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Effect of dry and MQL cutting condition on coated carbide cutting tool during the end milling of Ti-6Al-4V titanium alloy

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KEYWORDS

Tool wear titanium
MQL
Wear mechanism
Milling machining

ABSTRACT

The properties of titanium alloy caused some problems in dry cutting conditions such as rapid wear and reduced tool life because the heat cannot dissipate rapidly on the cutting tool. Thus, the objective of this paper is to examine and compare the tool wear of coated carbide cutting tool in end milling of Ti-6A1-4V (titanium alloy) between dry conditions and using the Minimum Quantity Lubrication (MQL). From the experiment, MQL is found better cutting condition than dry condition. It is proven that the improvement of 46.08% with the cutting parameters of spindle speed of 500 rpm, 0.2 mm/tooth and depth of cut of 0.3 mm and 81.94% with the cutting parameters of spindle speed of 1500 rpm, 0.4 mm/tooth and depth of cut of 0.3 mm. Abrasion, adhesion, notch, and crater wear of the cutting tool are explored in this study. The optimum cutting parameters were 500 rpm for spindle speed, 0.2 mm/tooth for feed rate, and 0.4 mm for depth of cut. Therefore, a higher cutting speed and feed rate with a lower depth of cut is preferable to achieve lower tool wear for the coated carbide cutting tool.

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1.0 INTRODUCTION

Titanium has distinct qualities and been used in a wide variety of applications due to its outstanding material properties such as good resistance to oxidative conditions and has high strength-to weight ratio. Along with its comparatively high melting point, it is useful as a protective layer. A few common qualities of these materials, such as exceptional heat resistance, high load bearing capacity, and corrosion resistance, classify them as super-alloys. However, the alloys are regarded as hard to machine material. Wang et. al, (2021) found that titanium alloy is a kind of typical hard-to-cut material due to its low thermal conductivity and high strength at elevated temperatures, this contributes to the fast tool wear in the milling of titanium alloys. As a result, a few researchers have been exploring the machinability of titanium alloy involving environmentally friendly lubrication approaches such as dry, minimum quantity lubrication (MQL), and nanofluid MQL (n-MQL). The milling of titanium alloy was not the same as machining of other materials. Titanium alloy, as an example, has more than 0.9 yield stress to tensile strength ratio, and increases substantially with the exceeding of strain rate (Maruda et. al, 2020), which is readily attained in any machining process. Despite the fact that dislocation motion reported in majority of plastic deformation in titanium alloy, twin-dislocation interactions had a substantial impact on strain hardening during deformation (Akash et. al, 2020). Khanna et. al, (2021) stated that high temperature, very low heat conductivity, low modulus of elasticity, higher strain hardening, and high chemical reactivity play important roles in the titanium alloy machining mechanism.

Dry machining is more ecologically friendly, and it will become a requirement for industrial companies in the coming years. In order to implement environmental protection regulations for occupational safety and health requirements, industries is forced to consider dry machining. This is due to dry machining offers various advantages, such as no contamination of the atmosphere, prevent oxidation of the workpiece surface, resulting in cheaper disposal and maintenance fees, no health issue, and it is non-injurious to skin and free from allergy. On the other hand, it reduces machining costs and time (Raza et. al, 2021). However, the biggest limitation of dry machining is that it produces high temperatures, and it causes excessive tool wear. Another major disadvantage of dry machining is that the chips formed are more prone to tangle at the tool tip and in the cutting zone, reducing tool life and producing poor surface finish. Therefore, the cutting process must be optimized such as cutting tool, cutting parameters, material of workpiece, lubrication and machining process (Vijay et. al, 2020). From another point of view, dry cutting may have beneficial consequences such as reducing thermal shock and thereby reducing the occurrence of comb-cracks. Chip formation is also influenced by higher machining temperatures. Both ribbon and snarl chips may emerge as a result of this. When precise control of chip formation is required, cutting inserts with specifically modified chip shaping grooves for dry cutting may be required. It was discovered that machining without cooling, comprising a combination of high cutting slow speed feed rate, is a sensible option in terms of energy usage. Sarah et. al, (2020) stated that the cutting parameters will influence the finishing process and resulting reduction in specific energy allows for an efficient manufacturing process.

Processing ferrous material and high-resistance alloys demanded better machining settings, which resulted in a significant heat output. This has resulted in severe wear and unsatisfactory the quality of surface finish in the completed product. Machining fluid is used to dissipate heat generated in the machining surface throughout the operation and to regulate the temperature during machining process. This also contributes to the rapid extraction of the chip and avoids the bottom from being clogged (Salur et. al, 2021). The usage of machining fluid is required in order to obtain lower surface roughness of workpiece and higher efficiency. It will also reduce the heat produced during the machining. There are four different types of machining fluids which are machining or soluble oil, synthetic fluid, and semi-synthetic oil are some of the others. Furthermore, in comparison to flood cooling, the results of various research show that MQL yields significant privileges (Aslan et. al, 2020). With this cutting condition especially when vegetable lubricants are utilized, machining is safe not only for operators but also the environment. On the other hand, the lubrication in MQL had been largely explored and been used in many types of machining. The usage of MQL also lowers production expenses by lowering coolant costs (Zhou et. al, 2021). Familiarizing the MQL system to the standard coolant system has numerous advantages, including cost savings, and improved working conditions. Thus, the objective of this paper is to examine and compare the effect of dry and MQL cutting condition on coated carbide cutting tool during the end milling of Ti-6Al-4V titanium alloy.

