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Experimental investigation on tool wear and surface integrity during wet and dry milling of carbon fiber reinforced polymer (CFRP)

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KEYWORDS

CFRP
Tool wear
Surface roughness
Milling
Damage mechanism

ABSTRACT

Carbon fiber reinforced polymer (CFRP) has been used as an alternative to conventional materials, especially in the aerospace and automotive industries due to its being light weight and having a high strength-to-weight ratio which can produce high performance part made. However, because of its abrasiveness, machining CFRP can be difficult and challenging. Therefore, this study aims to investigate the influence of cutting speeds on tool wear and the surface roughness of the CFRP upon milling in dry and wet cutting conditions. This edge trimming of CFRP was performed with cutting speeds of 50, 75, 100 m/min, at a constant feed rate and depth of cut of 475 mm/min and 1 mm, respectively. The highest average tool wear of 0.051 mm was obtained at V=100 m/min in a dry cutting condition. While the surface roughness of CFRP was observed higher (2.868 μm) at V=50 m/min in dry cutting condition. Therefore, it is recommended to perform the milling operation at a lower cutting speed in dry cutting condition and at a higher cutting speed in wet cutting conditions for a better surface roughness value as well as to reduce the damage to the surface of the CFRP.

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1.0 INTRODUCTION

The carbon fiber reinforced polymer (CFRP) material is known for having high fatigue resistance, good wear resistance, high stiffness and strength, and dimensional stability, making it seen as a promising material. It is increasingly being applied in industries mainly in the aerospace and automotive industries replacing conventional materials (Yiwen et al., 2022). The aircraft industry shows a high utilization of CFRP, such as 53% of the Airbus A350 components such as the main body parts, wings, and tails are made of the composite. It is also manufactured into the bumpers of vehicles in the automotive industry for its ability to resist high compressive loads (Borges et al., 2023; Pollock et al., 2023). Due to the light weight and high strength-to-weight ratio, application of CFRP in automotive and aerospace industries could lead to the reduction in fuel consumption and 20% carbon emissions during operation (Borges et al., 2023; Geier et al., 2023). However, secondary machining such as drilling and milling are still required to achieve the dimensional accuracy of the parts (Slamani & Chatelain, 2023). Carbon fiber reinforced polymer (CFRP) consists of carbon as a fiber and polymeric resin as a matrix material. The matrix resin helps the transfer of the load of elements between the fibers which enables the material to produce a superior strength that improves the material resistance towards the influence from the environment (Karatas & Gokkaya, 2018). However, the inhomogeneous and anisotropic properties of the carbon fiber and the matrix resin result in the abrasive nature of the CFRP material. This causes aggressive rubbing between the cutting tool and the workpiece, which increases the cutting force and results in rapid wear of the cutting tool during machining (Geier et al., 2023; Slamani & Chatelain, 2023). Consequently, performing machining operations with worn-out tools generate high heat and cutting temperature, which degrades the matrix resin of the material and affects the surface condition.

Along with the abrasiveness of CFRP and the matrix resin degradation, problems such as delamination, fiber pull-out, matrix smearing, and cracking are always found during machining CFRP (Devan et al., 2022). Machining CFRP also produces a dust-like chip, which causes poor heat dissipation and an increase in temperature during machining. The generation of dust may be harmful and toxic to the environment and the machine (Elgnemi, Songmene, et al., 2021). The increase in temperature causes degradation of the material and poor quality of CFRP as the matrix resin softens at high temperatures. Hence, the temperature during machining needs to be maintained below the glass transition temperature (Tg) of the matrix resin (Halim et al., 2017). Poor surface condition due to the damage directly breaking off the continuity of the fiber and decreasing the performance and strength of the CFRP material (Geier et al., 2023). The suitable selection of cutting parameters, cutting tool geometry and material is important in achieving high quality parts (Geier et al., 2023; Halim et al., 2017). The tungsten carbide cutting tool is often selected in the machining of CFRP as it is harder and more durable than normal tungsten tool and can withstand the abrasiveness of the material while producing a good finish on the material surface (Devan et al., 2022; Geier et al., 2023). Despite the cutting tool being durable, its edges may experience rounding due to the abrasions resulting from the harsh contact between the cutting tool and the CFRP (Devan et al., 2022; Xu, 2022). The continuous abrasion caused by the rubbing of cutting tool against the CFRP leads to the removal of the binder phase, causing the dislodging and loss of WC particles from the tool material. Eventually, using a chipped and worn-out cutting tool can lead to tool fracture and negatively affect the finishing quality and outcomes (Devan et al., 2022; Shahruddin et al., 2021). Cutting parameters such as cutting speed, feed rate, and depth of cut gives significant effect on the progress of tool wear and the surface condition. The occurrence of tool wear results in a high cutting temperature and an increase in surface roughness, which increases damage and reduces the strength of CFRP (Shahruddin et al., 2021). This emphasizes the necessity of controlling the progress of tool wear.

