitrogen and -78°C for carbon dioxide) helps with effective heat transfer and vaporization while machining. Besides, cryogenic cooling maintains the hardness of the cutting tool, reducing tool wear and prolonging tool life (Dhananchezian and Kumar, 2010; Park et al, 2015). In another study, it was found that cryogenic cooling can improve the integrity of machined surface where better surface roughness was obtained and the microstructural alteration was found to be inconsequential (Musfirah et al. 2017). It was reported that the surface roughness can improve by up to 88% as compared to dry machining. In a different study conducted by Dhananchezian and Kumar (2011) and Shokrani and Dhokia (2016), it was found that the surface roughness of the machined surface decreased by 31% and 36–39% when using cryogenic cutting on Ti-6Al-4 V titanium alloy compared to dry and flood coolant-based cutting methods, respectively. A study by Umbrello (2012) has shown that cryogenic cutting can decrease the thickness of the hardened layer on the machined surface and refine the surface grain size. This is due to the effectiveness of rapid cooling during cryogenic machining that minimizes heat generation at the cutting zone which prevent excessive hardening at machine surface and resulting in lower residual stress. In addition, rapid cooling can modify the rate of recrystallization, resulting in the formation of smaller grains in the machined surface layer of the material. The mechanism was proved by Kaynak et al. (2014), who found that using LN_2 cooling in cryogenic cutting of alloy steel results in a reduced thickness of hardened subsurface, decreased residual stresses, and improved precision of machined surface.

Advancements in cooling and lubrication have led to the development of nano-hybrid cryogenic-MQL, combining the benefits of cryogenic cooling and MQL enhanced with nanoparticles. This blend approach aims to take advantage of the strengths of each method, providing efficient cooling and lubrication. According to Sharma et al. (2015) and Kim et al. (2021), the presence of nanoparticles in the lubricant enhances its capacity to lower friction, improve lubrication, and reduce wear. The addition of 50 nm-sized nanoparticles such as graphene, carbon nanotubes, or metallic oxides to the lubricant enhances its thermal conductivity and load-carrying capacity (Talib et al., 2022). These nanoparticles fill the micro-grooves and asperities on the tool and workpiece surfaces, forming a protective layer that reduces direct metal-to-metal contact. This protective layer minimizes friction and wear, further improving the machinability of Ti-6Al-4V (Singh et al., 2021). Yaun et al. (2018) in their study found that the used of nano-MQL during machining resulted in a significant reduction in cutting force and surface roughness by 10.71% and 14.92%, respectively, compared to dry machining. In another study, Shokrani et al. (2019) claimed that tools subjected to nano-hybrid cryogenic-MQL exhibit lower wear rates which is 30 times longer service life compared to those using conventional cooling methods, along with a 50% increase in efficiency compared to the latest flood coolant machining technology. This reduction in tool wear is crucial for maintaining consistent machining performance and reducing tool replacement costs. Moreover, nano-hybrid cryogenic-MQL effectively reduces cutting forces by providing better lubrication and cooling. The lower cutting temperatures help in maintaining the hardness of the cutting tool and preventing thermal softening, which can otherwise lead to increased tool wear (Dhananchezian and Kumar, 2019; Prabhu and Tiju, 2017). Venugopal and Chattopadhyay (2007) demonstrated that by cryogenically cooling rake and flank surfaces, wear growth was greatly minimized at a speed of 70 m/min during the turning of Ti-6Al-4V. However, a decrease in tool performance was observed at higher speeds. The reason for this was the inadequate penetration of LN_2 on the tool chip-interface. Besides that, research has shown that the efficiency of cryogenic machining on titanium alloy is greatly affected by the position of the coolant nozzle and adjusting the nozzle of LN_2 spraying direction can enhance tool longevity by up to 80% (Bermingham et al., 2012).