2.0 EXPERIMENTAL PROCEDURE

The experiment of milling titanium is conducted under two different conditions which are dry condition and MQL. The parameters of the milling of titanium alloy by using a vertical CNC milling machine is shown in Table 1. Taguchi L4 is applied for this experiment and is executed for both dry and MQL.

The material used for the workpiece is the titanium alloy. The Table 2 and 3 illustrates the composition (wt%) of titanium alloy and mechanical properties of titanium alloy at room temperature.

To maximize tool life and wear resistance, a coated carbide tool insert is used for the cutting tool in this experiment. The cutting tool with insert of coated carbide which used in the experiment is shown in Figure 1 and the Workpiece dimension; 160mm x 110mm x 50mm is shown in Figure 2.

Table 1: Milling machine parameter.

No. of experiment	Spindle speed (rpm)	Feed rate (mm/tooth)	Depth of cut (mm)
1	500	0.2	0.3
2	500	0.4	0.4
3	1500	0.2	0.4
4	1500	0.4	0.3

Table 2: 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	Balance

Table 3: 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 1: The cutting tool with inserts of coated carbide.

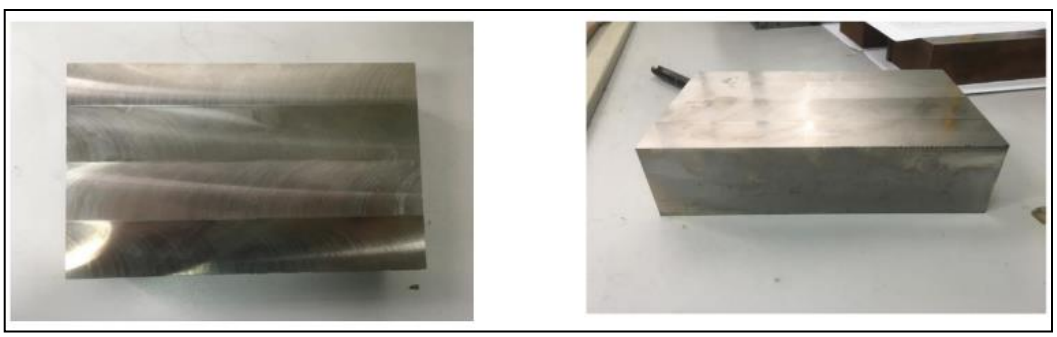


Figure 2: Dimension of workpiece, titanium alloy.

The Dino Lite digital microscope is a portable digital microscope that captures images, including time-lapse video, record audio associated with the image, annotate the image, and measure and calibrate the image. On the other hand, the scanning electron microscope (SEM) is a type of electron microscope that produces images of a sample by scanning the surface with a focused beam of electrons. The electrons interact with atoms in the sample, producing various signals that contain information about the surface topography and composition of the sample. Both equipment are used for tool wear measurement and tool wear mechanism observation as shown in Figure 3.

MQL system is portable equipment that uses air pressure and the lubricant will be sprayed out through the nozzle. Lubrication from MQL plays a significant role in many types of machining such as milling, turning and drilling. Accurate positioning of nozzle to the cutting tool and workpiece must be set properly to give the best result. The MQL system can control the amount of sprayed by adjusting the level but in this research the flow rate of the MQL system is 10 m^3/s. The distance of the nozzle to spray out also play an important role to enhance the surface roughness and tool wear. In this experiment the distance is 100 mm as shown in Figure 4.

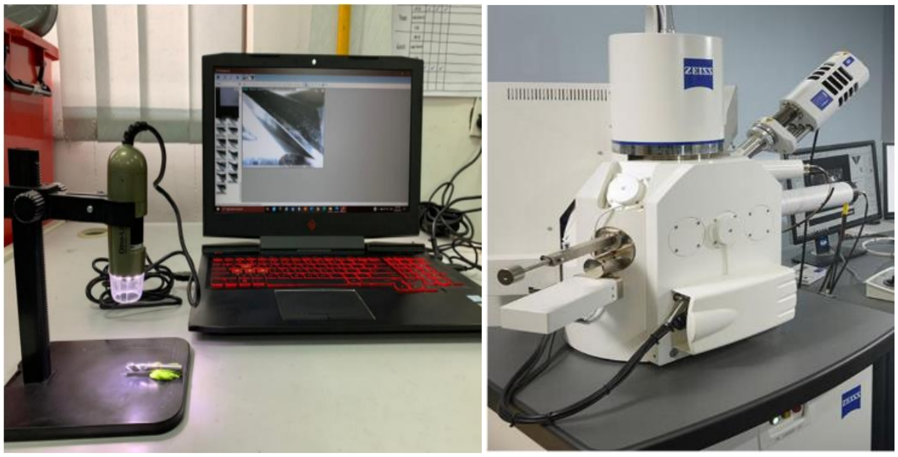


Figure 3: Dino lite digital microscope and scanning electron microscope (SEM).

