Jurnal Tribologi 36 (2023) 99-107

MYTRIBOS
Malaysian Tribology Society

Jurnal Tribologi
Website : jurnaltribologi.mytribos.org e-issn: 2289-7232

Analysis on tool wear during milling carbon fiber reinforced polymer in dry, coolant and chilled air condition

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KEYWORDS

Tool wear
CFRP
Composite
Chilled air
Coolant
Dry

ABSTRACT

The demand of the Carbon Fiber Reinforced Polymer (CFRP) has been significantly increasing over the years especially in automotive and aerospace since CFRP possesses an excellent strength-to-weight ratio. However, milling CFRP challenging due to its anisotropic and heterogeneous property therefore produce brittle and dust-like chips. As CFRP is a combination of layers of carbon fibers embedded in matrix resin, machining process must be conducted below the glass transition temperature (Tg) of the matrix resin as it can degrade the CFRP. In this experiment to investigate the effect of cutting speed and cutting conditions on the tool wear during the milling process, CFRP was machined with 6mm diameter uncoated tungsten carbide tool with helix angle of 30°. Milling of CFRP was performed with three cutting speeds of 130, 150 and 170 m/min in three different cutting conditions which is dry, coolant and chilled air with constant feed rate of 2100 mm/min and depth of cut of 2 mm. The highest average tool wear of 110 μm was obtained during milling the CFRP with cutting speed 170 m/min in chilled air condition, 25.5% higher than the average wear of 82 μm at low cutting speed of 130 m/min in the same condition.

Received 2 March 2022; received in revised form 22 July 2022; accepted 14 September 2022.
To cite this article: Abd Halim et al. (2023). Analysis on tool wear during milling carbon fiber reinforced polymer in dry, coolant and chilled air condition. Jurnal Tribologi 36, pp.99-107.

1.0 INTRODUCTION

Composite material specifically carbon fiber reinforced polymer or CFRP has been increasingly demanded over the years especially in heavy industries such as automotive, aerospace and architecture. Possessing desirable properties such as excellent strength-to-weight ratio, high stiffness, excellent wear and corrosion resistance has made CFRP superior compared to metallic materials. Majority body parts of Boeing 787 such as the fuselage and wings, are made from composites therefore proven in improving the weight of the aircraft thus reducing the fuel consumption(Karataş and Gökkaya, 2018). Besides, CFRP is desirable since it can be manufactured nearest to its final shape hence minimizing the production cost and time. However, in most cases, machining processes for hole making and final product accuracy such as drilling, and milling are still required to conform to the final product specifications. Due to the physical and mechanical properties characteristic of carbon fiber and matric resin that consist in CFRP, it exhibits an anisotropic and heterogeneous behavior. Therefore, these characteristics could result in rapid tool wear, poor surface roughness and surface damage after machining. Unlike plastic deformation that occurs in metal cutting, CFRP undergoes brittle fracture of the carbon fiber that produce series of dust-like chips. Therefore, the amount of heat that removed is very minimal as compared with metal cutting during machining process. In addition, selection of cutting parameters during machining such as cutting speed, feed rate, depth of cut and cutting conditions are crucial. It is essential to machine below the Tg of the matrix resin since higher cutting temperature generated will softens the matrix resin thus degrading the mechanical and physical properties of CFRP (Huda et al., 2016). It was observed that when the cutting temperature is near to the glass transitions temperature of the matrix resin, the degraded matrix resin and smeared matrix was found on the cutting tool and the machined surface (Halim et al., 2017; Shahruddin et al. , 2021). The assistance of coolant during the machining has been a common practice in reducing the high cutting temperature caused especially in metal cutting (Ozkan et al., 2019). However, in composite machining especially when dealing with polymeric resin, the absorption of moisture can degrade the bond between the carbon fiber and the matrix resin. Alternatively, cooling technique such as the application of chilled air aided in reducing the cutting temperature hence improving the tool life of the cutting tool. Numerous research have been carried out in investigating the effect of cutting parameters and cutting condition during milling of CFRP since selection and combination of the cutting parameters are very vital. Chen et al., (2018) found that at higher cutting speed of 200 m/min resulted the highest flank wear of 48.81μm, whereas 34.15 μm flank wear was observed when milling with 50 m/min. They claimed that cutting edge radius of the cutting tool reduced due to the carbon chip that scratched and grounded the tool flank surface. However, Ozkan et al. (2019) reported that higher cutting speed of 300 m/min produced lower tool wear (83.7 μm) as compared with lower cutting speed of 100 m/min (143.3 μm) when milling CFRP in a dry condition. They claimed that at lower cutting speed, higher contact time produced between the cutting edges and CFRP thus generate more friction. Also, Elgnemi et al. (2017) found that milling CFRP at 20000 rev/min in vegetable oil produced the lowest tool nose wear area of 1.7 μm^2 while the highest tool nose wear area of 3.4 μm^2 achieved in dry condition. This is attributed from the presence of the oil provided lubrication at the cutting edge therefore reducing the friction during the milling process. Jiaying et al. (2020) discovered a similar case where average flank wear of 80 μm during milling in lubrication is lower than the 110 μm in dry condition using helical milling CFRP/Ti-6Al-4V. However, milling in cryogenic condition resulted in highest flank wear of 140 μm where they claimed that adhesion and breakage at the cutting edge was caused by the high cutting forces.

