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Effect of feed rate on tool wear and surface condition during milling of CFRP

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KEYWORDS

CFRP
Tool wear
Surface roughness
Tungsten carbide
Abrasive wear
Damage

ABSTRACT

Application of carbon fibre reinforced polymers (CFRP) is rapidly increasing for use in industrial applications such as in the aerospace and automotive industry. However, issues such as rapid tool wear during CFRP milling remain significant, due to the abrasiveness of the carbon fibre. Thus, this study was conducted to investigate the effect of feed rate (1250, 1500 and 2500 mm/min) on tool wear and surface conditions during milling operations. The cutting speed and depth of cut were kept constant during the milling test at 100m/min and 3 mm respectively. Milling of CFRP with an uncoated tungsten carbide end mill was carried out and the progression of tool wear was observed until a machining length of 6000 mm. It was observed that the lowest tool wear was achieved when employing the highest feed rate of 2500 mm/min. It was observed that all cutting tools experienced abrasive wear as it was observed that pull out of WC-Co occurred on the flank surface of the cutting tool. The abrasiveness of CFRP leads to the flank wear of the carbide cutting tool. Damages such as fibre pull out, delamination and matrix smearing were observed on the CFRP machined surface.

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1.0 INTRODUCTION

Apart from excellent its stiffness and mechanical properties, Carbon Fibre Reinforced Polymer (CFRP) is also widely known for its high resistance to corrosion and low thermal expansion. As CFRP possesses a desirable strength-to-weight ratio, it is widely implemented in the aircraft and aerospace industry, whereby it improves fuel consumption efficiency. Aside from aerospace, CFRP is also widely used in other fields such as construction, automotive, marine and sports.

CFRP is always manufactured near towards the net shape, therefore secondary machining processes such as milling, and drilling are required. However, in contrast to its exceptional and desirable mechanical properties, machining CFRP is a challenge due to its heterogeneous and anisotropic properties. These drawbacks induce damage to the cutting tool such as rapid tool wear and increasing the cutting temperature. Therefore, research on machining CFRP is very important to increase efficiency, and to reduce the damage during the machining operation of this material (Halim et al., 2017). It was reported that the increasing of cutting temperature during the machining of CFRP significantly affected the properties of the CFRP (Huda et al., 2016). Rapid tool wear commonly occurs during CFRP milling operations and is observed to be more visible compared to other materials due to the hardness and extremely abrasive nature of carbon. Mustafa et al. (2021) compared the effects of different cutting conditions and cutting speeds on the tool wear and it was observed that the tool wear condition was most severe when milling CFRP in a dry condition. Mustafa et al. (2022) also mentioned that increasing the cutting speed during milling of CFRP significantly increased the tool wear and shortened the tool life of the uncoated tungsten carbide end mill tool. Ozkan et al. (2019) also mentioned that the tool wear increased as the cutting speed increased, and they proposed that milling of CFRP should be carried out by employing high cutting speeds with low feed rates. Luiz Lara Oliveira et al. (2020) observed that increasing the cutting speed from 113 m/min to 221 m/min resulted in increasing of cutting temperatures. As a result, it was observed that the increasing of the cutting temperature significantly increased the tool wear of the cutting tool.

Similar results were also found across different feed directions that were manipulated in the experiments. Gao et al. (2016) noted that the level of tool wear is reflected by the cutting force, which increased as the cutting speed increased from 60m/min to 300 and 600m/min. Similar results were across different fibre orientations. At a fibre orientation of 45°, they found that the cutting forces produced were 3.25 N/mm, 4.50 N/mm, and 5.00 N/mm from the increment of each cutting speed. Chen et al. (2018) stated that based on their experiment, high-speed cutting produces high mechanical and thermal loads that affect the adhesion between the coating and substrate material of the diamond coated cutting tool. This causes the tool wear to increase as fractures and shedding of the coating occur significantly which further increases the radial and tangential cutting force. In contrast, Ozkan et al. (2019), and Elgnemi et al. (1996) who mentioned that tool wear increases as the feed rate increases due to the larger chip formations produced that resulted in increasing in the cutting force.