Figure 4: The MQL system and the distance between the nozzle and cutting tool is 100 mm.

3.0 RESULTS AND DISCUSSION

3.1 Dry Condition

The coated carbides tool used for milling titanium alloy in dry condition showed inferior performance with the notch wear that occurred at the cutting parameter (f = 0.4 mm/tooth) with the spindle speed of 1500 rpm. It recorded the highest tool wear which is 0.825 mm (Figure 5) known as notch wear. On the other hand, the least wear occurred on the experiment 2 at the cutting parameter (f = 0.4 mm/tooth) with the spindle speed of 500 rpm and known as flank wear. From a scoring mark on the face of cutting tool for the overall milling process, it can be inferred that the dominant wear mechanism is flank wear. According to Ghani et. al, (2015), most of these wear mechanisms occurred at high cutting speed where the heat generated exceeded the chemical dissolution temperature 1100°C of tungsten carbide. Furthermore, the tool's cutting edge is subjected to a combination of high pressures, high temperatures and chemical reactions causing the tool to wear.

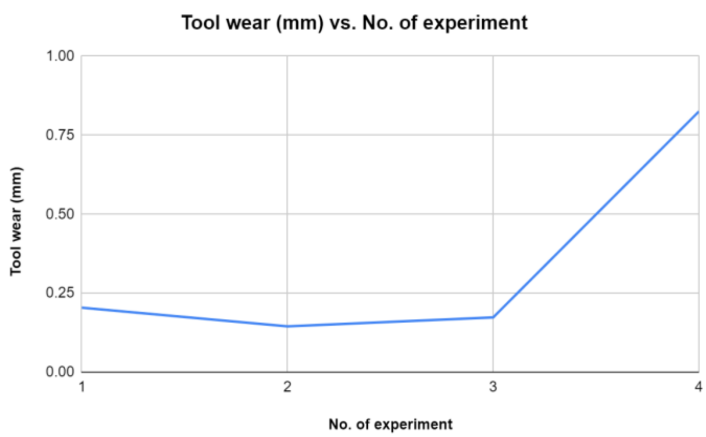


Figure 5: Tool Wear in Dry Condition – Spindle speed, feed/tooth, depth of cut (Exp 1: 500 rpm, 0.2 feed/tooth, 0.3 mm; Exp 2: 500 rpm, 0.4 feed/tooth, 0.4 mm; Exp 3: 1500 rpm, 0.2 feed/tooth, 0.4 mm; Exp 4: 1500 rpm, 0.4 feed/tooth, 0.3 mm).

3.2 MQL Lubrication Technique

The uses of MQL slightly improve the milling process by reducing the tool wear and increasing the tool life. The MQL show superior performance without the presence of the notch wear. At the cutting parameter (f = 0.2 feed/tooth) with the spindle speed of 500 rpm, the smallest wear is recorded which is 0.11 mm as shown in Figure 6. Furthermore, the tool wear obtained from the experiment using MQL is smaller and did not exceed 0.2 mm compared to the dry cutting condition. According to Salur et. al, (2021) the benefit of MQL is that the oil droplets are transmitted to the cutting area during milling and reducing the cutting forces by improving the cutting ability of the cutting tool and directly reducing the power consumption. The improved cutting ability leads to greater wear resistance, hence increasing tool life. Therefore, the MQL technique is proven in lowering the tool wear in milling titanium.