The literature review has revealed that cryogenic cooling can improve the machinability of Ti-6Al-4V (Sadik et al., 2016; Khan et al., 2023). Each analysis stated that the use of cryogenic cooling when machining Ti-6Al-4V can increase tool life by 250-350% when liquid CO_2 (LCO_2) is applied in lieu of an emulsion flood cooling strategy, and a comparative analysis with dry conditions indicated that tool life is enhanced by up to 100% using cryogenic media. However, a study by Tapoglou et al. (2017) stated that the use of cryogenic methods can cause a lack of lubrication at the cutting area. This is because CO_2 primarily serves as a cooling function rather than acting as a lubricant. Therefore, their research found that using hybrid techniques (cryogenic + MQL) is the most effective approach. Most of the research in this field focuses on single point turning operations, where less research has been conducted on milling Ti-6Al-4V under nano-hybrid cryogenic-MQL cooling technique. Although cryogenic machining with CO_2 as medium strategies offer promising benefits, the application of CO_2 as a metalworking fluid remains limited in machining titanium alloy. This is primarily because, while LN_2 has been extensively researched in machining titanium alloy, studies on CO_2 are still in their early stages and less developed by comparison. Therefore, this study aims to evaluate the machinability performance and tribological behavior under cryogenic cooling-MQL nano-hybrid using 20 nm-sized silicon dioxide (SiO_2) nanoparticles, as well as the effect of CO_2 on Ti-6Al-4V machining. The machining test was carried out using a cryogenic method with different cutting parameters such as speed and feed rate. The study analyzed tool wear, tool life, surface roughness, and tribology behavior in terms of friction of coefficient for nano-MQL. The results obtained from the analysis will then determine the main effect on the machinability performance of Ti-6Al-4V. This research thoroughly examines how the machinability of Ti-6Al-4V titanium alloy is affected by a new hybrid cryogenic MQL system, cutting speed and feed rate, while also comparing the use of nanoparticles in the nano-MQL system against the absence of nanoparticles.

2.0 EXPERIMENTAL PROCEDURE

2.1 Nano Lubricant Preparation for Machining Operation

In this study, two main materials were used to produce nano fluid for MQL system. The nano-MQL preparation consists of 1% silicone dioxide (SiO_2) powder (20 nm-sized) with 200ml crude palm oil mixture. The nano MQL system was configured to spray directly to the cutting zone at a maximum flow rate of 20ml/hour and an air pressure of 8 bar. Generally, nanofluid is prepared by using two-step methods suspending a small amount of nanoparticles in base fluids such as water, ethylene glycol, oil and so forth, with or without stabilizing techniques. In this experiment, the same nanofluid preparation method will be applied by mixing palm oil with nanoparticles of SiO_2. The concentration for SiO_2 is 1%. The step-by-step preparation of nanofluid is shown in Figure 1. First, the weight of 2 g SiO_2 nanoparticle has been weighed using the electronic scale and after that, the nanoparticle was mixed with 200 ml palm oil in a beaker. Then, the mixture was stirring using a magnetic stirrer for 30 minutes. For the final step, ultrasonic emulsification was used for 1 hour to disperse nanoparticles in the palm oil to get a stable solution.

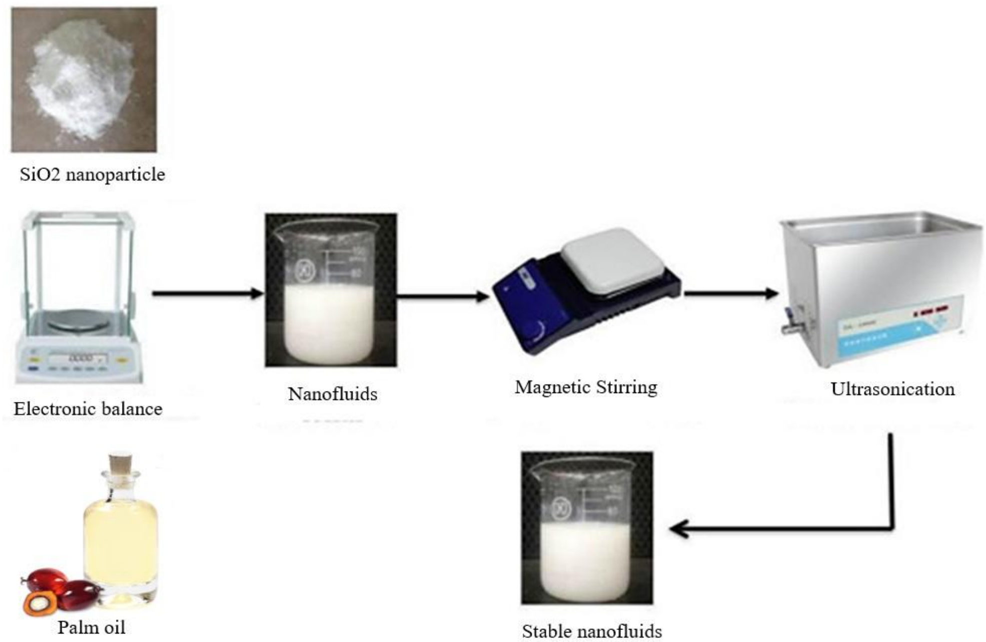


Figure 1: Step-by-step preparation of nanofluid.