In term of surface conditions, Mustafa et al. (2022) also observed that when applying higher cutting speed of 132m/min the occurrences of voids on the machined surface were severe when compared with lower cutting speed (94m/min). The increasing of cutting speed could lead to the increasing of heat generated during machining that affect the machined surface. It was also recommended that to apply low cutting speed to produce better surface conditions. Huda et al. (2017) also observed that the thermally degraded resin was found on the machined surface after machined 10 meters when milling of CFRP with multifaceted diamond tool. Therefore, this research is intended to study the effect of increasing feed rates on tool wear during CFRP milling, as well as its effects on surface conditions in terms of roughness after machining.

2.0 EXPERIMENTAL PROCEDURE

Milling of the CFRP was conducted using the Mazak Nexus 410A-II Vertical Machining Centre. Multiple workpieces made from multidirectional CFRP in either strips or panel sizes were chosen for this study. The panel size was 200 mm x 200 mm x 3mm while the strip size was of 50mm x 200 mm x 3mm. The CFRP panel was machined to monitor the formation of tool wear of cutting tool while CFRP strips were used to observe the surface roughness of the composite during the machining process for each 1000 mm of machining length. The CFRP is comprised of fibres in a multidirectional orientation impregnated with epoxy resin which was supplied by PiCarbon Sdn Bhd. The CFRP workpiece specification was tabulated in Table 1. End mills from Precisetech Sdn Bhd, made from uncoated tungsten carbide with a diameter of 8 mm were used as main cutting tool throughout this study. The cutting tool was changed for each combination of cutting parameters. Table 2 details the specification of the cutting tool employed. Figure 1 shows the CFRP and cutting tool employed.

(a) (b)

Figure 1: a) CFRP plate and (b) The 8mm uncoated tungsten carbide tool.

Table 1: Specifications of CFRP workpiece.

Spec.	Density (g/cm^3)	Tensile strength (MPa)	Tensile modulus (GPa)	Fibre mass per unit area	Fabric type	Fibre volume fraction
Value	2.0	4000	430	281	ABR 1-0006	40/60

Table 2: Specifications of K3EPEN 080U tool supplied by Precisetech.

Spec.	Number of flutes	Tool diameter (mm)	Shank (mm)	Length of cutting (mm)	Helix angle
Value	Three	8	8	14	30°

The selection of cutting parameters is important as it has significant influence on the tool wear value outcome. In this experiment, the feed rate is the manipulating parameter in which three different feed rates were employed with a constant cutting speed and cutting condition. The values of cutting parameters that were used in this experiment were shown in Table 3. The Dino-Lite Premier optical microscope, which is equipped with digital imaging and measurement software, was used to capture and measure the progression of wear of the cutting tools after every 1000 mm distance travelled. The tool wear of a cutting tool for every 1000 mm machining length was taken based on the average tool wear value of each tool flute. Observations of the wear mechanism of cutting tool were carried out in higher magnifications by using the Scanning Electron Microscope (SEM) after cleaning the cutting tool. Surface roughness and conditions of the machined surface of CFRP were also observed using the Alicona SL 3D surface profiler. The values of the surface roughness were only taken at 1000, 4000 and 6000 machining length to observe the progression of roughness and the effect of tool wear on the surface conditions.