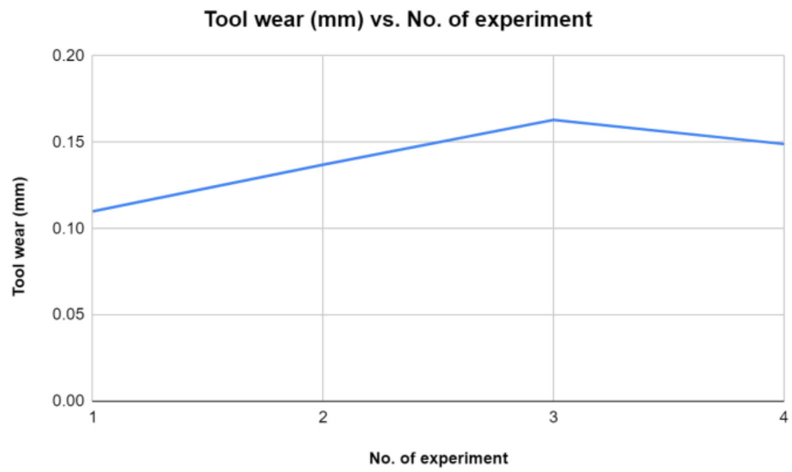


Figure 6: Tool Wear in MQL Condition – Spindle speed, feed rate, depth of cut (Exp 1: 500 rpm, 0.2 feed/tooth, 0.3 mm; Exp 2: 500 rpm, 0.4 feed/tooth, 0.4 mm; Exp 3: 1500 rpm, 0.2 feed/tooth, 0.4 mm; Exp 4: 1500 rpm, 0.4 feed/tooth, 0.3 mm).

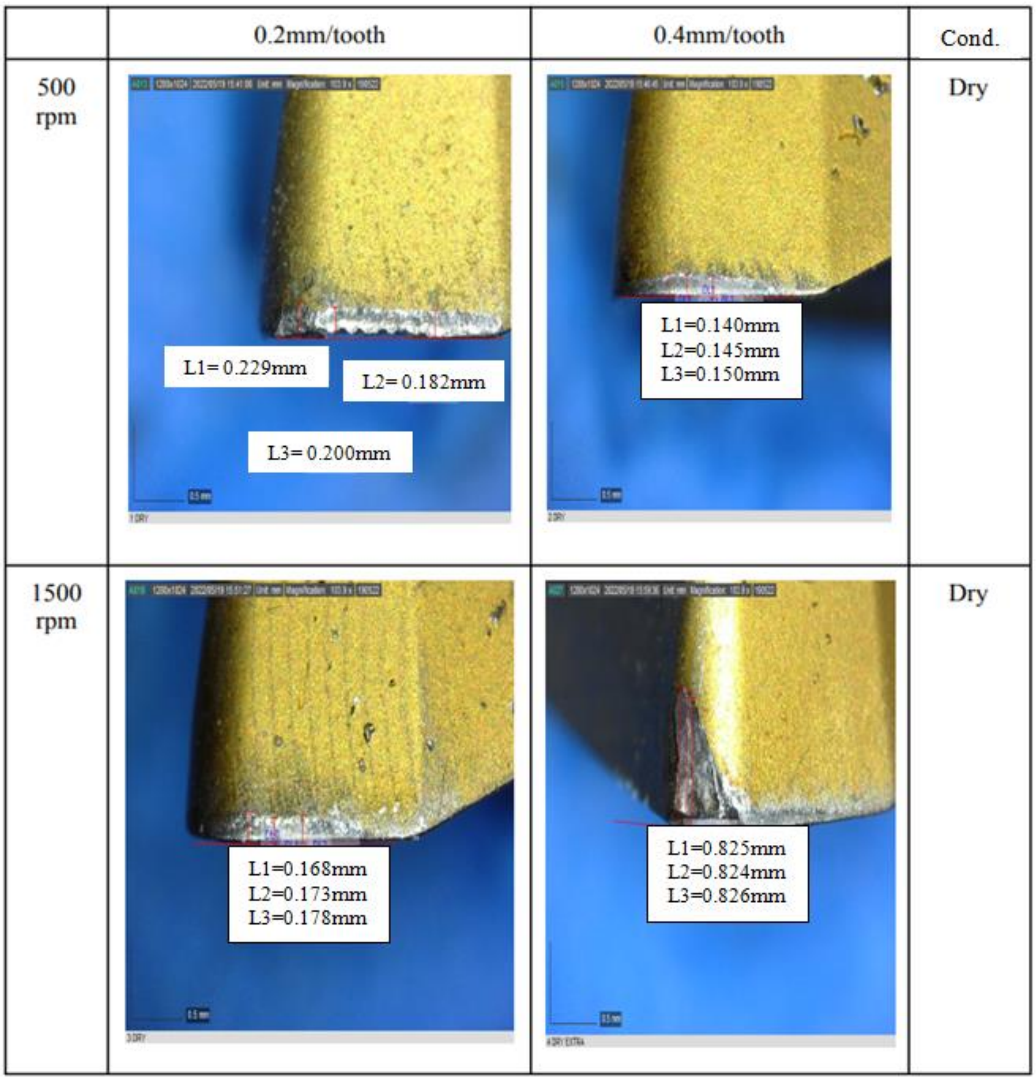
The huge difference in the measured value between dry and MQL is because in the dry machining, the heat generated between tool and workpiece does not dissipate rapidly and resulting in excessive tool wear. According to Khanna et. al, (2021) most of the energy during milling is converted to heat which results in extremely high temperatures at the cutting zone. Consequently, the excessive temperatures are damaging to the material properties, reducing the tool life and increasing tool wear. However, MQL helps in reducing heat generated in the machining surface throughout the operation and to regulate machining temperature during the machining process. According to Gupta et. al, (2018) the cutting fluids are used in machining to extend tool life and produce a good surface finish by cooling and lubricating the cutting zone. Therefore, it is proven that MQL helps in reducing the tool wear and increasing the tool life compared to the dry cutting condition during the end milling of titanium alloy.