Therefore, the purpose of this study is to observe how the cutting speeds and cutting conditions affect the tool wear of the uncoated tungsten carbide during end milling CFRP.

2.0 EXPERIMENTAL PROCEDURE

To perform all the milling experimental runs, Mazak Nexus 410A-II Vertical Machining Centre was employed. 6mm diameter uncoated tungsten carbide (WC-Co) tool with 30º helix angle as shown in Figure 1 was utilized for each cutting speed and condition. Carbon fiber reinforced polymer (CFRP) was selected as main work pieces in this study. The properties of the CFRP are tabulated as in Table 1. The CFRP panel with dimension 200 mm x 200 mm x 5 mm and strips of 200 mm x 50 mm x 5 mm have been clamped separately on the machine table as shown in Figure 2(a). The panel and strips were utilized for progression of tool wear and surface roughness measurement, respectively. The milling of the CFRP was conducted with three different cutting speeds in three different cutting conditions as tabulated in Table 2. The Vortec Cold Air Gun in Figure 2(b) with 6.9 bar pressure and -9.0 °C cooling temperature was employed for chilled air condition. The nozzle was located 10 mm from the cutting tool throughout the experiment to maintain the consistency of the cooling effect. Water based coolant type X-Ten C82 supplied by Belling was employed for milling in coolant condition.

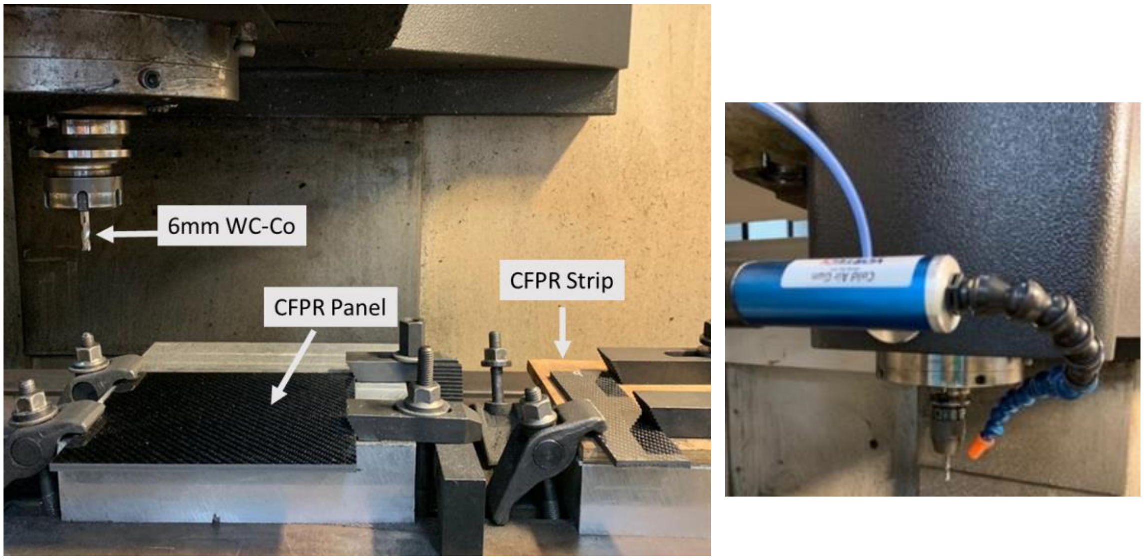
Table 1 : CFRP material properties.

