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To cite this article: Aisyah Madihah Mustafa *et al* 2021 *J. Phys.: Conf. Ser.* **2051** 012053

An Experimental Investigation on Surface Quality of CFRP after Milling in Cutting Fluid Environment

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Abstract. Carbon fiber reinforced polymer (CFRP) are becoming more widely used in replacing metallic component as it offers better strength-to-weight ratio compared to steel while having high corrosive resistance. Although CFRP have always been manufactured near to net-shape, secondary machining process is still required to achieve the final dimension. Machining can cause CFRP to experience surface defects such as delamination, fiber pull-out and smeared matrix which lead to part rejection. The aim of this study is to investigate the effect of cutting parameters on the surface roughness and its quality. In this investigation, cutting speeds of 132, 151 and 170 m/min with constant feed rate of 1800 mm/min were applied during end milling of CFRP using uncoated tungsten carbide end mill tool in cutting fluid condition. It was observed that high cutting speed (170 m/min) produced 45.3% lower Ra than lower cutting speed (132 m/min) after machining for 6500 mm cutting distance. The occurrence of thermally degraded resin on the machined surface was apparent at higher cutting distance between 3000 to 6500 mm. Also, it was observed that the smearing of thermally degraded resin was more obvious on higher cutting speed when compared at 132 m/min cutting speed suggesting that at higher cutting speed more heat generated that resulted in increasing the cutting temperature. Fiber pull-out was also found on the machined surface and the cavity formation changes with increasing of cutting distance resulting in relatively larger cavity.

Keywords: CFRP, surface roughness, uncoated tungsten carbide tool (WC), milling.

1. Introduction

Carbon Fiber Reinforced Polymer (CFRP) has been highly in demand especially in high end industries such as automotive and aerospace as CFRP possess a desirable strength-to-weight ratio, substituting the application of metal in parts that requires good strength and weight properties [1]. Besides having a lighter weight than metal, CFRP also comes into favour as it can be produced near its final shape. This reduces the overall cost of a product and increase the efficiency of the production as less material removal process needed to achieve its final shape [2]. However, secondary machining such as milling, drilling, and slotting are necessary to achieve its final product dimensional [3]. As CFRP consists of lamination of carbon fibers that infiltrated with matrix resin, its exhibits an anisotropic and heterogenous behaviour due to the different in mechanical and physical properties. This behaviour resulted in abrasive property that causing rapid tool wear and high cutting force to occur. These also causing series of brittle carbon-fiber chips that carries away minimum amount of heat during the machining process [4,5]. Cutting parameters such as cutting speed and cutting environment plays a big role during machining process of CFRP. Defects such as delamination and fiber pull-out are prone to occur due to rapid tool wear of cutting tool contributed from the high cutting speed process. Apart from that, it is crucial to machine the CFRP below its glass transition temperature (Tg). High cutting temperature can degrade the matrix resin and inducing defects that influence the surface quality of the CFRP [6]. Machining with the presence of cutting fluid is recommended to aid in reducing the high cutting temperature when machining with high cutting speed. This research was executed to investigate the effect of cutting parameters on the surface roughness of the CFRP with the presence of cutting fluid.

2. Methodology and Experimental Set-Up

Milling of CFRP was carried out using MAZAK-NEXUS 410A-II with maximum spindle speed of 12 000 RPM. Carbon fiber reinforced polymer impregnated with epoxy resin having a glass transition temperature of 180°C was chosen as a main workpiece in this study. CFRP workpiece with dimension of 200 x 200 x 50 mm and 200 x 50 x 5 mm were prepared for tool wear and surface roughness measurements, respectively. The cutting tool employed in this experiment is a 6mm diameter of tungsten carbide (WC-Co) with three flutes square end mill, as shown in Figure 1 while Figure 2 shows the overall setup for this machining process. Overall experiment parameter carried out in this test with the presence of cutting fluid were tabulated in Table 1.

Figure 1. 6mm diameter uncoated tungsten carbide tool mounted on the machine spindle

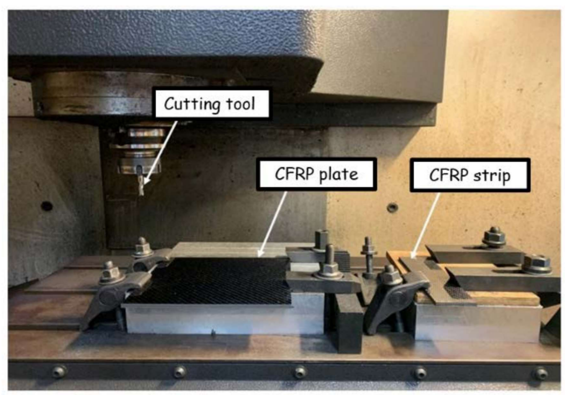

Figure 2. Overall set-up for milling CFRP in cutting fluid environment

Table 1. The cutting parameters for the experiments

Parameter	Value
Cutting speed, V	132,151,170 m/min
Feed rate, f	1800 mm/min
Radial depth of cut, a	1 mm
Machining environments	Coolant