3.3 Comparison Between Dry and MQL

Table 4 illustrates the percentage improvement of the tool wear for milling titanium alloy in dry cutting condition and using MQL. While Figure 7 illustrates the cutting tools condition for minimum and maximum wear for each condition; dry and MQL. It shows that the MQL improving the machining efficiency. According to Maruda et al. (2020) overheating can damage cutting tools and workpiece materials and hence, cooling is the primary approach used to keep the temperature under control, which can be achieved with MQL. The ability to keep the cutting temperature at the desired level is critical to machining efficiency, which is measured by tool life, surface integrity, production costs, and environmental factors.

Table 4: Percentage Improvement between Dry and MQL lubrication technique.

No. of exp	Spindle speed (rpm)	Feed per tooth (mm/tooth)	Depth of cut (mm)	Tool wear (mm)		Improvement (%)
				Dry	MQL	
1	500	0.2	0.3	0.204	0.110	46.08
2	500	0.4	0.4	0.145	0.137	5.52
3	1500	0.2	0.4	0.173	0.163	5.78
4	1500	0.4	0.3	0.825	0.149	81.94



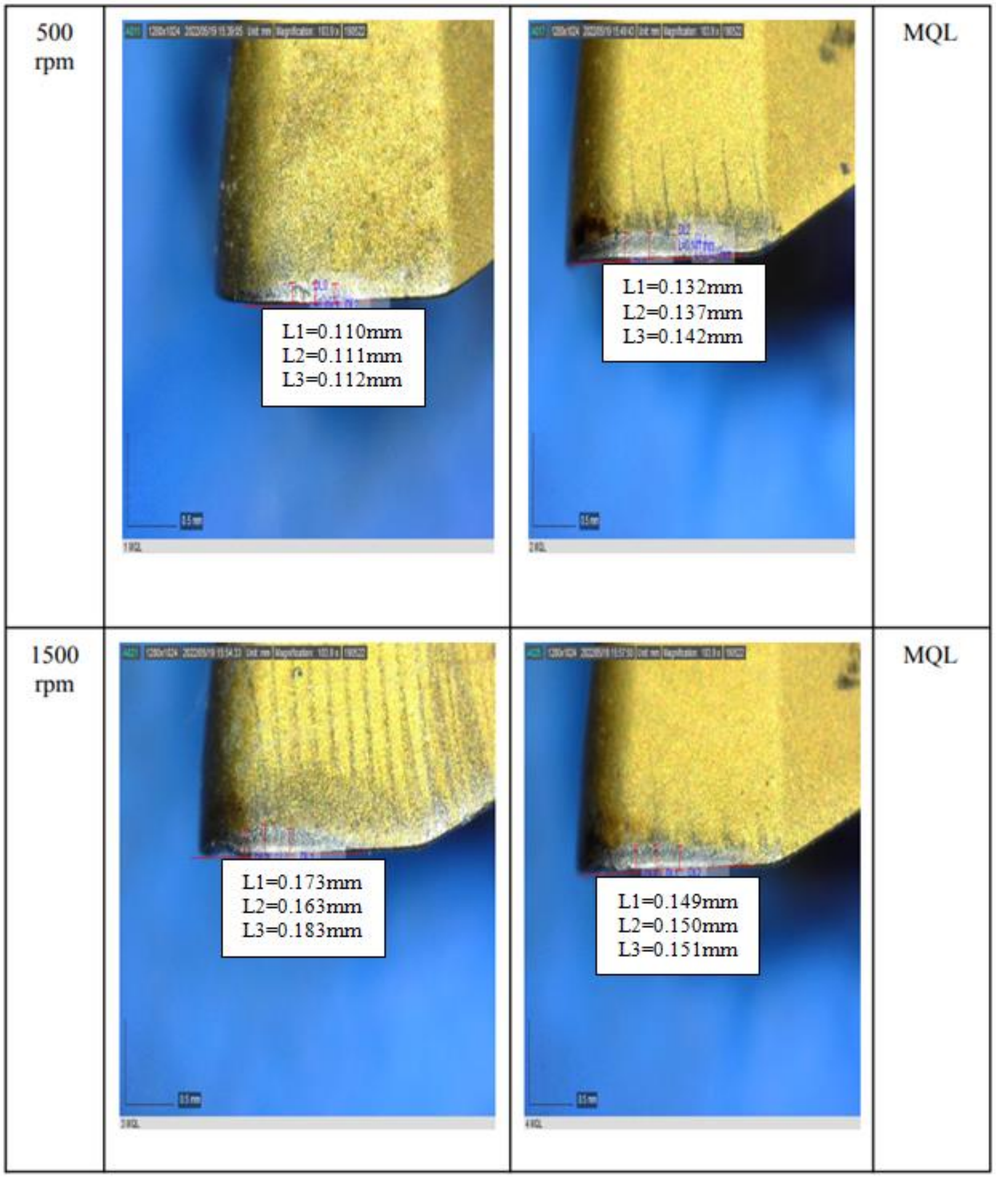


Figure 7: Tools Condition for minimum and maximum wear for each condition; dry and MQL.