Parameters	Value
Resin type	Epoxy
Density, g/cm^3	1.6
Compressive strength, MPa	570
Maximum operating temperature, ^{o}C	80
Fiber volume fraction, %	50

Figure 1: 6 mm tungsten carbide end mill tool supplied by Precisetech.

Table 2: Overall cutting parameters during milling CFRP.

Parameter	Value
Cutting speed, V	170, 150 and 130 m/min
Radial depth of cut, a	2 mm
Feed rate , f	2100 mm/min
Machining environments	Dry, coolant and chilled air



(a) (b)

Figure 2: (a) Experimental setup for milling of CFRP with a variation of cutting speeds and cutting conditions and (b) set-up for milling CFRP in chilled air.

Dino-Lite Premier optical microscope connected to personal computer equipped with DinoCapture 2.0 software was employed to measure and record the progress of the tool wear. The tool wear was measured at every of 600 mm machining distance until it reached 6000 mm machining distance. The average tool wear was measured from each flute of the cutting tool. To quantify the average tool wear, the difference between the original length and the worn-out edges of the cutting tool after every round of machining was calculated. Jeol JSM-5600 Schottky Field Emission scanning electron microscope was employed to study the wear mechanism of the cutting tool and further analyzed using EDX analysis.

3.0 RESULTS AND DISCUSSION

3.1 The Effect of Cutting Speeds on Tool Wear

Figure 3 shows the progression of tool wear in milling of CFRP with three different cutting speeds, 130, 150 and 170 m/min in three different cutting conditions which is dry, coolant and chilled air. It can be observed after 600 mm machining length; the wear is significant before gradually increases along the machining length until 6000 mm machining length for every cutting speeds in three cutting conditions. During milling in dry condition as in Figure 3(a), it was observed that after milling 6000 mm, the highest wear (90 µm) was obtained by the lowest cutting speed of 130 m/min, whereas lower wear was observed when milling with highest cutting speed of 170m/min (83 µm). When milling with higher cutting speed the heat generated is expected to degrades the strength of the matrix resin therefore aided the CFRP removal process, hence reducing the force needed in milling the CFRP (Ozkan et al., 2019). The slow traverse feed at low cutting speed increase the surface of contact between the grain of uncoated tungsten carbide and the abrasiveness of CFRP thus worn out the uncoated tungsten carbide rapidly(Rodriguez et al., 2019). In coolant condition, lower tool wear of 86 µm was observed when milling with cutting speed 170 m/min as compared with lower cutting speed of 130 m/min where 90 µm tool wear was measured as shown in Figure 3(b). This is due to the increasing of the surface contact from the slow traverse movement of the cutting tool along the machining length. The coolant that fully flooded the cutting zone helps in reducing the cutting temperature hence allowing the cutting tool to maintain its hardness. Nonetheless, it produces slightly higher or similar tool wear compared to dry condition due to the higher forced needed to remove the CFRP from the retained hardness of cutting tool (Helmy et al., 2018). Presence of coolant is expected to provide lubrication and reduced the amount of friction between the cutting edge and the working material (Elgnemi et al., 2017). However, similar case was observed with dry milling when milling with lower cutting speed of 130m/min where the low traverse movement of the cutting tool resulted to higher friction together with the high abrasion of the hard cutting tool and the abrasive CFRP fiber.

