An experimental study of tool wear during end milling of carbon fibre reinforced polymer in cutting fluid condition.

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Abstract. Carbon fibre reinforced polymer (CFRP) is replacing metallic components and become a valuable material that has been used in many industrial applications including biomedical, marine and automobile. This is due to their excellent performance in term of reliability, high strength and light weight. However, the machining of CFRP is challenging because the abrasiveness of their reinforcement component often resulted in high tool wear rate. This experiment was carried out to investigate the effect of cutting parameters (cutting speed and cutting condition) on tool wear of uncoated tungsten carbide end mill tool, and to observe the wear mechanism of the carbide tool mill during milling of CFRP. In this study, machining test was carried out with the presence of coolant to aid in removing the cutting heat during machining. The effect of cutting speed of 132 m/min, 151 m/min and 170 m/min with a constant feed rate of 2100 mm/min during milling process of CFRP by using uncoated tungsten carbide end mill tool were discussed. Based on the result obtained, it was found out that the value of tool wear at cutting speed of 170 m/min is higher compared to the wear value at cutting speed of 132 m/min due to the high frequency friction of tool against machined surface. Analysis of tool wear using Scanning Electron Microscope (SEM) found out that the primary wear observed is abrasive wear due to the rubbing action between the tool and the surface of workpiece. The cutting tool is observed to have the lowest tool wear when low cutting speed is implemented along with the presence of coolant.

Keywords — CFRP, tool wear, uncoated tungsten carbide tool (WC), milling

1. Introduction
In this recent years, application of carbon fibre reinforced polymer (CFRP) has been increasingly applied in wide range field especially in aerospace, transportation, and construction industries [1]. The interest toward this composite increases due to its excellent mechanical properties, high strength and stiffness, good dimensional stability with moderate cost offered [2]. Due their high strength and stiffness, CFRP involves in 53% of Airbus 350 aircraft main component such as door, wings, fuselage, and tall cone. Other than these mechanical properties of CFRP, the high load bearing capacity of this composite allow plane to have more passengers, fly further with less fuel burn [3]. The rigid bond of matrix and its reinforcement allow the effective load transfer from the matrix to the reinforcement of fibres uniformly [4]. The reliability of CFRP make these materials as an ideal replacement with other industrial product.
Although CFRP are manufactured near to net shape, secondary machining process such as milling are still needed specially to remove the excessive materials in surface machining [1-3]. It is considered as a corrective operation to produce well defined and high-quality surfaces that being one of deciding factor in evaluating the machinability of CFRP [5].

However, anisotropic of CFRP and it non-homogenous in nature becomes challenges in machining. Abrasiveness of CFRP create difficulties to be machined without producing problems such as rapid tool wear, fibre delamination, high cutting force, high surface roughness, fibre and matrix pull out, smearing and matrix cracking that always found during milling CFRP[6]. Thus, right selection of tool material is crucial when machining CFRP under unconventional machining due to the highly abrasive nature of CFRP and its non-homogenous properties [7]. It is recommended that that the cutting tool must have enough hardness and strength, toughness and wear resistance to produce good quality and economical parts[8]. Rapid tool wear that resulted in excessive cutting force and poor surface roughness are some of the problems during milling CFRP. Cutting parameters such as cutting speed, feed rate and depth of cut are significant in influence surface quality of the FRP and the tool wear value [9-10]. The presence of tool wear will lead to reduction in cutting edge strength, degradation of surface finish, increasing of cutting temperature and affect the surface roughness. Therefore, the formation of tool wear should be minimized and control. The cutting condition during milling process is very important as it will also affect the surface finish of the CFRP and the tool wear. Heat that generated during machining, cause acceleration of cutting forces and reduce tool life which more likely produce poor surface roughness with defects on the machine surface can be reduce with presence of coolant [7].

2. Methodology and Experimental Setup

The end milling of carbon fibre reinforced polymer (CFRP) was performed using Mazak Nexus 410A-II Vertical Machining Center using 6 mm diameter of uncoated tungsten carbide (WC-Co) with 3 flute square end mill tool as shown in figure 1. Multidirectional CFRP impregnated with epoxy resin was chosen as a main workpiece in this study. 200 mm x 200 mm x 5 mm plate of CFRP was used in this study to monitor the progression of tool wear. Figure 2 shows the experimental setup for this study where the CFRP workpiece was located on the machine table using a special fixture. Three different cutting speed were employed in this study with a constant value of feed rate and the presence of cutting fluid for each milling process as tabulated in table 1.