3.4 Analysis of Variance (ANOVA) and Optimization

An analysis was conducted using ANOVA to confirm the factor that affected most of the tool wear values. Table 5 illustrates the analysis of variance and SN ratio for the coated carbide tool wear. According to the results of the analysis, the most important factor that influences the tool wear value is spindle speed since it has the biggest contribution of 39.84% which is calculated from the sequential sums of squares. The second and third factors, which are depth of cut and feed per tooth, each contributed 37.14% and 23.02% to the final result. Next, by evaluating the signal to noise ratio of the response value, the most significant milling parameters that affect the tool wear value can be obtained. Table 6 shows that the 1st rank of the most important factor that affects the tool wear of coated carbide during the milling of titanium alloy is spindle speed. It was followed by depth of cut and feed per tooth. The reason is because the increase in spindle speed will increase the cutting force which causes the increase of vibration of the cutting tool and the workpiece. According to Yahya (2015), the increases in spindle speed or cutting speed will increase the cutting forces and also increase the tool wear.

Table 5: ANOVA Analysis for tool wear

Source	DF	Seq SS	Adj SS	Adj MS	F-Value	P-Value
Spindle speed	1	40.256	40.2565	40.2565	2.24	0.000
Feed rate	1	23.258	23.2579	23.2579	26.94	0.010
Depth of cut	1	37.522	37.5218	37.5218	137.00	0.004
Residual Error	0	0.09330	0.08340	0.02085		
Total	3	101.036				

Table 6: S/N Ratio for significant factors that affect the tool wear (Smaller is better).

Level	Spindle speed (rpm)	Feed rate (mm/tooth)	Depth of cut (mm)
1	16.36	15.60	10.13
2	10.02	10.78	16.25
Delta	6.34	4.82	66.13
Rank	1	3	2

Optimization of machining parameters for obtaining lower tool wear is analyzed by using Taguchi method. Figure 8 illustrates the main effect plot for S/N ratio in dry and MQL lubrication technique to obtain lower tool wear. Based on the figure, the optimum result can be obtained by using the spindle speed of 500 rpm, feed per tooth of 0.2 mm/tooth and 0.4 mm depth of cut. The optimum parameters can be obtained by using lower spindle speed and feed rate but higher in depth of cut. This is because the lower depth of cut has higher temperature at the cutting tool compared to the higher depth of cut. According to Agrawal et al. (2021) the lower depth of cut will produce higher cutting temperature compared to the higher depth of cut. The reason is because the rubbing action occurred at the lower depth of the cut. Therefore, the lower depth of cut produces greater wear at the cutting tool.

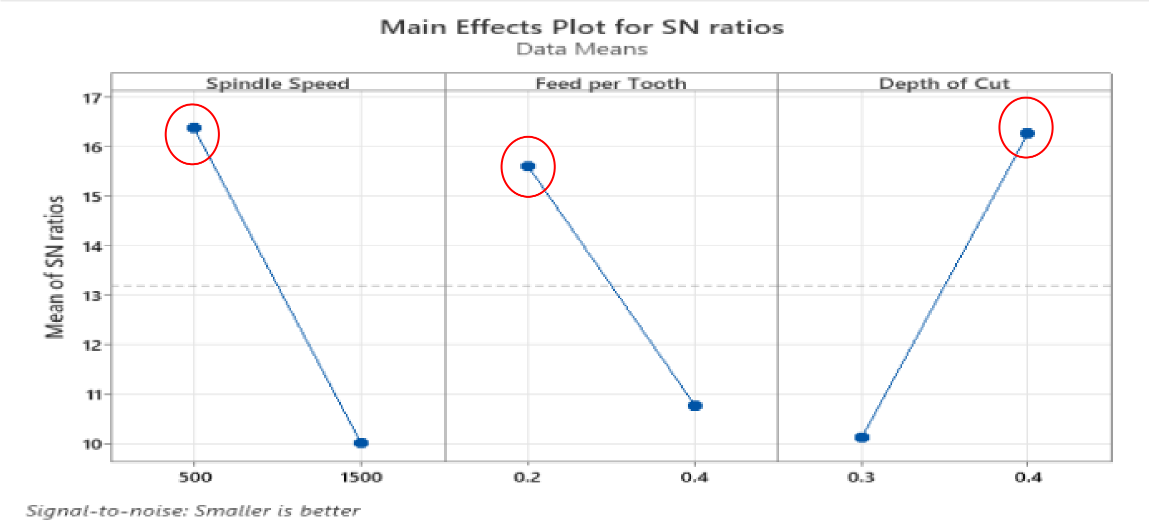


Figure 8: Main effects plot for S/N ratio – smaller is better.