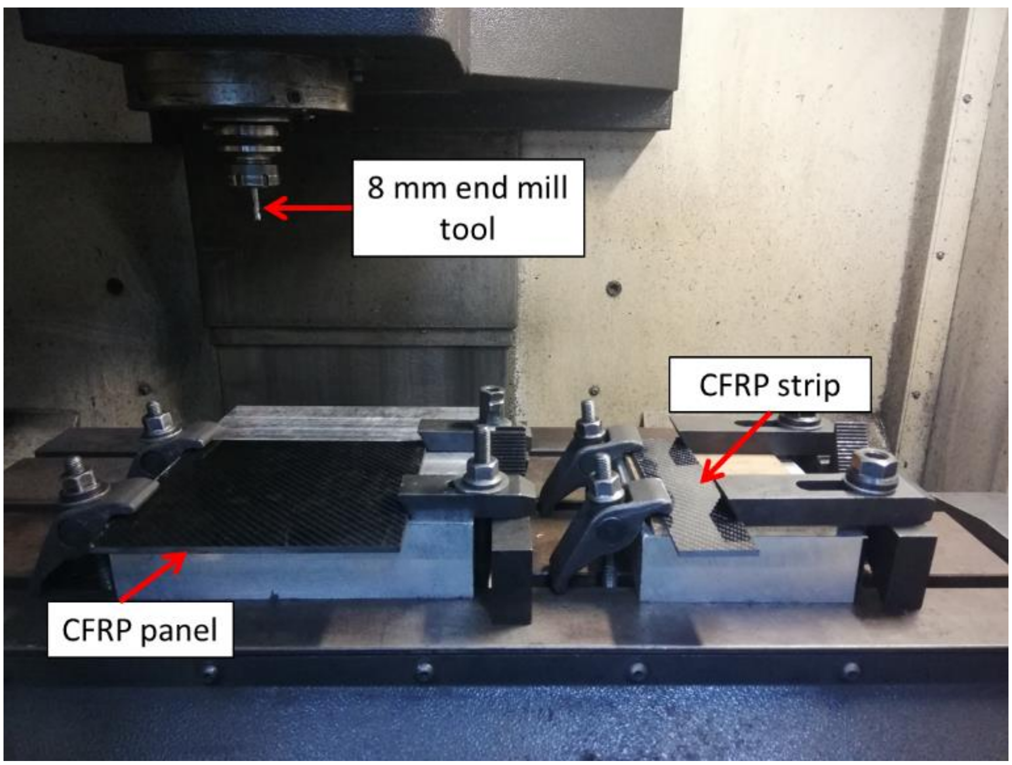


Figure 2: Overall experimental set up for milling of CFRP using Mazak CNC machine.

Table 3: Cutting parameters for the experiment.

Parameter	Cutting speed (m/min)	Feed rate, f (mm/min)	Radial depth of cut (mm)	Cutting condition
Value	100	1250,1875,2500	3	Dry

3.0 RESULTS AND DISCUSSION

Figure 3 shows the progression of the tool wear when milling at feed rates of 1250, 1875 and 2500 mm/min over a machining length of 6000 mm. It was observed that the tool wear of the cutting tool increased as the machining length increased, tool wear also increased as the feed rate decreased. After 6000 mm machining length, it was measured that the tool wear for feed rates of 2500 mm/min, 1875 mm/min and 1250 mm/m were 0.064 mm, 0.118 mm, and 0.110 mm respectively. As a comparison, the tool wear at the feed rate of 2500 mm/min was approximately 45% lower than at the feed rates of 1875 mm/min and 1250 mm/min. It was expected that when applying higher feed rate, the heat generated due to the friction between the tool and the workpiece increases, thus increasing the cutting temperature (Kumar, D., & Gururaja, S., 2020). It was suspected that when applying 2500mm/min feed rate, the heat generated during milling softens the matrix materials, thus aiding the materials removal process, resulting in lower tool wear as compared with the lower feed rates of 1250 and 1875 mm/min.

Figure 5 shows the images of the cutting tools observed in SEM. It was observed that all cutting tools experienced edge rounding regardless of the value of the feed rate employed. This can be explained due to the rubbing and scratching of the carbon fibres which are harder and highly abrasive compared to the tungsten carbide. The harder material scratches and removes some particles of the carbide tool which produces voids, edge rounding, and particle removal. The thermal properties of the cutting tool material also have a significant factor in the abrasion mechanism. However, in this case, the CFRP was more influenced by the cutting temperature as the resin matrix has a relatively low glass-transition temperature T_g. The higher the cutting temperature as it nears the T_g, the more surface failures occur during the machining process such as delamination and fibre pull-outs. These factors increase the effect of abrasion as more delaminated and detached carbon fibres can worsen the rubbing and sliding between the carbon fibres and the tool edge. Therefore, the cutting tool is more likely to has defects such as edge rounding and voids (Helmy et al. ,2018; Kalpakjian, 2001). The images from the SEM prove the abrasive nature of CFRP as the occurrence of abrasive wear can be observed during CFRP machining which is concentrated at the flank face of the cutting tool. The brittle and hard carbon fibres further cause edge rounding on the cutting edge which is observed to be more apparent and severe at higher feed rates. The cobalt (Co) binder was observed to have been removed from the cutting tool surface due to machining process.