Surface roughness and surface profile of CFRP machined surface were measured using Alicona Infinite Focus SL. Single measurement function that available in MeasureSuite software by Alicona was employed to measure all machined surface. The measurement was carried out using 5X lens magnification with evaluation length of 4mm and cut of length of 800 µm accordance to ISO 4288. To produce better resolution and measurement using the device, the vertical and lateral resolution were set to 1.98 µm and 8.39 µm, respectively. Surface defects and surface damages were examined using scanning electron microscope Jeol JSM-5600 Schottky Field Emission. Prior to SEM measurement, the machined surface was cleaned using alcohol in ultrasonic bath to remove the carbon chip and other debris that might affect the measurement. The CFRP machined surface also coated with the gold palladium using Quorum SC7620 Sputter Coater to create the conductive surface for SEM examination.

3.0 Results and Discussion

3.1 The effect of cutting speed on CFRP surface roughness.

Figure 3 shows the progression of surface roughness of CFRP machined surface when milling with three cutting speeds after 6500 mm machining length with the presence of cutting fluid. It can be seen the surface roughness increases with the increasing of machining length for all cutting speed. This is caused by the rounded of cutting-edge radius attributed from the increasing of tool wear along the machining length. Besides, due to the anisotropic and heterogeneous structures of CFRP that produced brittle fracture instead of plastic deformation at the working zone, excessive tool wear can occur with increasing of the cutting distance which was also supported by Halim et. al [6].

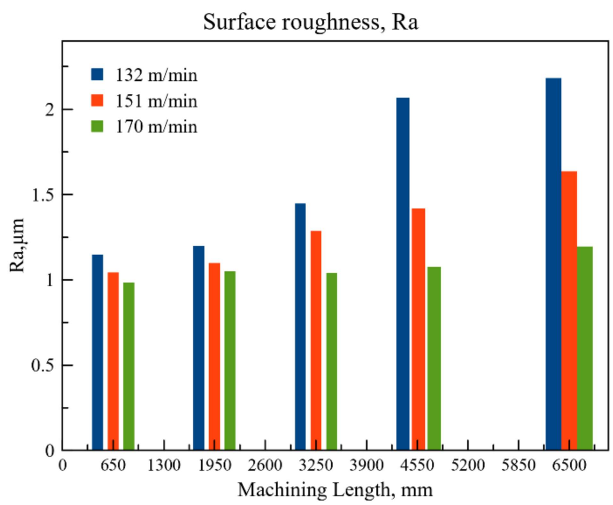

Figure 3. Average surface roughness, Ra of the CFRP machined surface measured by Alicona Infinite Focus SL

However, opposite phenomenon can be observed in studying the relationship between the surface roughness and the cutting speed as the surface roughness decreases with increasing of the cutting speed. High cutting speed of 170 m/min shows a better surface roughness of 1.193 µm with minimal increment compared to other cutting speeds. The highest average surface roughness was observed to be at 2.181 µm after milled with cutting speed of 132 m/min at cutting distance of 6500 mm, 45.3% higher compared to 170 m/min. This is due to the higher cutting temperature generated during machining in high cutting speed softens the matrix resin, offering less friction between the cutting tool and the machined surface thus eases the CFRP removal process. It is suggested that the softening of the matrix resin was occurred during milling of CFRP [4,7]. Figure 4 shows the topography image and its surface roughness profile of CFRP strips after 650 mm and 6500 mm of machining length for cutting speed of 132 m/min analysed under Alicona SL 3D. A lot of purple spots were observed at cutting distance of 6500 mm which indicates significant areas with fiber pull-out compared to cutting distance of 650 mm. At highest cutting distance of this investigation, the surface produced when using cutting speed of 132 m/min appears to be roughest.

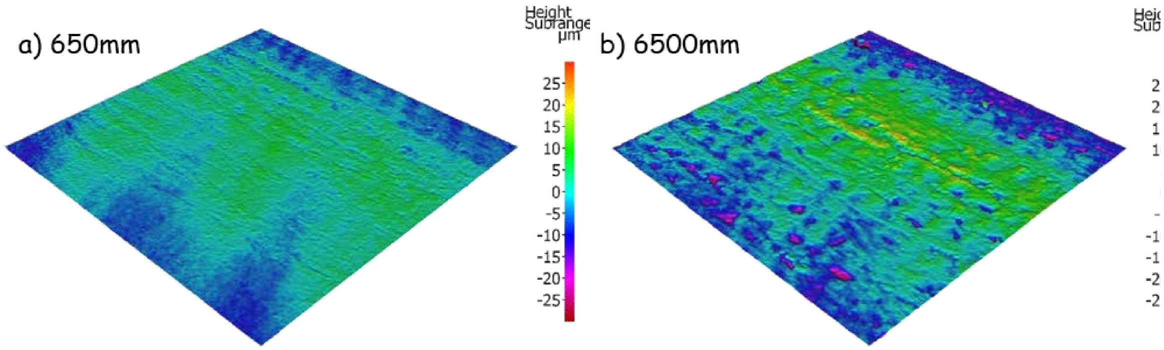

Figure 4. Topography images in Alicona SL 3D for 132 m/min after machining for a) 650mm and b) 6500mm cutting distances