However, when milling in chilled air condition, higher tool wear of 110 µm was observed at high cutting speed of 170 m/min. It was 25.5% higher than the average wear of 82 µm obtained during milling at 130 m/min in the same cutting condition as shown in Figure 3(c). This is due to the increasing of friction by the presence of CFRP dust-like chips attached to the cutting edge which elevated the tool wear progress. The different of result between the two cooling methods can be clarified with the difference of cooling method between the coolant and chilled air during the machining process. Sufficient cutting fluid flooding the cutting zone provides maximum cooling effect on the cutting tool and efficiently removing the dust-like chips of the CFRP. However, employing the chilled air that focusing only on cooling the cutting tool insufficiently removing the heat at the cutting zone during the milling process. The chilled air allows the uncoated tungsten carbide to retain its hardness however offer less helps in reducing the high cutting temperature at the cutting zone. Unlike coolant, chilled air lacks in flushing the dust-like chips away therefore the fractured fiber add up to excessive friction between the cutting tool and the surface of the CFRP(Helmy et al., 2018).

The early phase of the tool wear is caused by the grinding between the improper fracture of the carbon fiber and the cutting edge of the fresh uncoated tungsten carbide (Chen et al., 2018). The abrasiveness of the CFRP further contributes to the gradual growth of the tool wear. Figures 4(i) and (ii) shows the significant wear of the cutting edges before and after milling the CFRP with cutting speed 150 m/min in dry condition for 6000 mm machining length process. This is because during milling at high cutting speed, the brittleness of the cutting edge is subjected to elevated temperature and stress (Danish et al., 2021). Besides the rounded of the cutting tool that leads to the progression of the tool wear shown in Figure 5(i), there is also evidence of chipping on the cutting edge as in Figure 5(ii) that contributes to the rapid progress of the tool wear. This is also caused by the elevated stress and force required especially during milling in chilled air condition (Jiaying et al., 2020). Chilled air has high thermal conductivity in dissipating the heat, thus allowing them to prolong the hardness of the cutting tool (Danish et al., 2021). However, as mentioned before, the presence of brittle CFRP dust-like chips causing additional friction between the cutting tool and the machined surface. Figure 6(i) shows that the pull out of the WC-Co grain from the cutting tool. This phenomenon occurs due to the binder that were gradually removed due to the continuous abrasion between the cutting tool and the CFRP (Shahruddin et al., 2021). This scenario is further confirmed with the Energy Dispersive X-Ray analysis on Figure 6(ii).