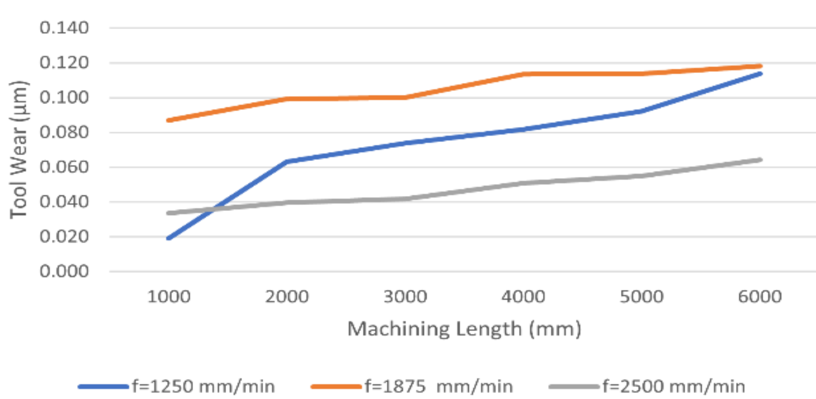


Figure 3: Progression of tool wear when milling with different feed rates over a length of 6000 mm.

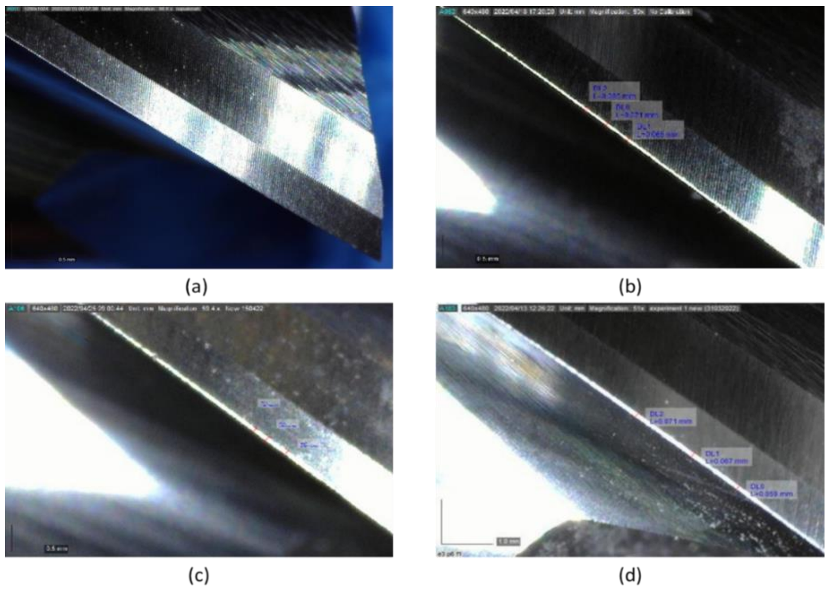


Figure 4: (a) Dino-Lite image of fresh tool, Dino-Lite wear images of carbide tools after 6000 mm of travelled distance with feed rates (b) 1250 mm/min (c) 1875 mm/min (d) 2500 mm/min.