Figure 5 compares the roughness profiles for cutting speed of 132 m/min after machining for 650 mm and 6500 mm cutting distances. It is expected that as cutting distance increases, the tool wear of the cutting tool increases. Therefore, damaging the surfaces of the CFRP. These can be seen when the roughness profile after machining for 6500 mm has the highest peaks and lowest valleys of 8 to -8 µm, and the lowest range of peaks and valleys belongs to 650 mm with range of 3 to -4 µm. It validates that the surface roughness increases with increasing of cutting distances. The highest peaks and lowest valleys after machining for 6500 mm also explains the presence of defects such as fiber pull out and matrix smearing. Figure 6 compares the roughness profiles for cutting speed of 132 m/min and 170 m/min after machining for 6500 mm cutting distances. The roughness profile for 132 m/min has the highest peaks and lowest valleys of 8 to -8 µm while the 170 m/min only range of 5 to -5 µm peaks and valleys. It affirms that the surface roughness decreases with increasing of cutting speed. This is due to the softening of matrix resin that eases the milling process, as discussed before.

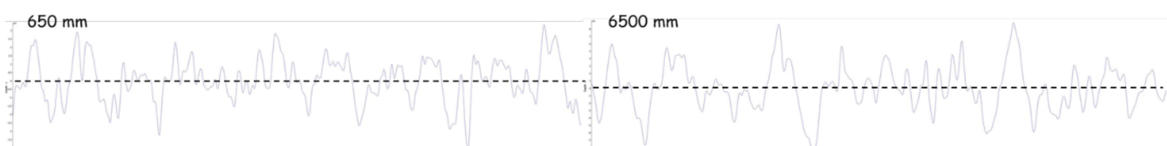

Figure 5. The roughness profiles for cutting speed 132 m/min for machining distance of 650 mm and 6500 mm

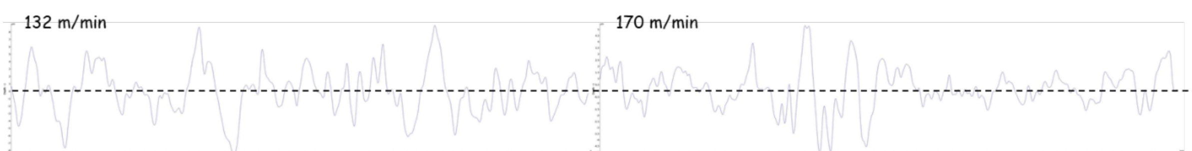

Figure 6. The roughness profiles for cutting speed 132 m/min and 170 m/min after machining for 6500 mm

3.2 Damage mechanism and surface quality observations

Figures 7 and 8 show the Scanning Micron Electroscopy images of CFRP machined surfaces after machining. During further investigation using SEM, few defects were observed on the CFRP machined surface such as crack propagation, delamination and fractured fiber as shown in Figure 6. These phenomena are believed to occur due to the abrasiveness of the CFRP that complicates the CFRP removal process at the cutting edge of the tungsten carbide tool. Unlike metallic material that undergoes plastic deformation, CFRP inhibits brittle fiber fracture resulted to dust-like chips. High cutting forces

Journal of Physics: Conference Series **2051** (2021) 012053 doi:10.1088/1742-6596/2051/1/012053

on the working zone contributed by the abrasiveness of the CFRP exhibits improper fractured of fiber, therefore initiated the propagation of cracks and delamination, also generally known as damage of the top layer lamination, which also supported by [2] during edge trimming of CFRP. Figure 7 can be observed almost on all the CFRP machined surfaces that indicates the CFRP experiencing a high cutting temperature during the milling process. High cutting temperature induced by the high cutting speed causing the matrix resin to soften, thus allowing the cutting tool to drag it along the cutting edge, causing the matrix smearing on the machined surface. The defects found was also experienced by Doboust et.al [8] where it is caused by inappropriate cutting parameter during edge trimming CFRP.

