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Study of tool wear progression using nano-hybrid Cryogenic MQL in milling titanium alloy

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KEYWORDS

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Titanium Alloy
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ABSTRACT

Titanium is recognized for its excellent strength-to-weight ratio, resistance to corrosive environments and extensively utilized in a range of industries. However, due to excellent properties of this material, it has become a difficult-to-cut material. The high heat generated during the machining process should be cooled with sufficient lubricant or coolant. High cutting temperature and stress generated when machining titanium alloy and primarily contributed to tool wear issues, resulting in various cutting tool wear behaviors. This paper investigates end milling of Ti-6Al-4V alloy using nano-hybrid cryogenic-MQL cooling system with responses to tool wear, machining time, and surface roughness. The cutting speeds of 130 and 150 m/min were selected for the experiments, with feed rates of 0.2 and 0.5 mm/rev, and the depth of cut constant at 0.5 mm using a single insert carbide tool. In this experiment, nano-hybrid cryogenic -MQL were used as the main system. The impact of cooling system and cutting parameter selection in determining optimal cutting conditions to improve tool life and tool wear was highlighted. The outcomes result shows that the cutting speed of 130 m/min and a feed rate of 0.2 mm/rev improve tool life approximately 50% and generate good surface roughness compared to other cutting parameters. To conclude, the nano-hybrid cryogenic-MQL system satisfies industry-relevant requirements, proving this approach as a viable alternative for more sustainable and environmentally friendly cooling systems.

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1.0 INTRODUCTION

Titanium is recognized for its excellent strength-to-weight ratio, resistance to corrosive environments and may be extensively utilized in a range of industries due to its excellent material properties (Polishetty et al., 2014). However, due to its low machinability, titanium alloy's application has been limited and can be classified as a difficult-to-cut material in general. Titanium also have specific material properties such as low heat conductivity, high chemical reactivity, and high strength, which result in shorter tool life and poor machining performance. (Park et al., 2014). The demand for titanium and its alloys has massively increased in the aerospace, marine, chemical, and medical industries despite the complexity of machining and manufacturing limitations. (Shokrani et al., 2019). High stresses and high cutting temperatures generated when titanium alloys are being machined. These mostly contribute to a poor effect on tool life, machinability and can result in early tool failure (Hegab et al., 2018). Tool wear is an issue in the titanium alloy machining process that cannot be avoided; various types of wear, such as flank wear, crater wear modes, and other wear behavior occur on the cutting tools, and substantial attention for optimal machining investigation is given in previous studies (Sulaiman et al., 2014). In this experiment , cutting tool selection is key for tool wear behavior observation , several research has resulted that tungsten coated carbide tools are among the best especially for machining titanium alloy (Chetan et al., 2019)(Bordin et al., 2015).

Recently, the concept of sustainability has begun receiving global interest and become a trend for modern research especially in machining titanium alloy. Researchers starting to investigate many alternatives to accomplish sustainable and eco-friendly cooling techniques as an alternate to conventional flood cooling. The potential of minimum quantity lubrication (MQL) and cryogenic lubricating techniques as an alternate to flood lubricating cooling are finally being discovered. These two approaches, also known as hybrid cryogenic MQL, minimize the utilization of cutting fluid used, which is highly cost effective because it reduces costs of lubrication (Boswell et al., 2017). Other than that, the MQL technology has made it possible for the advancement of newer technologies that complement the existing MQL machining process and one of advancement is the use of nanoparticles in MQL lubricant, also known as NMQL technique (Nanofluid minimum quantity lubrication) and they are widely used due to their superior lubricity. Machining with NMQL showed that highest decrease in cutting force and surface roughness of 10.71% and 14.92%, respectively, compared to dry machining (Yuan et al., 2018). For cryogenic cooling it also represents an efficient solution for machining titanium alloy. The cooling method lowers cutting temperature by supplying gas directly to the cutting zone, minimizing tool wear, and enabling the use of more severe cutting parameters. (Bordin et al., 2015).

Table 1 shows a comparative study of four main parameters were investigated by Boswell et al.,2017. in order to evaluate the effectiveness of all advances MQL operations, the following machining parameters must be considered: tool wear, tool life and surface quality. Five types of MQL were investigated which are MQL+ Nano Particles (NP), MQL + Cryogenic (CRYO), MQL + Supercritical CO_2, MQL+Ranque-Hilsch Vortex Tube (RHVT) and MQL+Ionic Liquid (IL) It has been described on the basis of the comparative study that the nanofluid based MQL and MQL with cryogenic cooling system has obtained better results than other advanced techniques.