Elgnemi et al. (2021) did an experimental study on dry routing of CFRP and observed that after a cutting distance of 105 mm, machining at spindle speed of 20,000 rpm shows 25% higher average wear rates compared to machining at 10,000 rpm with the same feed rate of 0.006 mm/tooth. Furthermore, as dry machining generates high cutting temperature, the use of cutting fluid aids in reducing the heat generation during machining. Thus, reducing the rapid generation of tool wear and producing better surface condition (Karatas & Gokkaya, 2018). Sundi et al. (2020) observed that trimming CFRP at the combination of the lowest cutting speed of 50 m/min and feed rate of 376 mm/min produces the lowest average surface roughness value of 1.31 μm, 90% lower than the surface roughness value in trimming at the combination of the highest cutting speed (150 m/min) and feed rate (1128 mm/min). Lesser damage and better surface condition were seen on the photomicrographs of the trimmed CFRP surface for the lowest cutting parameters. However, the higher cutting speeds of 100 m/min and 150 m/min, showed poorer conditions where damage such as matrix degradation, uncut fibers and fibers pull-out were seen on the trimmed surface. Different observation also found by Mustafa et al. (2021) during milling CFRP with the presence of cutting fluid, in which the surface roughness decreased with the increase of cutting speeds. The study showed that after milling through 6500 mm, the lowest cutting speed of 132 m/min shows a surface roughness value of 2.181 μm, while the highest cutting speed of 170 m/min produces a better surface roughness value of 1.193 μm. Moreover, it is also observed that milling at the higher cutting speed causes more damage to the surface of CFRP such as delamination, matrix smearing, fiber pull-out and fractured fiber. Therefore, controlling the cutting parameters during machining CFRP is necessary to lower the progress of the wear of the cutting tool, minimize surface roughness, and reduce damage to the surface of CFRP.

2.0 EXPERIMENTAL PROCEDURE

The investigation on the milling of CFRP employing a three flute 8 mm diameter solid uncoated tungsten carbide end mill was carried out using the MAZAK-NEXUS 410A-II Vertical Machining Center. Figure 1 shows the CFRP workpiece material, that was prepared into two dimensions of 200 × 200 × 3 mm and 200 × 50 × 3 mm. The 200 × 200 × 3 mm workpiece was used for the milling operation and tool wear analysis, while the 200 × 50 × 3 mm workpiece was milled once after every round of machining (600 mm) to observe the surface roughness. The CFRP workpiece utilized in this study is composed of a matrix resin of epoxy, for the necessary bonding and structure of the composite material, with its properties detailed in Table 1. Figure 2 displays the end mill tool used for the milling process, supplied by Precisetech SDN BHD. The tool features three flutes, an 8 mm diameter, and an overall length of 50 mm, as specified in Table 2. The workpieces were clamped using fixtures on the machine bed as shown in Figure 4. The experiments were performed at three cutting speeds at a constant feed rate and depth of cut as tabulated in Table 3. The tests were carried out in two cutting environments which are dry and wet condition. The machining in wet condition was carried out using Belling X-TEN C82 coolant.

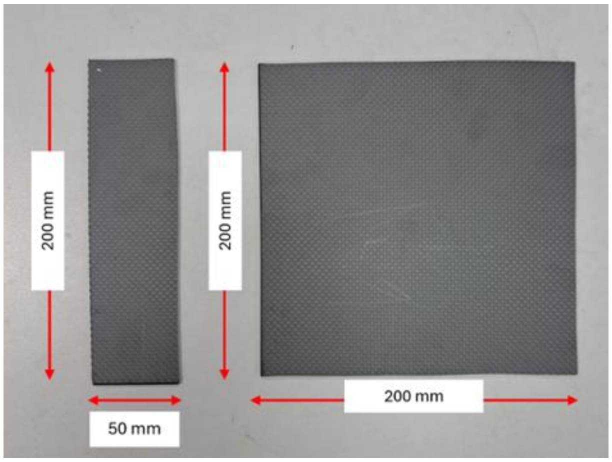


Figure 1: CFRP plate and strip.

Table 1: Properties of CFRP.