2.2 Experiment Procedure for Tribology Testing

Tribology testing is carried out to measure the lubrication effect of using MQL fluid during the cutting process. Therefore, this testing will not involve the cryogenic system due to limitations in testing CO_2 using the tribological tester and the cryogenic system functions more as a cooling system during the cutting process. The tribological testing was conducted with a TR 30L, DUCOM four-ball tester to measure the coefficient-of-friction (COF) of the nanofluid contact surface. Testing was conducted in accordance with the procedures outlined in ASTM D4172-94 (2016) standard. The speed, load, time, and temperature were as follows: 1200 rpm, 392.4N, 3600 secs, and 75^{o}C. Three carbon-chromium steel balls with hardness 61 HRC, density of 7.79 g/cm^3, surface roughness of 0.022 µm and measuring of 12.7 mm in diameter were fastened together and lubricated for assessment inside the four-ball tester. The same diameter of fourth steel ball which known as the top ball, was placed in a unique collet within a spindle, and turned by an AC motor. The highest ball spun against the three stationary balls in oil and the coefficient of friction was measured with a data processing system.

2.3 Experimental Set Up and Parameter Setting For Machining

In this research, the machining process was conducted using a three axis CNC Makino KE55 Vertical CNC Knee milling machine with attachment of nano-hybrid cryogenic-MQL system as shown in Figure 2. The workpiece used for this study is a titanium alloy Ti-6Al-4V block of 160 mm long, 110 mm wide and 50 mm thickness. Both the tool holder and tool inserts are chosen from MI – Mitsubishi. The tool holder is an indexable end mill with a single insert of PVD coated tungsten carbide. Figure 3 shows the dimensions of the PVD coated tungsten carbide insert. The nano-hybrid cryogenic-MQL system is equipped with two separate nozzles where one for the nano MQL system and another for the CO_2 cryogenic system. Both nozzles were kept at a 50 mm distance from the cutting tool. The CO_2 cryogenic system was set up to directly spray the cutting zone at an 8-bar pressure.

Different cutting parameters variations affected different tool wear mechanisms and tool lifespan. Two parameters were selected for feed rate and cutting speed based on suggestions from previous research on cutting tool wear variables (Zha et al., 2024; Jamil et al., 2022; Shokrani et al., 2019; Krishnaraj et al., 2017). This current study employed cutting speeds at 130 and 150 m/min, along with feed rates of 0.2 and 0.5 mm/rev. The axial depth of cut (a_p) was set at 0.5 mm and the radial depth of cut (a_e) was set at 2 mm for the cutting depth.

Figure 2: The nano MQL system and the CO_2 cryogenic system set up in milling machine.

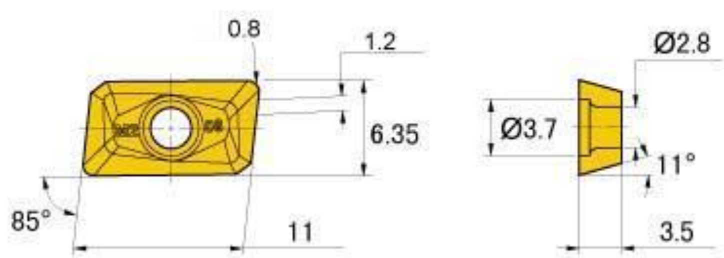


Figure 3: The dimension of PVD coated tungsten carbide insert.

A full experimental design comprised of 2^2 tests as in Table 1 was employed to identify the combination of these variables to investigate the impact of each variable on tool wear evolution and enhancing tool longevity.

Table 1: Machining performed on the 2^2 experimental design.

Test, N	V_c **(m/min)**	F **(mm/rev)**	a_p **(mm)**	a_e **(mm)**
1	130	0.2	0.5	2.0
2	130	0.5	0.5	2.0
3	150	0.2	0.5	2.0
4	150	0.5	0.5	2.0

2.4 Tool Wear Data Collection and Wear Mechanism Analysis

The progression of tool wear was monitored with a LEXT™ OLS5100 3D laser scanning microscope after every 110mm (1 path) of cutting distance. The experiment went on until the tool reached the tool life standard (average wear=0.3 mm or maximum wear=0.5 mm, whichever occurs first) as per ISO-8688 (1989). The tool wear progression was evaluated and presented at three key stages: first, at the initial stage (beginning) when the tool was still sharp and showed minimal wear; second, at the midpoint of the wear progression (middle), reflecting moderate wear; and finally, at the end of the tool's life (end), where significant wear had accumulated, and the tool had reached its failure point.