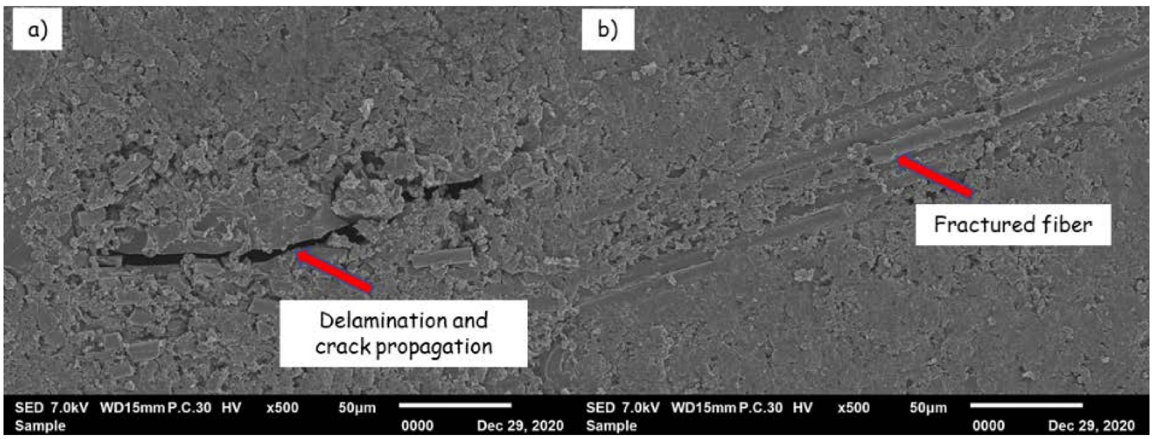

Figure 6. Defects such as a) delamination and crack propagation and b) fractured fiber observed under SEM microscope for CFRP machined with cutting speed of 132 m/min

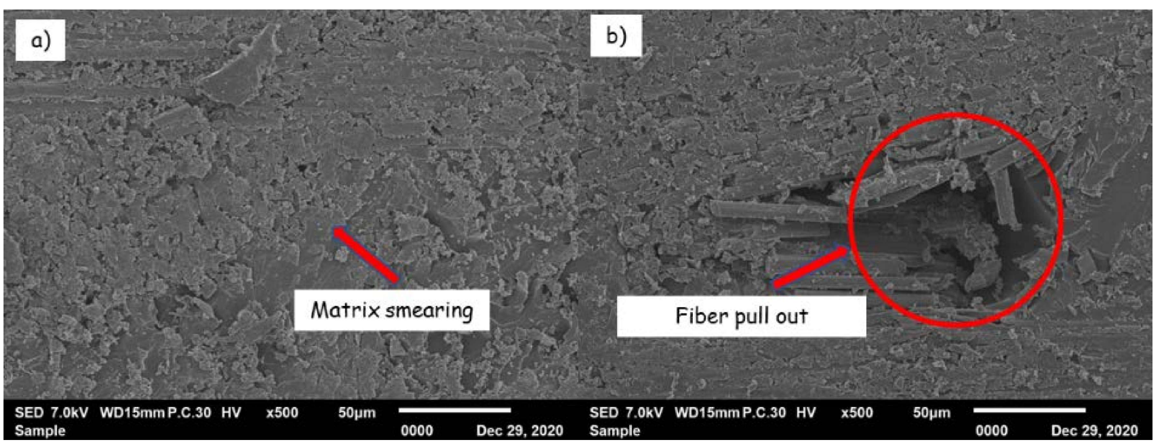

Figure 7. a) Matrix smearing and b) fiber pull out observed in SEM on CFRP for cutting speed 132 m/min

Besides that, the occurrence of matrix smearing and the formation of fiber pull-out signify that the high cutting temperature generated from the high cutting speed during the milling process deteriorates the bonding between the carbon fiber laminations and matrix resin. It also shows that the cutting temperature at the tool edge is higher than its surrounding which compromises the matrix resin glass transition temperature (Tg). The degradation of the matrix resin introduces the propagation of crack due to de-bonded of carbon fiber from the matrix resin, hence contributes to the formation of cavity along the cutting plane across the increasing of the cutting distance which is also experienced by Ozkan et al., [2] during edge trimming of CFRP.

4. Conclusions

Based on the results and analysis after milling the CFRP with 6mm uncoated tungsten carbide tool, with cutting speed of 132, 151 and 170 m/min, with the presence of cutting fluid, several conclusions can be drawn:

1. In this study, better surface roughness was obtained when milling of CFRP with higher cutting speed (170 m/min) as compared to low cutting speed (132 m/min). It was observed that the thermally degraded matrix resin smeared on the machined surface increases the value of surface roughness.
2. It was observed that the surface damages such as fiber pull-out and delamination were more apparent when milling with low cutting speed (132 m/min). Therefore, this explains the high value of surface roughness measured at lower cutting speed in contrast to high cutting speed.

5. Acknowledgement

This project is supported by Government of Malaysia and International Islamic University Malaysia under RMCG20-027-0027 research grant.

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