Parameter	**Properties**
Resin type	Epoxy
Density, g/cm^3	1.6
Compressive strength, MPa	570
Maximum operating temperature, °C	80
Fiber volume fraction, %	50

Figure 2: 8 mm diameter of uncoated tungsten carbide tool supplied by Precisetech Sdn Bhd.

Figure 3: 8 mm diameter of uncoated tungsten carbide tool with 3 flutes.

Table 2: K3EPEN 080U tungsten carbide end mill tool specification.

Parameter	Specification
Tool diameter, D	8 mm
Shank	8 mm
Overall length (OL)	50 mm
Length of cutting (LOC)	14 mm
Number of flutes	3

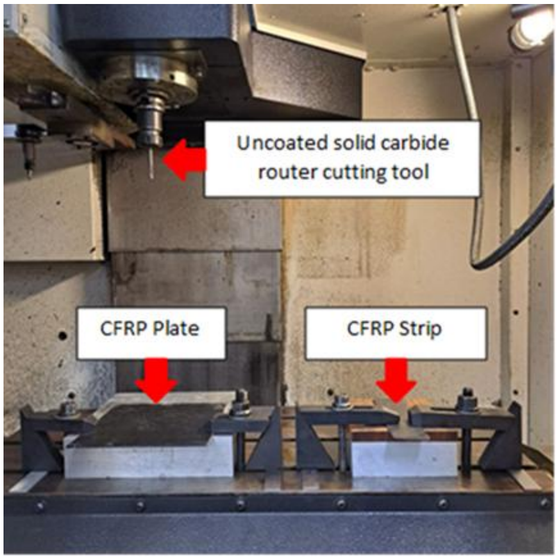


Figure 4: Experimental set up for milling operation of CFRP.

Table 3: Cutting parameters for the experiment.

Parameter	Value
Cutting speed, V_c (m/min)	50, 75, 100
Feed rate, f (mm/min)	475
Radial depth of cut, a_e (mm)	1
Stepover, a_p (mm)	1
Machining environment	Dry, coolant

The tool wear and surface roughness were measured for every 600 mm of distance travelled over a total distance of 3000 mm. The milling was done by edge trimming which was performed on the 200 × 200 × 3 mm CFRP plate, as shown in Figure 4, with three passes per round of machining, resulting in a total machined length of 600 mm. The image of the tool wear for each flute was captured using the Dino-Lite Premier digital microscope, and the tool wear was measured using the digital imaging and measurement software of the microscope as illustrated in Figure 5. The average tool wear was calculated based on the measured wear of each flute for every 600 mm machining length. The average surface roughness (Ra) of the CFRP strips was measured using the Alicona Infinite Focus SL surface profiler, displays in Figure 6, by referring to the guidelines outlined in ISO 4288. The surface roughness measurement was carried out with the evaluation length of 600 mm and with a cut-off length of 0.25 mm. The damage on the surface of the machined CFRP strip and the cutting tool was analyzed under the JEOL JSM-IT100 Scanning Electron Microscope (SEM) at high magnifications. The CFRP strips are coated using the sputter coater, while the cutting tools are cleaned before inserted into the SEM chamber.

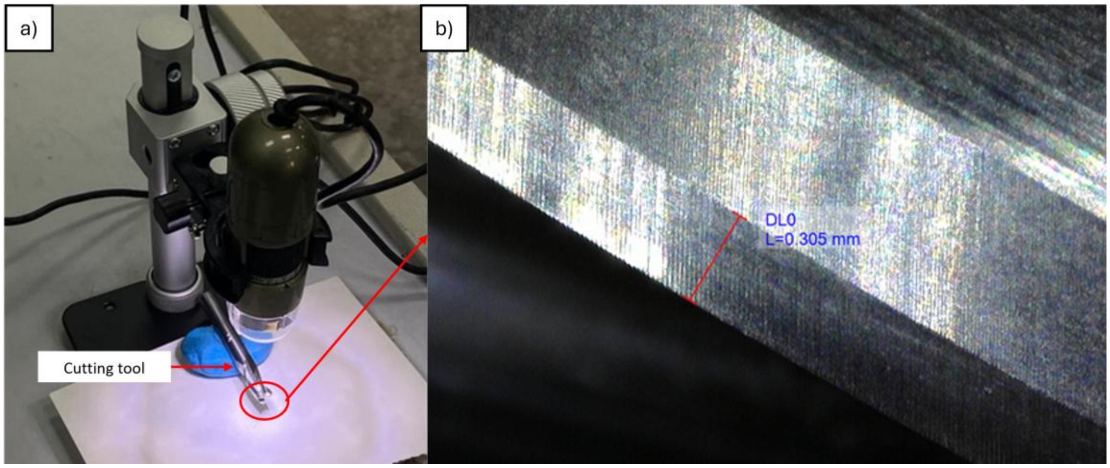


Figure 5: Measurement of tool wear using (a) Dino-Lite Premier digital microscope and DinoCapture2.0 software and (b) the tool wear measurement.