Advancements in understanding the tool wear mechanism were also emphasized during the machining operation. In this investigation, a Scanning Electron Microscope (SEM) equipped with Energy Dispersive X-ray Spectrometry (EDX) of the Hitachi TM3030 Plus model was used to analyze the impact of the nano-hybrid cryogenic-MQL technique on the tool wear mechanism under orthogonal cutting conditions. SEM analysis was performed to examine the tool wear mechanism on the flank surface, while EDX analysis was employed to evaluate the adhesive wear on both the tool flank and rake surfaces.

2.5 Surface Roughness Data Collection

The surface roughness (Ra) of machine surface was measured using a SURFCOM TOUCH 50 surface roughness machine based on ISO-4288 (1996). Sample reading will be taken three times for each series of cutting parameters to achieve the best average reading. The reading was taken at the beginning of the cut while the tool is still in a good shape.

3.0 RESULTS AND DISCUSSION

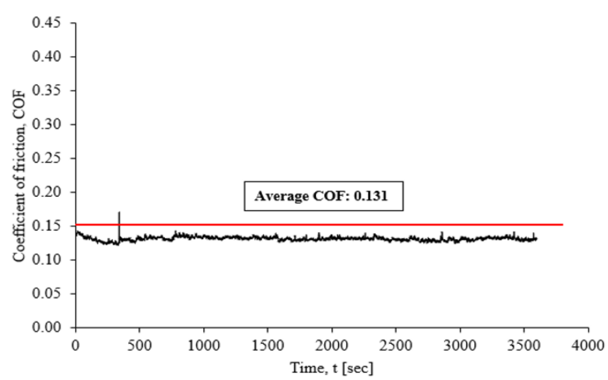
3.1 Tribology Study

Tribological research was carried out in this study, leading to the creation of a graph showing the relationship between coefficient of friction (COF) and time for data analysis. The friction coefficient is an important measurement in tribology, indicating the tangent of the angle formed by the normal force and the friction force. Even though weight and angle are commonly believed to impact friction, the material properties and surface qualities of the bodies in contact also have a substantial effect. This study examines the difference between using Minimum Quantity Lubrication (MQL) alone and MQL combined with nanoparticles.

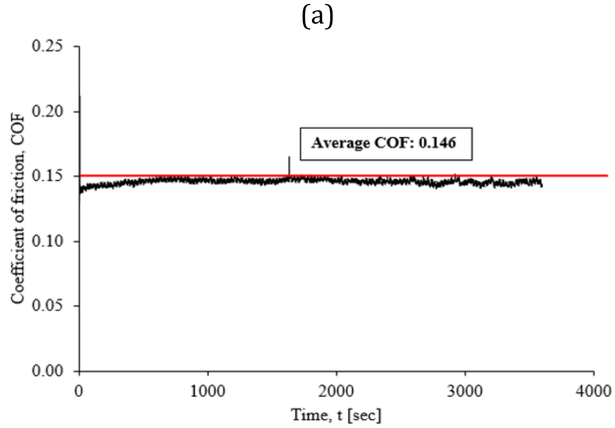
The results showed in Figure 4(a) that using nanoparticles in MQL resulted in a COF of 0.131 after 3600 seconds, slightly less than the 0.146 COF seen in MQL without nanoparticles showed in Figure 4(b). The findings are in line with the research conducted by Abdollah et al. (2020), who explained that the drop in COF was due to the nanoparticles' rolling action in the lubricant, which decreased shear strength and wear rates. Further examination of more current research reveals consistent results. Singh et al. (2022) found that adding nanoparticles such as silicon dioxide (SiO_2) or molybdenum disulfide (MoS_2) to MQL systems greatly improves tribological performance by increasing strength of lubricant film and decreasing friction. Sharma et al. (2015) found that nanoparticles filling micro-gaps between surfaces reduce metal-to-metal contact, decreasing friction and wear.

On the other hand, different studies such as Talib et al. (2022) indicate that although there is a noticeable decrease in COF because of nanoparticles, the specific type and amount of nanoparticles used are important. For example, the utilization of nanofluids based on graphene demonstrated better performance in reducing COF and wear compared to traditional nanoparticles, resulting in more significant enhancements in friction.