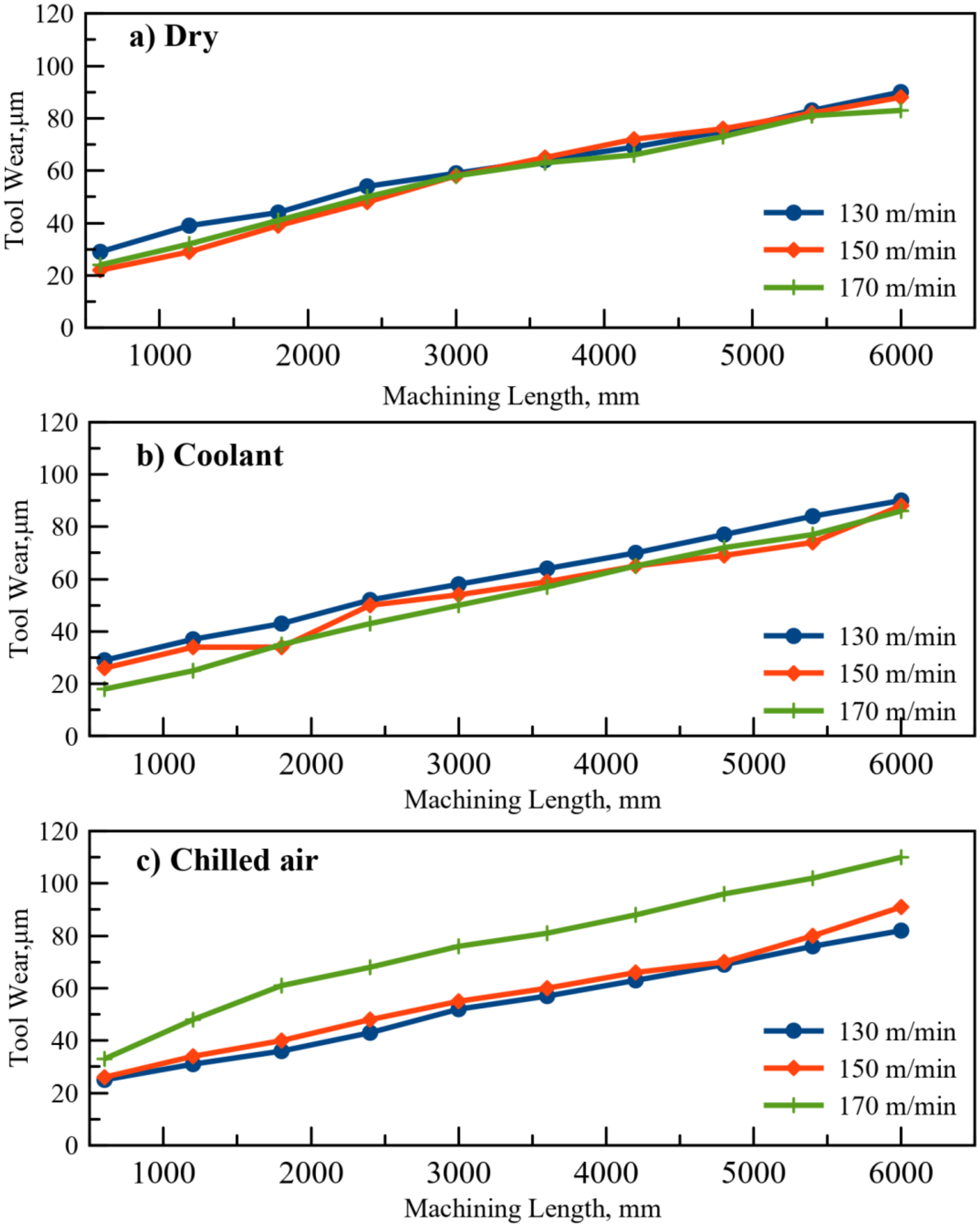


Figure 3: Progression of tool wear of uncoated tungsten carbide after 6000 mm machining length in (a) dry, (b) coolant and (c) chilled air cutting conditions.

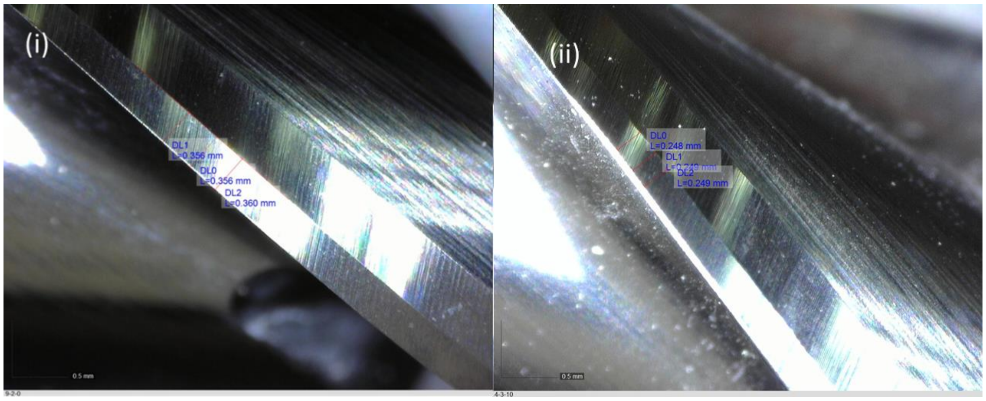


Figure 4: (i) Fresh cutting tool (ii) the flank wear after milling with 170 m/min for 6000 mm machining length in dry condition.