3.4 Wear Mechanism during End Milling of Titanium Alloy

The abrasion wear was the most common tool wear in the milling of the titanium alloy in dry condition and using MQL. From Figure 9, it was observed that the abrasion is one of the main factors of the flank wear on the flank face of primary cutting edges of the cutting tool. The frictional force between the tool and the workpiece caused the abrasion wear. According to the previous research, Khatri (2021), found that most of the abrasion occurring in machining titanium alloy is due to the friction of the tool and work material and the wear increase when the chips involved in the workpiece-tool interference.

Furthermore, Figure 10 shows the adhesion wear is also observed at the cutting tools in the dry cutting condition. The adhesion wear occurs when the titanium alloy gets attached to the cutting tools. This has the potential to change the geometry of the cutting tool. As a result, if further machining is performed, the cutting tool may break or result in a poor surface finish. The adhesion wear mechanism is higher in the dry cutting condition compared to MQL.

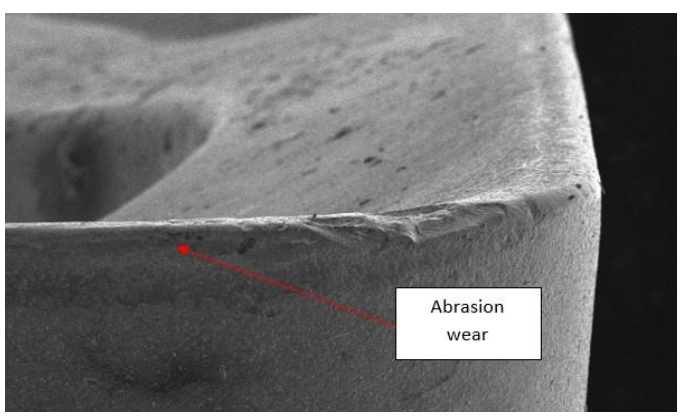


Figure 9: Abrasion wear for cutting parameter of 1500 rpm for spindle speed, 0.4 mm/tooth for feed rate and 0.3 mm for depth of cut in MQL.

This is because the friction between tool and workpiece did not dissipate quickly and caused the heat generated at the cutting tool. This finding is similar to the Khatri (2018) stating that the adhesion mostly occurred in the presence of the heat from machine with the higher feed rates or depth of cut. Therefore, the adhesion wear is common tool wear in milling the titanium alloy in the dry cutting condition. Figure 11 shows the energy dispersive x-ray spectroscopy (EDS) of the targeted analysis of sample surfaces for contaminant identification. The percentage of the contaminants that been found which are cobalt, titanium, aluminum, carbon and tungsten.

Additionally, Figure 12 shows the notch wear that was observed during the milling of titanium alloy in the dry condition with the spindle speed of 1500 rpm, feed rate of 0.4 mm/tooth and depth of cut of 0.3 mm. In this study, the notch wear only occurs in the dry machining. This is due to the temperature fluctuation or the thermal shock at the tool during the machining of titanium alloy. According to Jawaid (2020), the thermal shocks are the main reason for the formation of thermal cracks at the tool.

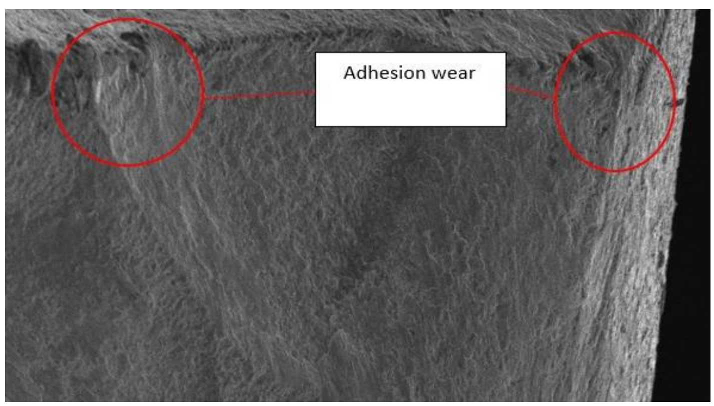
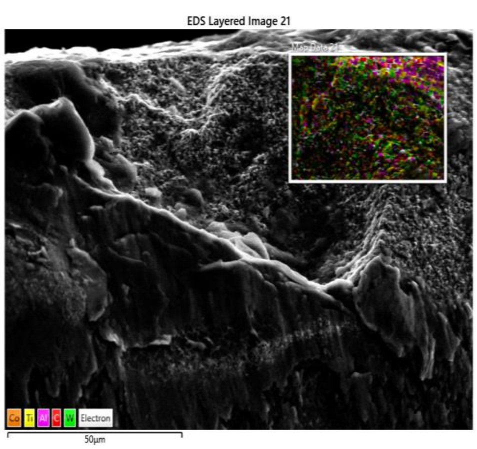


Figure 10: Adhesion wear for cutting parameter of1500 rpm for spindle speed, 0.4 mm/tooth for feed rate and 0.3 mm for depth of cut in dry condition.