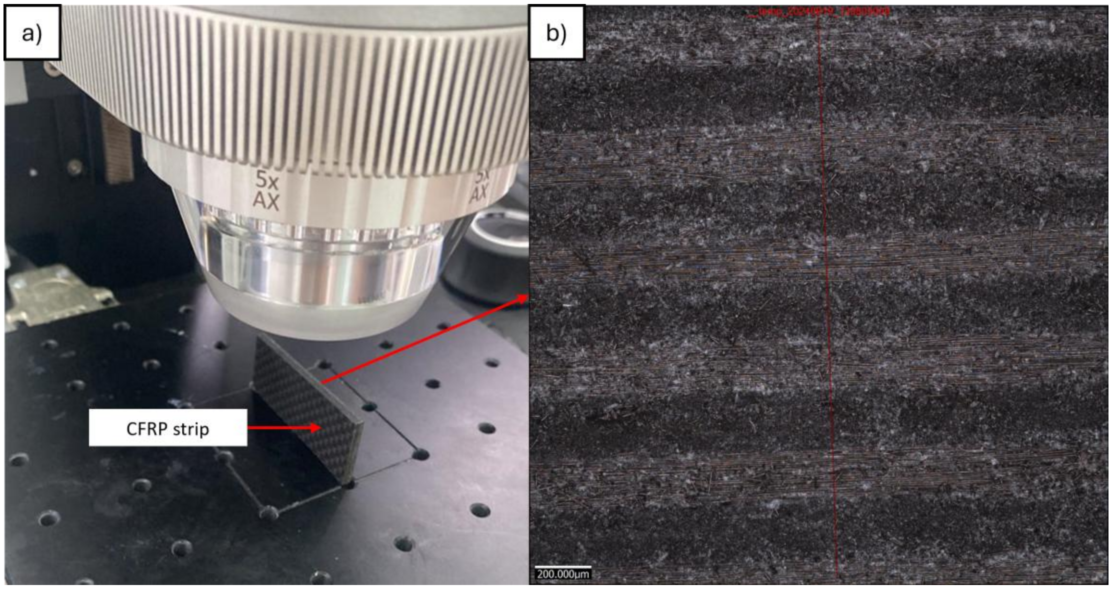


Figure 6: Measurement of surface roughness on the machined surface of CFRP using (a) Alicona Infinite Focus SL for scanning and (b) surface scanning and measurement.

3.0 RESULTS AND DISCUSSION

3.1 The Effect of Cutting Speed and Cutting Conditions on Progression of Tool Wear

The tool wear of the cutting tool is necessary to be observed as it progressively happens due to the abrasiveness of CFRP, which produces high friction in rubbing as the cutting tool comes into contact with the material and creates problems during machining. The effect of different cutting speeds of 50, 75, 100 m/min during milling of CFRP in dry and wet cutting environments over a 3000 mm machining length are shown in Figure 7 and Figure 8, respectively. It can be observed that after 3000 mm of machining length, the wear gradually increases along with the machining length for all cutting speeds at both cutting environments.

In dry cutting conditions as shown in Figure 7 it can be observed that after milling through 3000 mm, the highest wear of 0.051 mm was obtained at the highest cutting speed of 100 m/min, while the lowest wear of 0.030 mm was observed during milling at the lowest cutting speed of 50 m/min. Upon milling at a higher cutting speed, it increases the surface contact time between the material and the cutting tool, which results in an increase in rate of tool wear (Elgnemi, Songmene, et al., 2021). It is also observed that at high cutting speeds, it generates heat between the cutting tool and workpiece, which produces high cutting temperatures and leads to a higher tool wear rate (Shahruddin et al., 2021). The build-up of heat is due to the friction between the cutting tool and CFRP, as well as the low thermal conductivity of the material at a temperature higher than the glass transition temperature. These result in the softening of the cutting tool edge, which causes it to wear off easily (Kerrigan & Scaife, 2018). In wet cutting conditions where coolant is applied, the highest wear of 0.044 mm was observed at the highest cutting speed of 100 m/min, whereas the lowest wear of 0.031 mm was produced at the lowest cutting speed of 50 m/min, as shown in Figure 8. The observation of the higher rate of tool wear at higher cutting speeds is similar across machining in both dry and wet cutting conditions. However, milling in dry cutting environments shows 13.7% higher tool wear than milling in wet cutting conditions. The reason is that during milling in wet conditions, the coolant reduces the cutting temperature, which helps the cutting tool maintain its performance and lower the progress of wear (Mustafa et al., 2023).