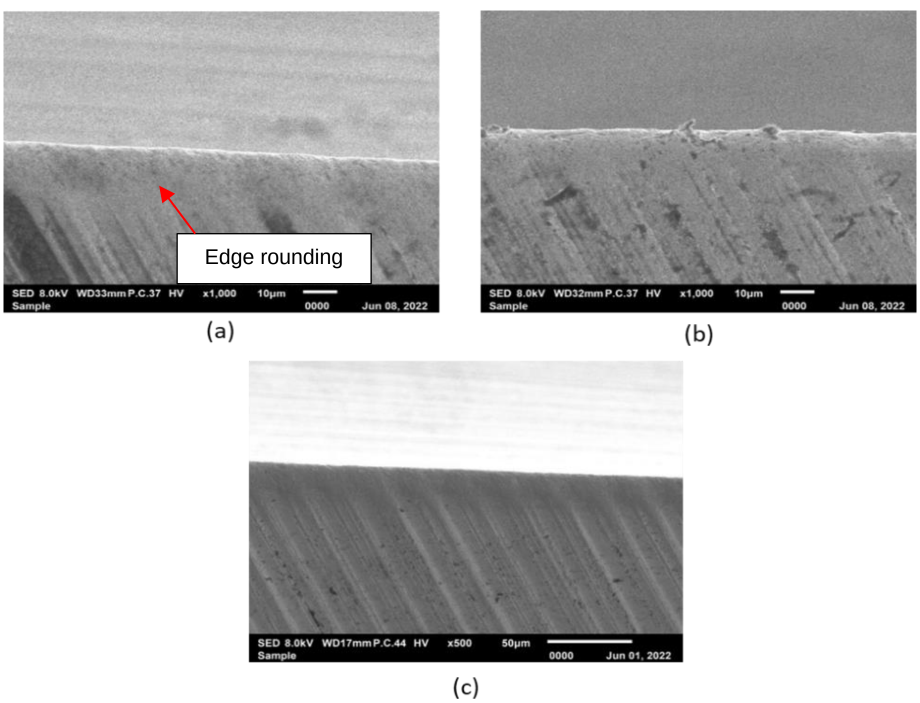


Figure 5: SEM images of three different carbide tools after milling of CFRP at 6000 mm of machining length at feed rates (a) 1250 mm/min (b) 1875 mm/min (c) 2500 mm/min.

Figure 6 shows the average surface roughness, R_a of the machined surfaces of CFRP after machining at 1000 mm, 4000 mm, and 6000mm length. In contrast with the tool wear observed, the R_a value increased as the feed rate. The R_a value for the highest feed rate of 2500 mm/min was 10-15% higher when compared to the lower feed rates of 1250 and 1875 mm/min. At 6000 mm of machining length, the R_a observed for the feed rate of 2500mm/min was 2.245 μm, while feed rates of 1250 mm/min and 1875 mm/min had 1.604 μm and 1.943 μm respectively.

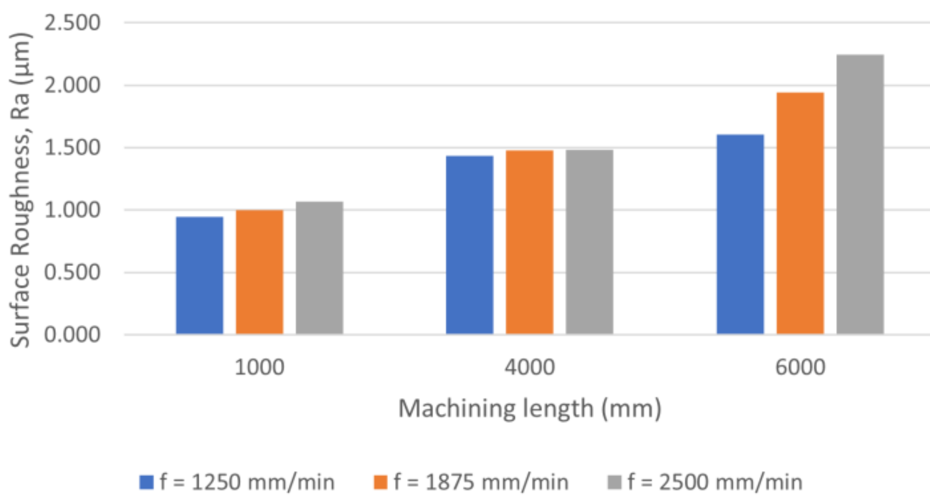
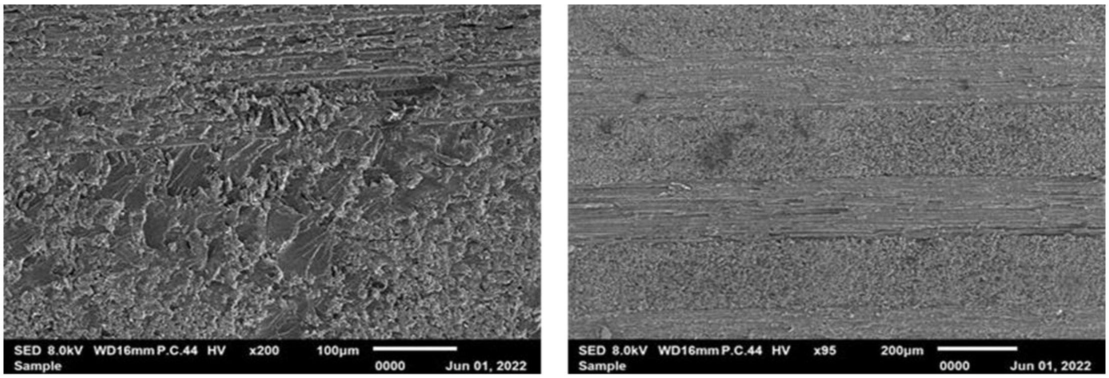