Element	Weight %	σ
O	47.1	2.7
W	28.1	2.0
C	12.4	1.6
Ti	6.0	0.4
Co	4.9	0.5
Al	1.6	0.2

Figure 11: EDS on the surface of adhesion.

Moreover, the wear caused by chemical reaction between cutting tools and the workpiece material is also observed in experiments which is known as crater wear. Figure 13 shows the crater wear that occurred during the milling process. It was discovered on the tool's flank face, but it was very close to the primary cutting edge. The crater wear is uncommon in this study because the experimental trials were comparatively low. According to Olsen et. al, (2021), the crater wear is common wear in the machining of titanium and when the crater wear reaches a critical size, the further experimental trials could result in a fracture and tool failure.

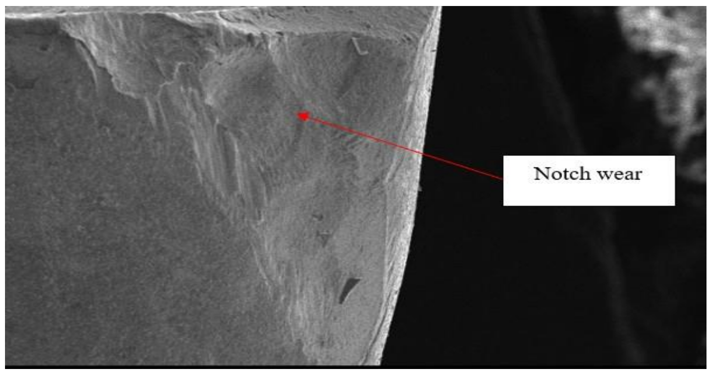


Figure 12: Notch wear for cutting parameter of 1500 rpm for spindle speed, 0.4 mm/tooth for feed rate and 0.3 mm for depth of cut in dry condition.

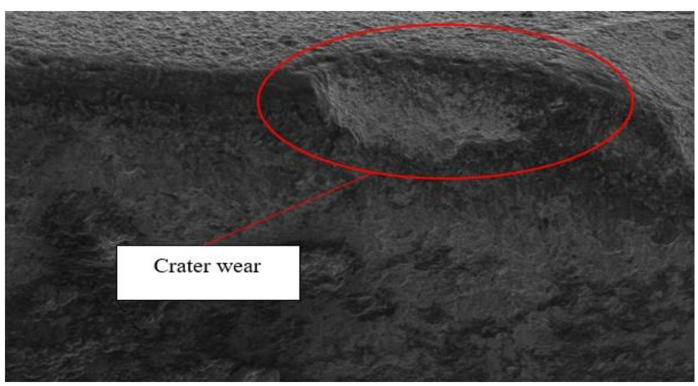


Figure 13: Crater wear for cutting parameter of 500 rpm for spindle speed, 0.2 mm/tooth for feed rate and 0.4 mm for depth of cut in dry condition.

CONCLUSIONS

This study discussed the tool wear and wear mechanism of coated carbide cutting tool during end milling of titanium alloy in two different conditions which are dry cutting condition and MQL. Based on the objectives of the study, it can be concluded as that:

Based on the result obtained by using a digital microscope, experiment with cutting parameter; 1500 rpm for spindle speed, 0.4 mm/tooth for feed rate and 0.3 mm for depth of cut recorded the higher tool wear compared to other experiment. It was recorded 0.825 mm for dry condition and 0.149 mm for MQL. In addition, the first experiment recorded the lowest tool wear compared to other experiments for both conditions; for dry (0.204 mm) and MQL (0.110 mm). The lower the tool wear, the higher the tool life. As the conclusion, spindle speed is the most significant factor that affected the tool wear followed by the depth of cut and feed rate.

From the experiment conducted, there are many types of wear mechanisms observed which are abrasion, adhesion, notch wear and crater wear. In this study, abrasion wear is the most dominant tool wear mechanism, followed by adhesion wear as the second most dominant wear. However, notch wear occurred only in the final stages of the dry machining experiment.

From main effects plot for S/N ratio; the 500 rpm for spindle speed, 0.2 mm/tooth for feed rate, and 0.4 mm for depth of cut shows the optimum results. From the SN ratio, it proves that using lower spindle speed and feed rate, but higher depth of cut is the best results.

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