![Figure 1. The 6mm uncoated tungsten carbide tool.](image-url)
In every 600mm distance traveled, progression of tool wear was measured using Dino-Lite Premier optical microscope which provided digital imaging and measurement software to be connected to personal computer. Average of tool wear value was calculated based on measured data from each flute on that machining length. Scanning Electron Microscope (SEM) used for observation on wear mechanism of cutting tool after the machining done in higher magnification. Cutting tools were cleaned first before being used for observation using both microscopes.

3. Result and Discussion

3.1 The effect of cutting speed on tool wear with presence of cutting fluid.

One of the main concerns in machining CFRP is the occurrence of tool wear due to the properties exhibit by the CFRP. The highly abrasive nature of carbon in the CFRP leads to the abrasion on the tool and workpiece during machining. Figure 3 shows the graph of tool wear against machined length when end milling CFRP in coolant condition measured at every 600 mm machining distance.
Figure 3 shows that the tool wear of the cutting tool increases as the machining length increases for all cutting speed. The pattern of tool wear value increase at a similar rate during the beginning of milling process. At the end of the machining, it was observed that the highest tool wear of 0.094 mm was recorded at 170 m/min cutting speed, whereas lowest tool wear of 0.074 mm was observed at low cutting speed at 132 m/min. It is expected that as the cutting speed increased, heat generated between the cutting tool and the workpiece increased, thus resulted in increasing of the tool wear at higher cutting speed. Furthermore, it is proposed that the increasing of cutting speed resulted in increasing of frequency of the friction that lead to the increasing of tool wear and reducing the sharpness of the cutting tool. This finding is similar to Turrillo [11] where he reported that the amount of wear increased with increasing of cutting speed over cutting distances due to high cutting temperature produced that beyond the glass transition temperature, accelerating cutting forces thus increase the tool wear. Ozkan et al. [12] also reported the same justification in their report where the tool wear values obtained with different cutting speeds indicate that, the lowest tool wear value occurred at the lowest cutting speed and the wear value increasing with increasing cutting speed.

The progression of the tool wear in this experiment can be divided into three stages based on tool wear average values measured. The early stage of wear was occurred within first 600 mm of machining length at all cutting speeds caused by initial breakdown of the sharp corners and weak spots of cutting edge. The second stage started after the 600 mm machined distance where the cutting edge started stabilized and the wear was a gradual removal of tool material until the cutting-edge geometry becomes dysfunctional. The stage 2 for cutting speed 132 m/min, 151 m/min and 170 m/min end at the machined distances of 3600 mm, 2400 mm, and 2400 mm, respectively. The stage 3 of tool wear formation occurred at uniform rate for every cutting speeds. The tool wear value of cutting tool of speed 151 m/min is the highest at the early stage of machining in compared to the tool wear value from the cutting tool of speed 170 m/min and cutting speed of 132 m/min due to the initial breakdown of the sharp corners and weak spots of cutting edges. The value of tool wear of the cutting tool with speed 170 m/min started increase after the machined length of 2400 mm and surpassed the tool wear value of cutting tool with speed of 151 m/min and 132 m/min at the machined length of 3600 mm with value of 0.066 mm. The value of the tool wear started increasing for the highest cutting speed due to the cutting heat produced along with the high gradual friction of tool.
3.2 *Observation of tool wear mechanism on SEM*

Figure 4 shows SEM images for fresh cutting tool whereas, Figure 5 (a), (b) and (c), the tool wear images on cutting tool with cutting speed of 132 m/min, 151 m/min and 170 m/min, respectively.

![Figure 4. SEM image of fresh cutting tool edge before undergo machining was performed.](image)

![Figure 5. SEM images of cutting tool edge with different cutting speeds.](image)
Figure 5. SEM images of 2 different cutting edges of cutting tool after 6000 mm machining length of milling CFRP with cutting speed of (a) 132 m/min, (b) 151 m/min and (c) 170 m/min.

Figure 5(a) shows the abrasion wear and flank wear on the edges of the cutting tool with speed of 132 m/min during milling with the presence of coolant. It was observed that similar observations were found on all SEM images of cutting tool regardless the cutting speeds. The flank wear, which is a result of abrasive wear occurred in all images of cutting tool taken from the SEM. The abrasive wear can be clearly seen in all images. Dislodged of WC particle occurred along with abrasion wear. Dislodged of WC particle happened when the binder phase was partly removed from between tungsten carbide grain by combination of plastic deformation and micro-abrasion. When sufficient binder had been removed, it involved the removal of carbide grain from surface by uprooting of WC particle. The flank wear was not uniform along the cutting edge and the visible waviness was due to the difference characteristics of the fibre and polymer phases in different plies as observed in figure 5(a) and (b). Figure 5(c) shows the rounding edge due to the gradual abrasion of control surfaces forming at the cutting edge. It can be seen that the wear of tool with cutting speed of 170 m/min worse than tool wear with cutting speed of 132 m/min and 151 m/min. It is expected that milling CFRP at high cutting speed generated high cutting temperature that resulted in the deterioration of the tool and the surface wear on the CFRP. It was observed that the broken fibre and thermally degraded matrix resin were adhered on the edge of the cutting tool as shown in figure 5(c), whereas the similar observation was not found on cutting tool when machining with lower cutting speed as in Figure 5(a) and 5(b). High cutting speed generated highest friction between the workpiece and tool even with the presence of cutting fluid.