Table 1. Comparison of Parameter improvement in different advancement in MQL.

Type of MQL	Tool Wear	Tool life	Surface Quality	Cutting Force
MQL + Nano Particles	✓	✓	✓	✓
MQL + Cryogenic		✓	✓	✓
MQL + Supercritical CO_2	✓	✓	✓	
MQL + Ranque-Hilsch Vortex Tube		✓	✓	
MQL + Ionic Liquid	✓		✓	✓

2.0 MATERIALS AND METHOD

The work material used in this experiment is cuboid titanium alloy Ti-6Al-4V block of 160 mm long, 110 mm wide, with 50 mm thickness. Both the tool holder and tool inserts are selected from MI – Mitsubishi. The tool holder is a single-insert indexable end mill, and the insert is tungsten carbide-PVD coated. Figure 1 presents the original machining setup of nano-hybrid cryogenic MQL in three axis CNC Makino KE55 Vertical CNC Knee milling machine to assist in understanding the experiment. Two independent nozzles were installed, one for the nano MQL system and one for the CO_2 cryogenic system. The following systems are explained:

(a) Nano-MQL preparation consists of one percent silicone dioxide powder and 200ml 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.
(b) Carbon dioxide (CO_2) was the main gas used in the cryogenic system for this experiment. The CO_2 cryogenic system was set up to directly spray the cutting zone at an 8 bar pressure.

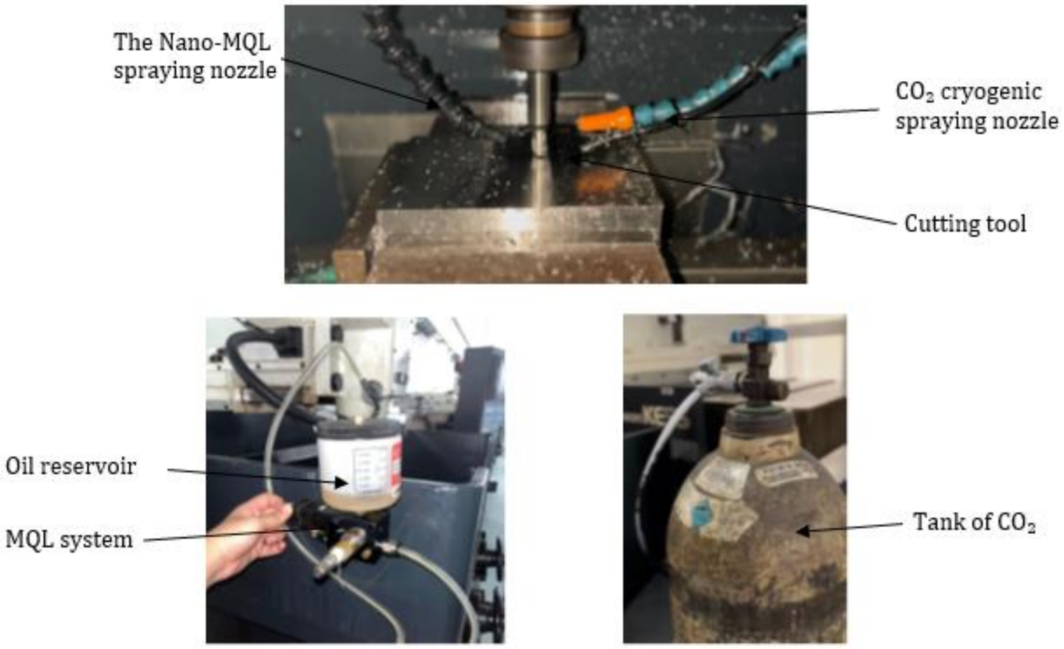


Figure 1: The original machining setup of nano-hybrid cryogenic MQL in three axis CNC Makino KE55 Vertical CNC Knee milling machine.

The variation of cutting parameters influenced various tool wear mechanisms as well as tool life. Among the variables related to cutting tool wear, two values were chosen from previous studies recommendations for feed rate and cutting speed. This present investigation used cutting speeds of 130 and 150 m/min and feed rates of 0.2 and 0.5 mm/rev. The axial depth of cut (DOC_A) and radial depth of cut (DOC_R) were fixed to 0.5 mm and 2 mm, respectively, for the depth of cut. The tool wear progression was measured using a LEXT microscope every 110mm (1 path) of cutting distance. A complete experimental design consisting of 2^2 tests was used to determine the combination of these parameters in order to study the effect of each parameter on tool wear progression and improving tool life. Table 2 summarized the complete experiment test performed. Developments in the tool wear mechanism were also highlighted throughout the machining process.