In summary, the use of 1% SiO_2 in the crude palm oil mixture for the MQL system can reduce the friction rate by almost 10.3% during the cutting process. Besides that, broader research shows that the choice of nanoparticle material and concentration, as well as surface conditions, are critical to optimizing tribological performance. The experiment's findings are consistent with trends in current literature that emphasize the growing importance of nano-enhanced lubricants for improving machining efficiency and durability.



(a)



(b)

Figure 4: (a) Coefficient of friction, COF vs time, t graph of tribology result with nanoparticles (SiO_2) (b) Coefficient of friction, COF vs time, t graph of tribology result without nanoparticles.

3.2 Tool Wear and Wear Mechanism

Tool wear refers to the failure of cutting tools caused by continuous use. For example, machine tool tipped tools, tool bits, indexable tools, and drill bits are affected (Zawada et al., 2020). In milling machining, tool wear can be produced by a combination of mechanical, thermal, chemical, and abrasive load factors acting on the tool's cutting edge. In this experiment, Figure 5 shows the graph of tool wear progresses for four serials of test (N) during cutting under nano-hybrid cryogenic-MQL conditions. In each test run, three data images and wear reading were pointed out to better comprehend the variation in tool wear evolution during each machining test: one for the beginning, one for the middle, and one for the end of the machining run. It was observed that the pattern is similar for all four test runs where at the beginning of the cutting, the tool wear is in an average wear form. Then, in the middle of the cutting, as the tool wear is gradually increase, the localized wear pattern is form. At the end of the cutting where the tool reaches its' tool life, notch wear pattern is a form of resulting tool wear that causes it to be categorized as a type of catastrophic failure. Based on Figure 5, the tool wear in run N3 increased gradually after the middle reading because flaking occurred at the localized point. Flaking is considered as a brittle fracture due to the cryogenic cooling effect. Similar finding was observed by Abdel-Aal et al. (2009) and Bagherzadeh et al. (2021) where they found that brittle fracture like cracking, chipping, and flaking was observed at localized flank wear during machining titanium alloy evidence of brittle fracture such as cracking, chipping and flaking at the cutting speeds of 60 and 150 m/min and feed rate of 0.15 mm/tooth.

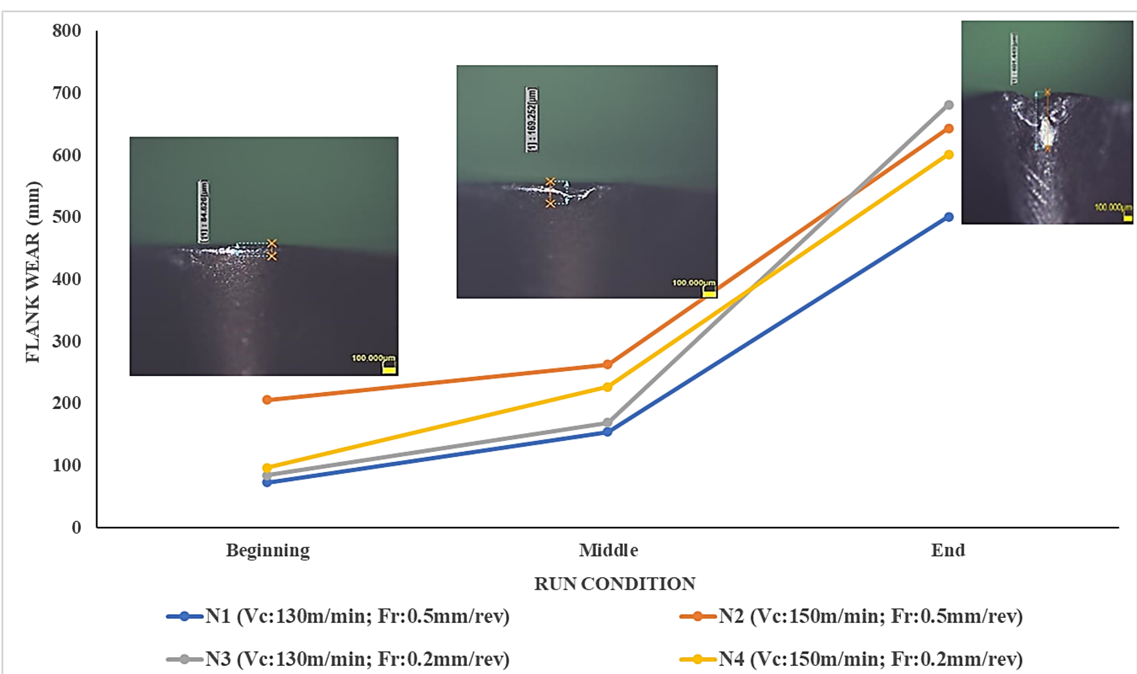


Figure 5: Graph of flank wear measurement for test N1 (Vc- 130 m/min, f- 0.2 mm/rev), test N2 (Vc- 130 m/min, f- 0.5 mm/rev), test N3 (Vc- 150 m/min, f-0.2 mm/rev) and test N4 (Vc- 150 m/min, f-0.5 mm/rev).