Figure 6: Graph of surface roughness vs machining length at different feed rates.

Similar observations were reported by Ozkan et al., (2019) in which they also found that increasing the feed rate significantly affects the surface conditions. Jamwal et al. (2021) mentioned that when the feed rate increased, the amount of chip formations increased, thus resulting in increasing of the friction and heat generated between the cutting tool and the CFRP workpiece. The increased in the temperature is due to the heat energy generated from the friction and causes the polymer resin to degrade and delaminate as well as various kinds of surface damages such as fibre pullouts, matrix degradation, and thermal degradation, as the temperature approaches the glass-transition temperature T_g (Halim et al., 2017). Surface damage also contributes to the increase in tool wear due to the detached fibres scratch and slid on the surface of the cutting tool. Although the result obtained for tool wear shows that at a higher feed rate (2500 mm/min), the tool wear was less when compared to the tool wear for lower feed rates (1250 and 1875 mm/min), it was surmised that at the feed rate of 2500 mm/min, the heat generated was increased due to the friction between the cutting tool and the materials (Sheikh-Ahmad et al. 2019). Therefore, the increasing of heat generated softens the epoxy matrix material, thus aiding in the machining process. However, softening of the matrix materials resulted in deterioration of the surface roughness and severity of the surface damages. Figure 7 shows the occurrences of the damages such as fibre pull out, delamination, matrix smearing as well as the void formations that contributed to the decreasing of the surface roughness at the feed rate of 2500mm/min.



(a) (b)

Figure 7: (a)Matrix smearing occurrence indicates the heat generated had softened the matrix resin and b) the fibre breakages and void formations were observed on the machining surface. Both SEM images were taken when milling at a feed rate of 2500 mm/min and for a machining length of 6000 mm.

CONCLUSIONS

Based on the analysis of tool wear during the milling of CFRP composites with varied feed rates of 1250 mm/min, 1875 mm/min, and 2500 mm/min, at a constant cutting speed of 100 m/min in dry condition, conclusions can be made from this experiment:

1. The feed rate has a great influence on the tool wear of carbide tool and surface roughness during the end milling operation of CFRP. Increasing the feed rate was expected to increase the heat generated during milling of CFRP subsequently aiding in the removal of the materials. However, increasing the heat generated during milling affects the surface conditions.
2. The average surface roughness, R_a measured for the higher feed rate of 2500mm/min was 10-15% lower when compared with the lower feed rates of 1250 and 1875 mm/min.
3. Matrix smearing, fibre pull out as well as degradation of the matrix resin were observed on the CFRP machined surface as the feed rate increased.
4. Abrasive wear was the main wear mechanism observed on the cutting tool. It was also observed that the cutting edges experienced edge rounding and the removal of the carbide binder on the cutting edge.
5. Although the tool wear does not reach 0.3 Vbmax, it was found that thermally degraded resin on the machined surface. It indicates that although the tool wear was not severe, increasing of the feed rate deteriorates the machined surface condition.

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