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

Test N	Vc (m/min)	F (mm/rev)	Adoc (mm)	Rdoc (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

3.0 RESULTS AND DISCUSSION

Cutting tool were inspected by using laser scanning microscope LEXT OLS500 to presents the image data of tool wear progression throughout the complete machining test. The result was observed from the starting machining run (first path) until reaching at standard tool life end point with recommended width of flank wear (VB) of 0.5 mm maximum on individual tooth. Cutting tool were inspected by using laser scanning microscope LEXT OLS500.

Figure 2 shows a plotted graph of flank wear versus machining time for the whole 2^2 test experimental design. As a result, test N1 (Vc- 130 m/min, f- 0.2 mm/rev) had the longest machining time to reach the tool life end point, lasting 204.10 min. with a maximum cutting distance of 140,800 mm. For test N2 (Vc- 130 m/min, f- 0.5 mm/rev), the machining time was 6.38 min, and the machining distance was up to 11,000 mm. The curved plot for test N2 displayed a rapid increase in tool wear from the machining run at 5,500 mm machining distance, which resulted in flank wear of 0.152 mm, to the sudden rise in tool wear that caused flank wear to reach a maximum of more than 0.5 mm. Compared to test N2, test N1 has a tool life that is up to 93% longer and performs machining with a longer travel distance.

For test N3 (Vc- 150 m/min, f-0.2 mm/rev), machining time was 53.51 min which up to machining distance of 41,800mm. The flank wear increment was a steady state, followed by incremental wear until the maximum tool life was reached at a flank wear of 0.522 mm. Lastly for test N4 (Vc- 150 m/min, f-0.5 mm/rev) machining time was 0.83 min which up to only 1,650mm machining distance. The initial run of the machining operation obtained flank wear roughly half of the maximum flank wear for tool life end point, which was 0.25 mm, and up to only 0.055 minutes of machining time, as shown by the graph plotted, compared to all other tests. The flank wear continues to increase significantly and this nano-hybrid cryogenic MQL lubricating system does not appear to have an impact on the reduction of tool wear increment. According to the results of all four tests, cutting speed at 130 m/min and a feed rate of 0.2 mm/rev gave the tool life with the longest, while cutting speed at 150 m/min and a feed rate of 0.5 mm/rev gave the tool life with the most critical tool wear increment.

In order to better understand the impact of nano-hybrid cryogenic MQL on each test toward tool wear progression of machining titanium alloy, a complementary study was conducted. Using a laser scanning microscope LEXT OLS500, imaging data of flank wear from each test was measured in order to observe the tool wear progression. Various types of wear mechanism, including flank wear and crater wear were observed during the cutting operation which can be caused by a combination of load factors (mechanical, thermal, chemical, and abrasive) acting on the cutting edge of the tool.

In the following data obtained, three data images representing the beginning, middle, and end of the machining run were highlighted to better understand how the tool wear evolution differed for each machining test. Figure 3 showed the microscope image of the progression of flank wear 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).

As shown in Figure 3, the test N1 (Vc- 130 m/min, f- 0.2 mm/rev) tool wear, which can be seen to gradually increase from the start of flank wear at 84.626 mm (0.085 mm) to the end of tool life end point at 501.720 mm (0.5 mm). Fracture and crater wear also developed during the final machining run as tool wear reached its maximum point. The tool progression was slightly different for test N2 (Vc- 130 m/min, f- 0.5 mm/rev), flank wear started at 72.537 mm (0.072 mm) and ended at a maximum value of more than 0.5 mm, both of which contributed to rapid tool failure. When the feed rate was increased, the flank wear value at the middle of the machining run increased massively from 154.140 (0.15mm) to a maximum flank wear value of more than 0.5mm. Various different tool wear mechanisms, such as severe fractures, crater wear, and abrasive marks, were seen.