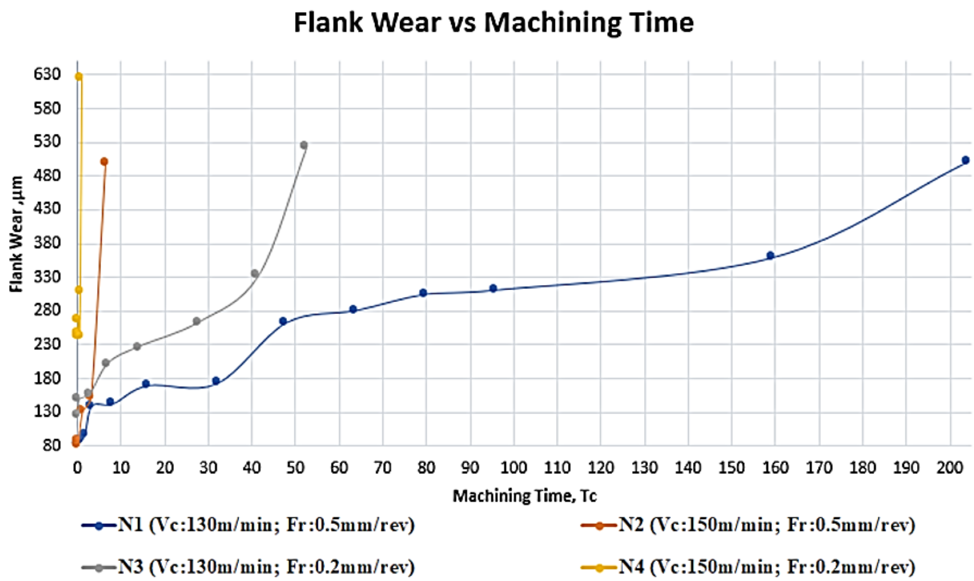
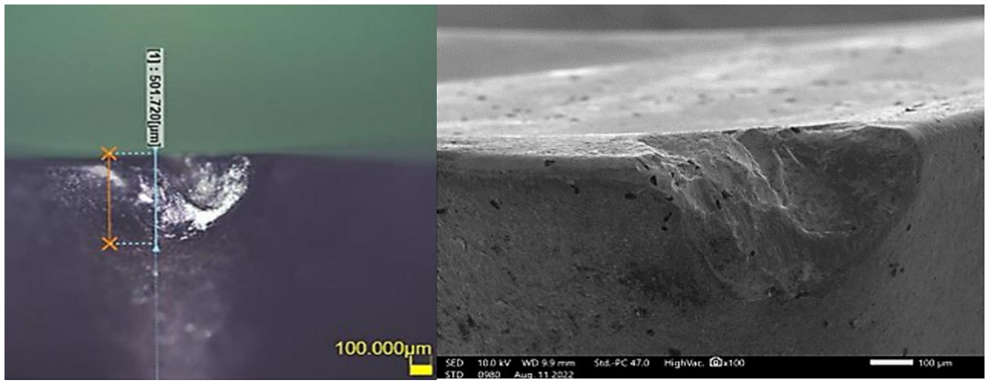


Figure 6: Plotted graph flank wear versus machining time of SiO_2 Nano Hybrid Cryogenic MQL.