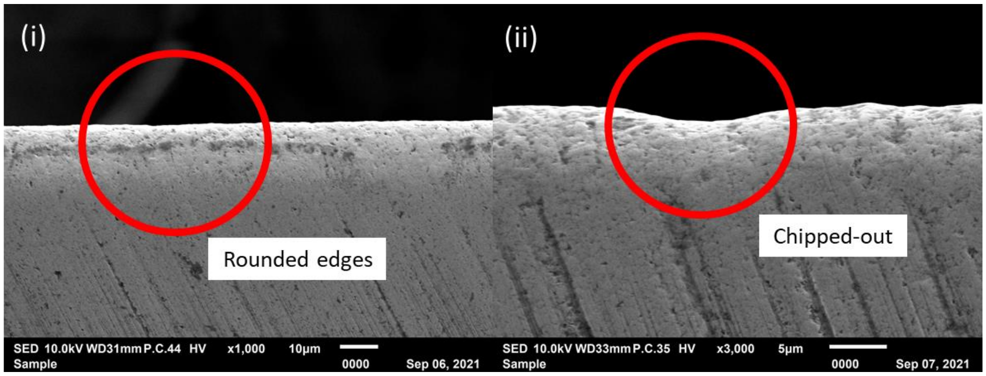


Figure 5: SEM image of (i) rounded edges of the cutting tool and (ii) the chipped-out of the cutting edges after milling with cutting speed 170 m/min in coolant condition for 6000 mm machining length.

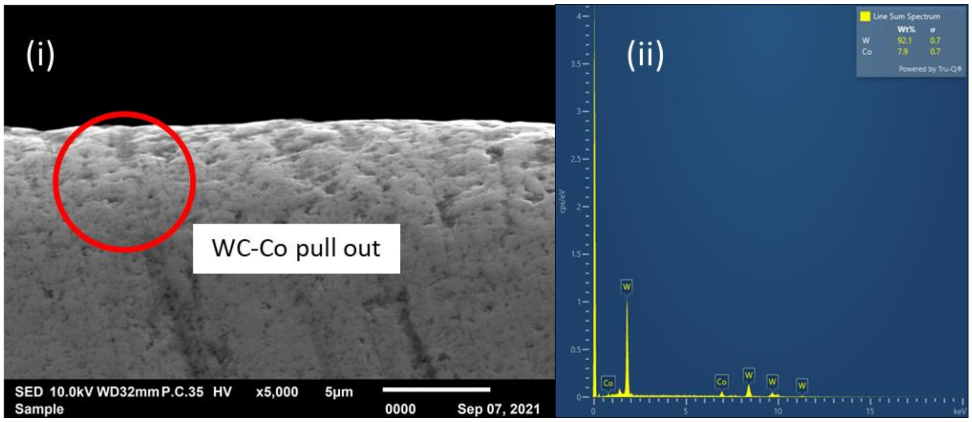


Figure 6: (i) SEM image of WC dislodged of the cutting tool and (ii) EDX analysis of the uncoated tungsten carbide tool when milling with 170 m/min in dry condition for 6000 mm machining length.

CONCLUSIONS

It can be concluded after milling the CFRP with uncoated tungsten carbide with three cutting speeds of 130, 150 and 170 m/min in three different cutting conditions, dry, coolant and chilled air.

(a) The highest tool wear (110 μm) was observed when milling with highest cutting speed of 170 m/min chilled air cutting condition.
(b) Milling CFRP in coolant condition produced the lowest differences of 4% average tool wear between the highest cutting speed 170 m/min and the lowest cutting speed 130 m/min compared to 7% and 25.5% during milling in dry and chilled air, respectively.
(c) Constant friction between the abrasive fiber of CFRP and the cutting edges contributes to the pull-out of the WC-Co grain of the uncoated tungsten carbide, chipping on the cutting edges and rounded of the cutting edge.

ACKNOWLEDGMENTS

The authors would like to acknowledge Ministry of Higher Education Malaysia and International Islamic University Malaysia under RMCG20-027-0027 and RACER/1/2019/TK02/UIAM//1 research grant for supporting this study.

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