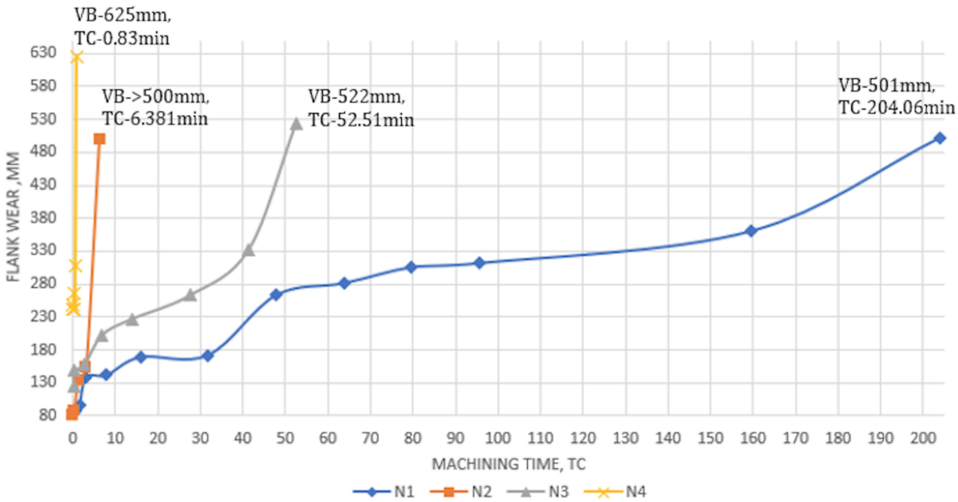


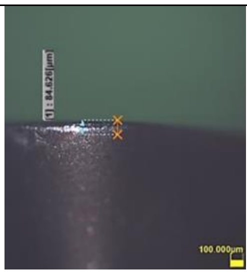
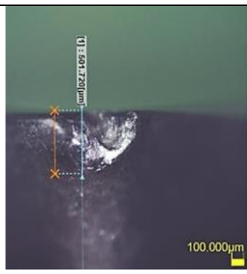
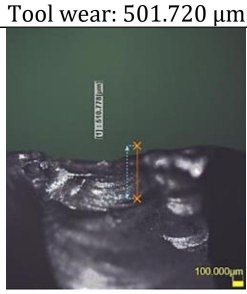
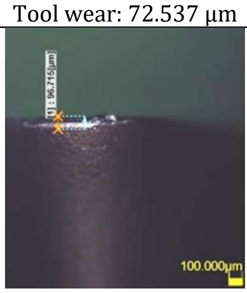
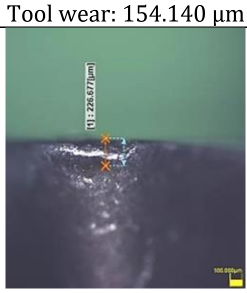
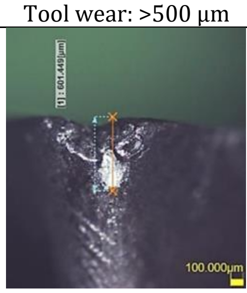
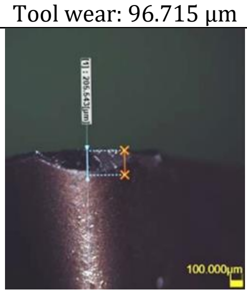
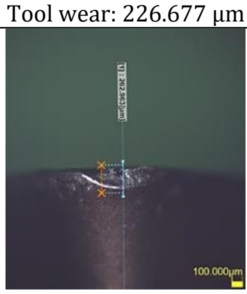
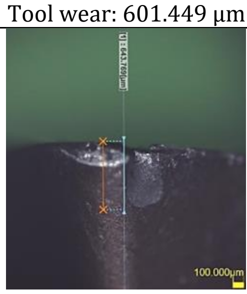
Figure 2: Flank wear versus machining time for the whole 2^2 test experimental design.

Tool wear increased gradually for test N3 (Vc-150 m/min, f-0.2 mm/rev), starting at flank wear at 96.715 m (0.096 mm), and ending at flank wear at 601.449 m (0.6 mm). Although the tool life was shorter, the pattern of tool wear increments appeared to be similar to test N1 (Vc-130 m/min, f-0.2 mm/rev). However, like with the earlier results of tests N1 and N2, when the feed rate was increased at test N4, the results ultimately contributed to poor tool life and the development of tool wear. At the start, the result of flank wear measured 205.543 mm (0.21 mm), which is high for a first cutting impact, and at the end, it measured 643.769 mm (0.64 mm), along with the appearing of fracture and crater wear. This experiment showed that the feed rate has the main effect on the rate of tool wear development and tool life under nano-hybrid cryogenic MQL machining conditions. The second effecting parameter is cutting speed, the higher the cutting speed the lower the tool life. Heat generation in the cutting zone becomes extremely important at higher cutting speeds and feed rates. The temperature at the tool/chip contact, which is made of a material with low thermal conductivity, increases significantly when one of these parameters is increased (Trabelsi et al., 2017). As a result, the cutting tool cannot be cooled by the nano-hybrid cryogenic MQL lubrication system. However, it appears that the nano hybrid cryogenic MQL lubricating technology has made significant advancements in the machining of titanium alloy. All that has been required is the optimum cutting parameter to give the best cutting conditions.