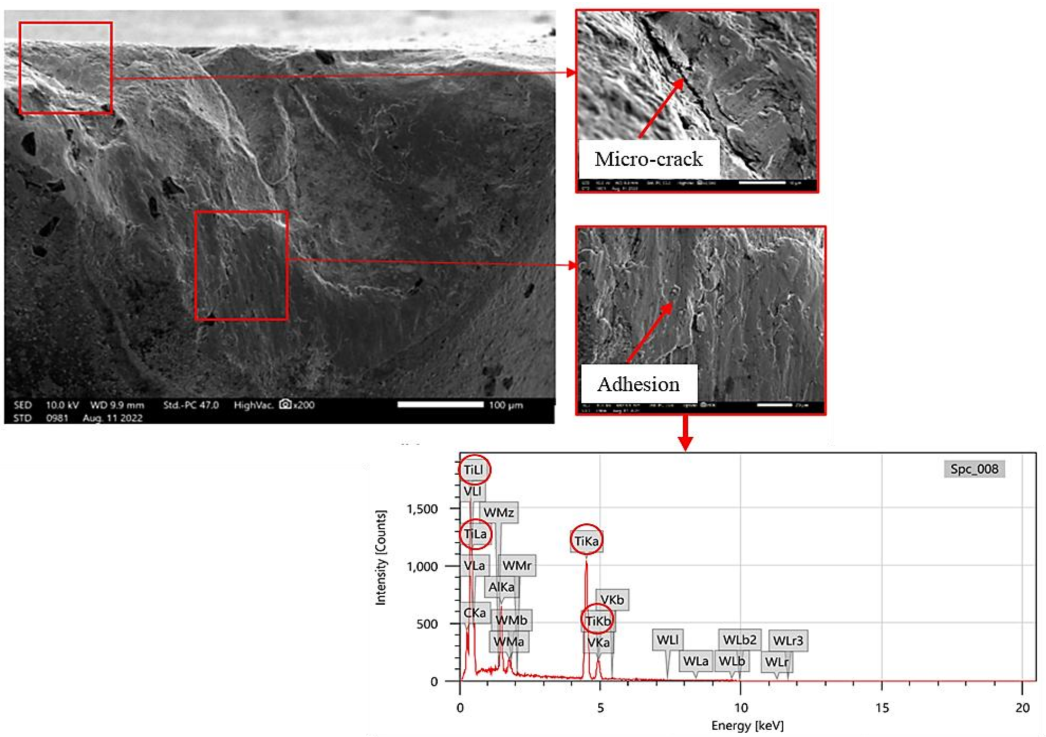
In Figure 6, a graph displays the relationship between flank wear and machining time for nano-hybrid cryogenic MQL machining process with 1% SiO_2. Consequently, test N1 had the longest duration for machining until the tool reached the end of its life, lasting 204.10 minutes with a maximum cutting distance of 140,800 mm. While test N4 shows the shortest machining time where the machining process took 0.83 minutes to cover only 1,650mm. From the result, it is clearly shows that the cutting speed has a big impact in determining the life of the tool. The results of the study show that the higher the machining speed, the shorter the tool life. This is due to the higher kinetic energy of the abrasive particles and deterioration of the cutting tool material. Besides that, the result also is in line with Taylor's tool life equation formula (Eq.1) which is:

$$V_c T^n = C \tag{1}$$

where, V_c is the cutting speed in m/min, T is the tool life in min, C is a Taylors constants and n is the exponent for conditions. In addition, the results of this finding show similarities with the results of previous studies conducted by Sheikh-Ahmad and Davim (2009) where they claimed that an increase in cutting speed leads to a significant drastic increase in flank wear.



(a)



Element	Line	Mass%	Atom%
C	K	4.29±0.05	15.05±0.19
Al	K	5.55±0.12	8.67±0.19
Ti	K	80.64±0.94	70.98±0.83
V	K	5.20±0.36	4.31±0.30
W	M	4.33±0.30	0.99±0.07
Total		100.00	100.00
Spc_008			Fitting ratio 0.0416

(b)

Figure 7: Microscopic image of the cutting tool edge at the end of tool life, (a) Flank wear image of coated carbide tool, (b) Wear mechanism of the cutting tool in result of using maximum parameter.