4. Conclusion

Based on the observation through the machining process of carbon fibre reinforced polymers by using uncoated tungsten carbide, WC-Co cutting tools with the present of cutting fluid, three different cutting speed (170 m/min, 151 m/min and 132 m/min), constant rate (2100 mm/min) and depth of cut of 1 mm, there are several conclusions that can be made:

- The tool wear increased with the increased of cutting speed. High cutting speed of 170 m/min produced highest value of tool wear with the value of 0.090 mm in compared to the low cutting speed of 132 m/min that produced tool wear value of 0.074 mm. High cutting speed produced high friction on the interface between the tool and against the fibre of the CFRP that increased the tool wear value.
- The tool wear images from SEM of uncoated inserts showed that the abrasive characteristic of CFRP composite material resulted in flank wear on uncoated inserts. Failure such as dislodged of WC particle were resulted from the interaction between the rubbing action of tool and workpiece surface during milling process.

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References

[1] A. C. Ozkan, D., Gok, M. S. and Karaoglanli, “Carbon fiber reinforced polymer (CFRP) composite materials, their characteristic properties, industrial application areas and their machinability.,” in Engineering Design Applications III, 2020, pp. 235–253.

[2] Du J, Zhang H, Geng Y, Ming W, He W, Ma J, Cao Y, Li X and Liu K, “A review on machining of carbon fiber reinforced ceramic matrix composites,” Ceram. Int., vol. 45, no. 15, pp. 18155–18166, 2019, doi: 10.1016/j.ceramint.2019.06.112.

[3] N. F. H. A. Halim, H. Ascroft, and S. Barnes, “Analysis of Tool Wear, Cutting Force, Surface Roughness and Machining Temperature during Finishing Operation of Ultrasonic Assisted Milling (UAM) of Carbon Fibre Reinforced Plastic (CFRP),” Procedia Eng., vol. 184, pp. 185–191, 2017, doi: 10.1016/j.proeng.2017.04.084.

[4] Y. G. Wang, R. M., Zheng, S. R., Zheng, “Polymer matrix composites and technology.” 2011.

[5] J. Y. Sheikh-ahmad, Machining of Polymer. 2009.

[6] A. Hosokawa, N. Hirose, T. Ueda, and T. Furumoto, “CIRP Annals - Manufacturing Technology High-quality machining of CFRP with high helix end mill,” CIRP Ann. - Manuf. Technol., vol. 63, no. 1, pp. 89–92, 2014, doi: 10.1016/j.cirp.2014.03.084.

[7] M. K. N. Khairussshima and I. S. S. Sharifah, “Study on Tool Wear during Milling CFRP under Dry and Chilled Air Machining,” Procedia Eng., vol. 184, pp. 78–89, 2017, doi: 10.1016/j.proeng.2017.04.073.

[8] S. Zhang and D. Zhao, “Aerospace materials handbook,” CRC Press, p. 743, 2013, doi: https://doi.org/10.1016/j/molimm.2018.03.004.

[9] M. A. N. Rashid, S. A. Khan, M. K. Nor Khairussshima, and N. Sariuddin, “Study on tool wear and tool life during milling JFRP using uncoated carbide cutting tool,” ARPN J. Eng. Appl. Sci., vol. 13, no. 8, pp. 2930–2934, 2018.

[10] M. A. Karatas, “A review on machinability of carbon fiber reinforced polymer (CFRP) and glass fiber reinforced polymer (GFRP) composite materials,” vol. 14, pp. 318–326, 2018, doi: 10.1016/j.dt.2018.02.001.

[11] J. Turrillo Jimeno, “Analysis of tool wear after machining of fibre reinforced polymers,” e-archivo.uc3m.es, Jul. 2012, [Online]. Available: http://hdl.handle.net/10016/17824.

[12] D. Ozkan, M. S. Gok, H. Gokkaya, and A. C. Karaoglanli, “The effect of cutting parameters on tool wear during the milling of carbon fiber reinforced polymer (CFRP) composites,” Medziagotyra, vol. 25, no. 1, pp. 42–46, 2019, doi: 10.5755/j01.ms.25.1.19177.