Additionally, the nano-hybrid cryogenic MQL system contributes to an improvement in surface roughness in addition to improving tool wear and life. Surface roughness of machining titanium alloy are one critical factor to achieve in insuring the desire quality (Fukuda et al., 2011). In this experiment, data of surface roughness has been collected for all complete experiment test.

At the end of the machining operation, typical surface roughness measurements were taken by using tungsten carbide-PVD coated single insert under nano-hybrid cryogenic MQL. The test N1 (Vc- 130 m/min, f- 0.2 mm/rev) shows the most improved surface roughness result with RA average value 0.2605 µm of compared to other tests. When cutting speed and feed rate were simultaneously increased, a slightly higher surface roughness value RA average value 0.511 µm was obtained on machining surface of test N4 (Vc-150 m/min, f-0.5 mm/rev). Four different points surface roughness values were measured after perform test N4 and the results showed very unstable surface roughness values. A dramatically increased surface roughness at P4 with a RA value of 0.754 m was most likely caused by rapid tool wear and fracture at the cutting tool's nose area. Test N2 (Vc- 130 m/min, f- 0.5 mm/rev) and Test N3 (Vc- 150 m/min, f- 0.5 mm/rev) generated surface roughness values of RA averages of 0.456 m and 0.469 m, respectively. In comparison to test N1, four surface roughness points for tests N2 and N3 were stable, but still higher. Refer to Figure 4, which displays a plotted graph of surface roughness at four points along with the most stable and unstable results. In conclusion, surface roughness of test N1 (Vc- 130 m/min, f- 0.2 mm/rev) was shown to be the best generated value as titanium alloy was being machined under nano-hybrid cryogenic MQL.

Figure 3: Microscope image of the progression of flank wear for all test conditions.

Condition	**Observation image**		
N1 Cutting speed: 130 m/min Feed rate: 0.2 rev/min	 Run 1 Tool wear: 84.626 µm	 Run 100 Tool wear: 169.252 µm	 Run 1280 Tool wear: 501.720 µm
N2 Cutting speed: 130 m/min Feed rate: 0.5 rev/min	 Run 1 Tool wear: 72.537 µm	 Run 80 Tool wear: 154.140 µm	 Run 240 Tool wear: >500 µm
N3 Cutting speed: 150 m/min Feed rate: 0.2 rev/min	 Run 1 Tool wear: 96.715 µm	 Run 140 Tool wear: 226.677 µm	 Run 380 Tool wear: 601.449 µm
N4 Cutting speed: 150 m/min Feed rate: 0.5 rev/min	 Run 1 Tool wear: 205.543 µm	 Run 8 Tool wear: 262.963 µm	 Run 15 Tool wear: 643.769 µm

CONCLUSIONS

Following conclusion are based on the result of obtained in machining titanium alloy using nano-hybrid cryogenic MQL system:

(a) Machining titanium alloy under nano-hybrid cryogenic MQL lubrication at cutting speed of 130 m/min and a feed rate of 0.2 mm/rev extending tool life up to 30 times over and reducing the chance of tool failure.

(b) The progression of tool wear reveals that the steadiest increment flank wear value was obtained at a cutting speed of 130 m/min and a feed rate of 0.2 mm/rev, with a maximum machining time of 204 minutes to achieve the tool life end point. The results of the tool wear mechanisms were observable towards the end of the tool life end point (flank wear at 0.5mm or more) for all parameters. The three main mechanisms for tool wear are fracture, crater wear, and adhesive markings.

(c) The experiment showed that increased feed rate and cutting speed values considerably decreased surface roughness quality and increased tool wear development by up to 50%.

(d) Nano-hybrid cryogenic MQL under optimal cutting parameter condition improved tool wear, tool life and surface roughness.

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