Figure 7(a) and Figure 7(b) show the tool wear and wear mechanism obtained by SEM under machining process of minimum parameter (longest tool life) in condition of nano-hybrid cryogenic MQL added with SiO_2. The coated carbide tool shows the flank wear size of 501.720 µm at the end of tool life. The worn flank face revealed the presence of major notching and fracture. The obvious presence of both tool wear mechanisms has been shown to be a significant factor in the process of tool wear. Figure 7(b) reveals that when the SEM image is enlarged, the tool mechanism reveals the micro-cracks at the perpendicular to the cutting edge, forming on the flank face. The presence of micro-cracks in the chip flow and workpiece travel directions is well known as the common characteristic of abrasive wear. This occurrence might result from the insufficient cooling capability of the nano-hybrid cryogenic MQL added with SiO_2, which mainly cools down the workpiece and the main body of the tool but does not effectively cool the interfaces between the tool and the chip or the tool and the workpiece. Moreover, the cracking is normally due to high cutting pressure or impact during machining. Among other tool wear mechanisms found in Figure 7(b) is adhesion. An examination of the Energy-dispersive X-ray analysis (EDAX) spectrum confirmed the existence of Ti-6AL-4V material in the adhesion layer spot. Based on spectrum EDAX analysis, the adhesion observed on the flank face is due to a mix of Ti-6AL-4V workpiece components and the tool material coating of AlTiN. This shows that the AlTiN coating on the carbide cutting tools has chipped away. This event led to the carbide substrate material being uncovered. This occurrence occurred frequently in most of the experiments carried out on the cutting tools.

3.3 Surface Roughness

Surface roughness was evaluated on machined surfaces for nano-hybrid cryogenic-MQL techniques. Average surface roughness values commonly observed during machining operations is displayed in Figure 8. Based on these findings, test run N3 give the lowest surface roughness reading with a value of 1.55µm and the highest value which is 2.54µm come from test run N2. From all the results obtained, it was found that most of the readings were in the range of the moderate rough category (Ra 1.0 - 2.0m), where the surface roughness reading is very suitable for the purpose of the implant because it provides more strength for bone reaction (Kim et al., 2022). The results of the study also show that cutting parameter which is cutting speed and feed rate play an important role in determining the value of surface roughness. High cutting speeds have a positive impact on surface roughness, leading to less chip fracture and a higher tendency for built-up-edge. Additionally, increasing the cutting speeds simplifies chip removal, leading to a reduction in cutting forces and ultimately enhancing the surface roughness (Usca et al., 2022). Then, the lower the feed rate, the better surface roughness can be obtained. This result was like Daniel et al. (2019) when milling composite. Therefore, a reduction in the feed rate narrows the gap between successive tool paths, resulting in improved clarity of roughness traces (Wu et al., 2018).

CONCLUSIONS

Based on the results of this study, several key conclusions can be drawn regarding the machining of Ti-6Al-4V titanium alloys using the nano-hybrid cryogenic MQL method:

a) Tribological studies demonstrated that the addition of nanoparticles to the cutting fluid notably reduced the coefficient of friction (COF), contributing to improved machinability of Ti-6Al-4V titanium alloy.

b) Machining Ti-6Al-4V titanium alloy with nano-hybrid cryogenic MQL lubrication at a cutting speed of 130 m/min and a feed rate of 0.2 mm/rev significantly extends tool life, achieving up to a 30-fold increase, while also delaying tool wear failure.
c) Notch wear was identified as the predominant tool wear mechanism, especially evident at the end of tool life when flank wear exceeded 0.5 mm across all parameters. Other wear mechanisms observed included fracture, crater wear, and adhesive wear.
d) At a machining speed of 150 m/min and a feed rate of 0.2 mm/rev, the resulting surface roughness was 1.55 µm, which falls within the moderate roughness range (Ra 1.0–2.0 µm). This level is ideal for implants, as moderate roughness enhances bone integration and strength.

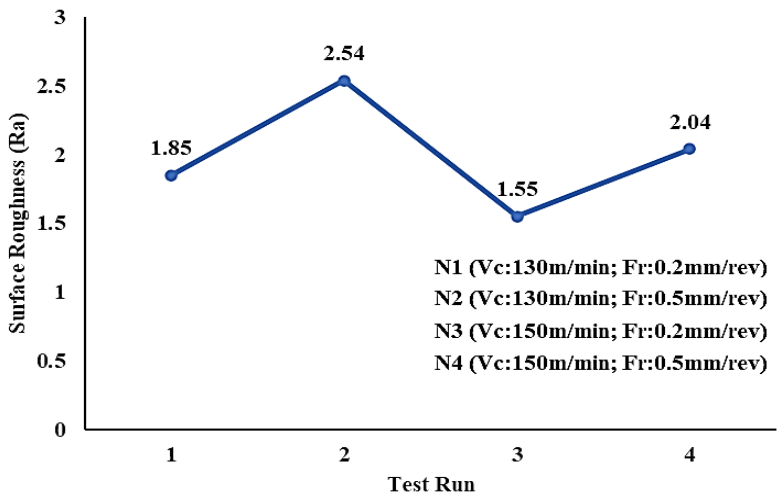


Figure 8: Graph of average surface roughness for all runs.

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