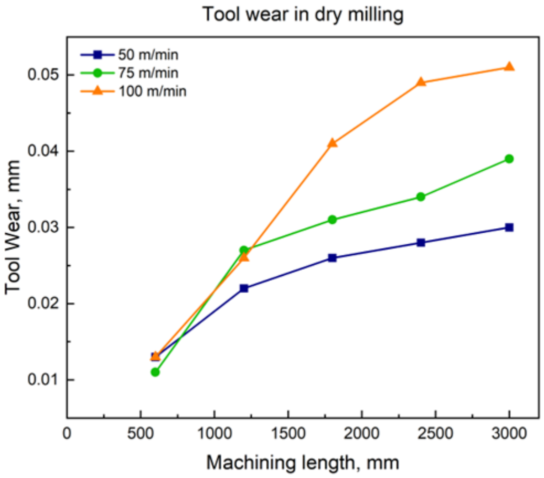


Figure 7: Tool wear progression in milling CFRP with 475 mm/min feed rate and 1 mm depth of cut in dry cutting conditions.

Besides, the coolant adds lubrication between the cutting tool and the chips produced from the milling process, which lowers the friction and wear of the cutting tool (Elgnemi, Jun, et al., 2021). In relation to the tool wear that happened, Figure 9(b) shows the zoom-in image of worn-out cutting tool in Figure 9(a) experiencing rounding at the edges as well as the dislodging of WC particles. These damages are due to the continuous abrasion on the cutting tool edges that weakens the binder and leads to the removal of carbide grain from the cutting tool surface (Elgnemi, Jun, et al., 2021; Xu, 2022).

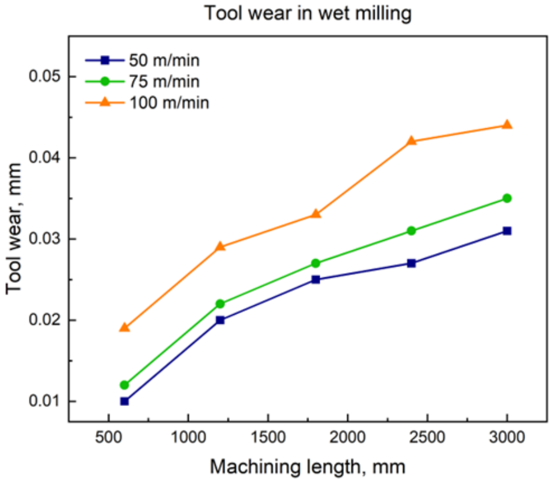
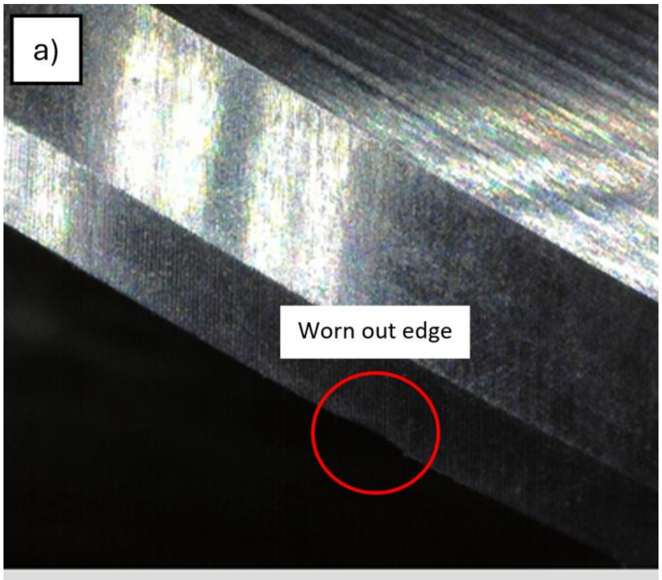


Figure 8: Tool wear progression in milling CFRP with 475 mm/min feed rate and 1 mm depth of cut in wet cutting conditions.



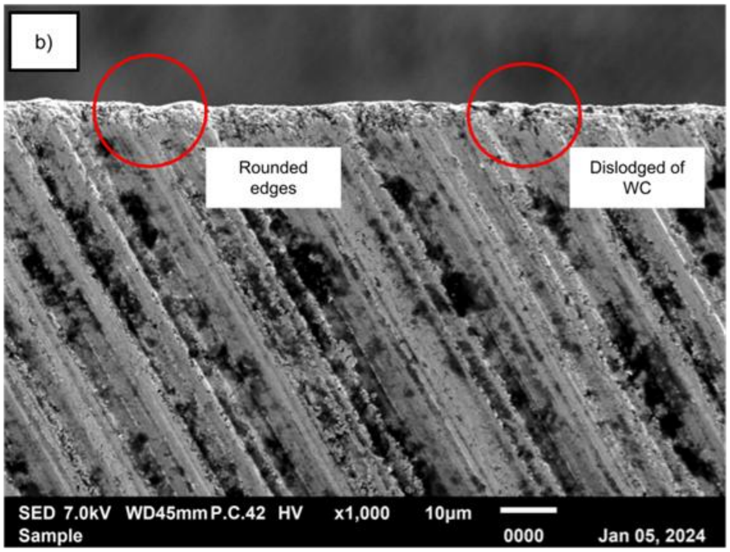


Figure 9: SEM image of cutting tool at 100 m/min after 3000 mm machining length (a) displaying worn out edge and (b) zoom-in image indicating the cutting tool experienced edge rounding and dislodged of WC was observed on the cutting tool surface.

3.2 The Effect of Cutting Speed and Cutting Conditions on Progression of Surface Roughness

The surface roughness progresses in milling at the cutting speeds of 50, 75, 100 m/min in dry and wet cutting conditions is compared in Figure 10 and Figure 11, respectively. It can be observed that the roughness varies as the machining length increases for all cutting speeds in both cutting conditions. The occurrence of tool wear along the machining length and the development of rounding on the cutting tool edge during the milling of CFRP create damage to the machined surface and result in poor surface roughness [15].

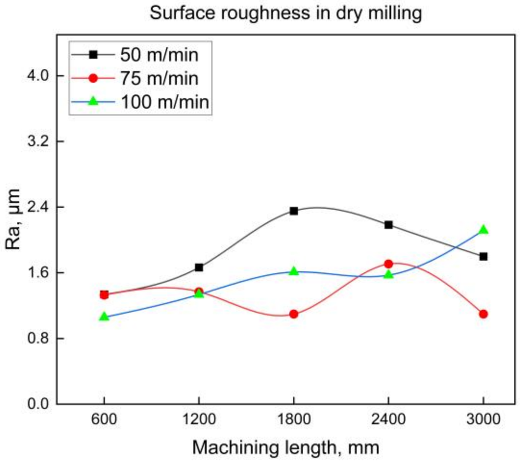


Figure 10: Surface roughness value, Ra, in dry milling over 3000 mm length.

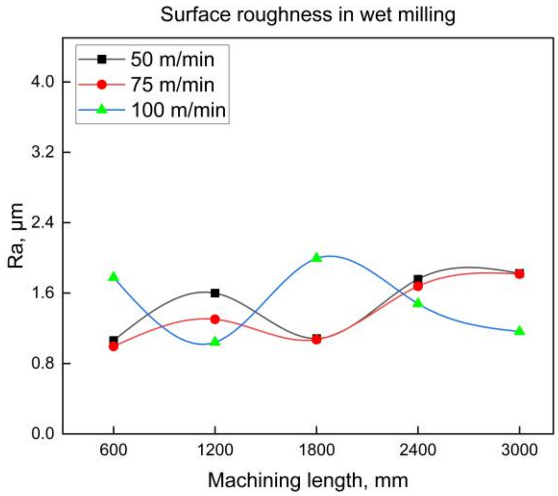


Figure 11: Surface roughness value, Ra, in wet milling over 3000 mm length.

In the dry cutting condition as shown in Figure 10, the highest surface roughness, Ra, observed with regard to the cutting speeds at a machining distance of 3000 mm was 2.116 µm, which is at the highest cutting speed of 100 m/min. The surface roughness value produced was approximately 14% and 48% higher than the lower cutting speeds of 50 m/min and 75 m/min, respectively. The cutting speed of 75 m/min shows the lowest surface roughness value, Ra, of 1.097 µm. This is caused by the elevation of the high cutting temperature in milling at a high cutting speed, which results in the smearing of the matrix resin and smoothing of the machined surface (Kumar et al., 2020). This also proves that the increase in tool wear with respect to the cutting speed, as shown in Figure 7, influences the surface quality and of the machined surface, where the higher rate of tool wear results in poor surface roughness (Sundi et al., 2020). Besides, the forces generated during milling using the worn-out tool cause damage and breaking of the fiber and increase in the roughness of the machined surface. Figure 12 and Figure 13 show the variations in peaks and valleys during milling in dry cutting conditions. Figure 12 exhibits higher peaks upon milling at 100 m/min resulting in an average roughness, Ra of 2.116 µm, compared to the cutting speed of 75 m/min as shown in Figure 13 (Ra=1.097 µm).

In milling with wet cutting conditions, an unexpected observation between the surface roughness and the cutting speed was recorded after milling through the machining distance of 3000 mm, as the surface roughness, Ra, decreased with the increase in cutting speed. At 3000 mm of machining length, the highest cutting speed of 100 m/min shows a better surface roughness of 1.163 µm, while the highest surface roughness, Ra of 1.825 µm was produced by the lowest cutting speed of 50 m/min, 36.3% higher compared to milling at 100 m/min. The surface roughness profiles in Figure 14 and Figure 15 shows significant differences in the Ra values produced during wet milling. Figure 15, at a cutting speed of 50 m/min shows more variations in peaks and valleys, resulting in a higher Ra value (Ra=1.825 µm).

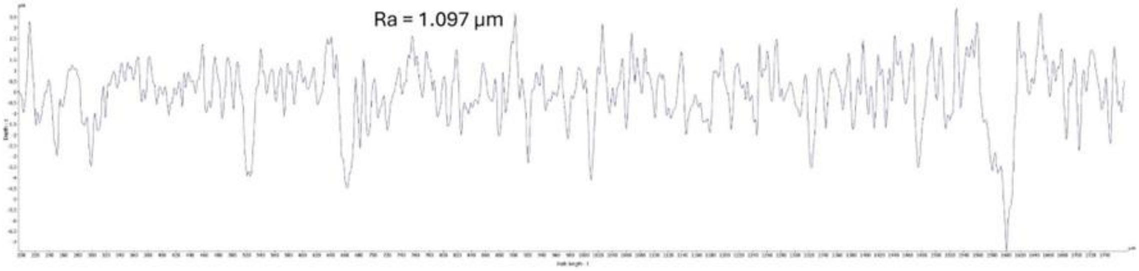


Figure 12: Surface roughness profile of machined CFRP surface during milling in dry cutting condition with cutting speed of 75 m/min.

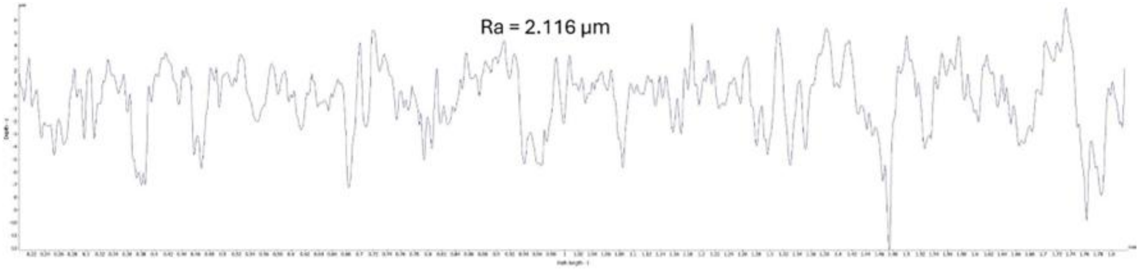


Figure 13: Surface roughness profile of machined CFRP surface during milling in dry cutting condition with cutting speed of 100 m/min.

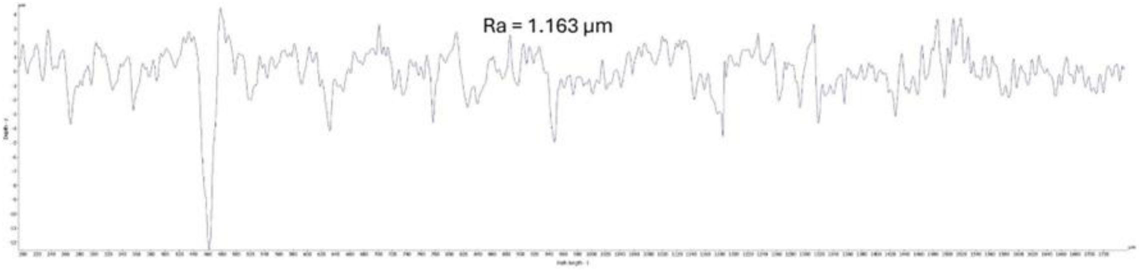


Figure 14: Surface roughness profile of machined CFRP surface during milling in wet cutting condition with cutting speed of 100 m/min.

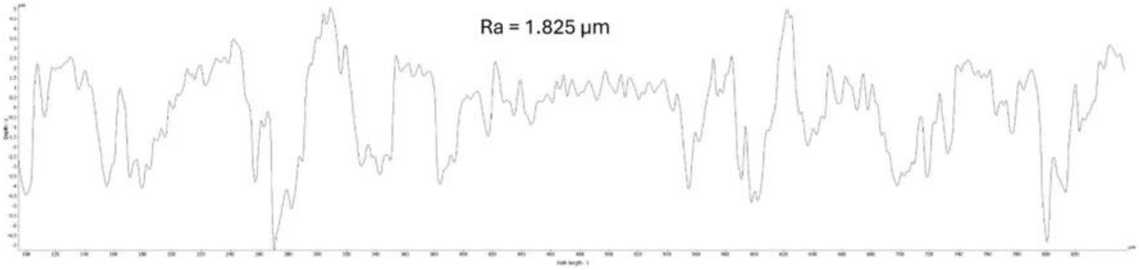


Figure 15: Surface roughness profile of machined CFRP surface during milling in wet cutting condition with cutting speed of 50 m/min.

Additionally, Figure 15 shows lower average peaks and valleys as machining performed at a cutting speed of 100 m/min. The presence of coolant aids in lowering the cutting temperature. This helps reduce the chances of delamination caused by the abrasive effect of the cutting tool, which creates friction between the cutting tool and the machined surface of the material (Kumar et al., 2020; Mustafa et al., 2023; Mydin et al., 2022).

In terms of the areal surface roughness or the arithmetical mean height (Sa), of the machined surface, the results show similar trends with Ra values as machined at cutting speeds of 50 m/min, 75 m/min, and 100 m/min in both dry and wet cutting conditions. Yet, the Sa values can be seen higher than the Ra values due to the different methods of measuring the roughness value. Ra values are measured only over a specific line length, while Sa values are determined by analysing the scanned area of the machined surface. Sa gives a better representation of the surface condition as it scans and measures the average peaks and valleys on the surface selected, which indicates the surface textures and roughness over the entire selected area. While Ra only measures the average roughness along a single line as illustrated in Figure 12, Figure 13, Figure 14, and Figure 15.

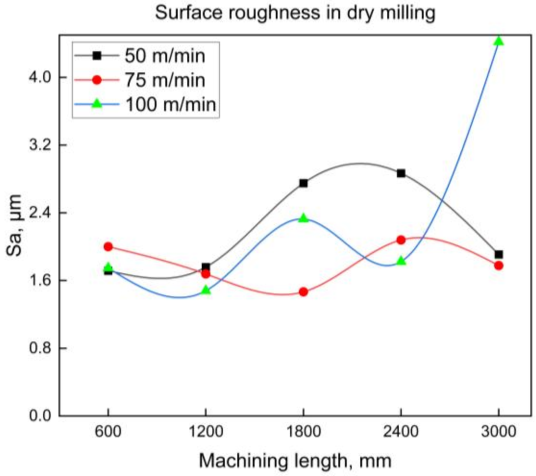


Figure 16: Areal surface roughness value, Sa, in dry milling over 3000 mm length.

According to Figure 16, it can be observed that the highest areal surface roughness value, Sa, as machining over 3000 mm of machining length in dry cutting conditions was 4.419 µm, which is at the highest cutting speed of 100 m/min. While the cutting speeds of 50 m/min and 75 m/min showed lower Sa values of 1.909 µm and 1.778 µm, respectively. In regards with the rate of tool wear in Figure 7, it can be seen that the tool wear is higher at the highest cutting speed. This justifies the higher Sa values, as the worn out tool contributes to an increase in cutting force during machining process, leading to damage on the machined surface (Xu, 2022). The areal surface roughness values, Sa, can be confirmed with the surface topography shown in Figure 17(a) and Figure 17(b). According to the height subrange of the surface topography shown in Figure 17(b), some parts on the scanned surface exceed the acceptable height subrange, indicating poor surface roughness and damage in machining at a cutting speed of 100 m/min. The blue and purple colours in the pseudo-colouring of the height subrange indicate damage such as fiber pull-out and delamination. This occurs as the fibers break and separated as machined with a worn-out cutting tool, leading to fiber pull-out and an increase in delamination depth (Ozkan et al., 2020). In contrast, Figure 17(a) shows less variations in the height subrange, which indicates machining at the cutting speed of 75 m/min produces better surface roughness and less damage.

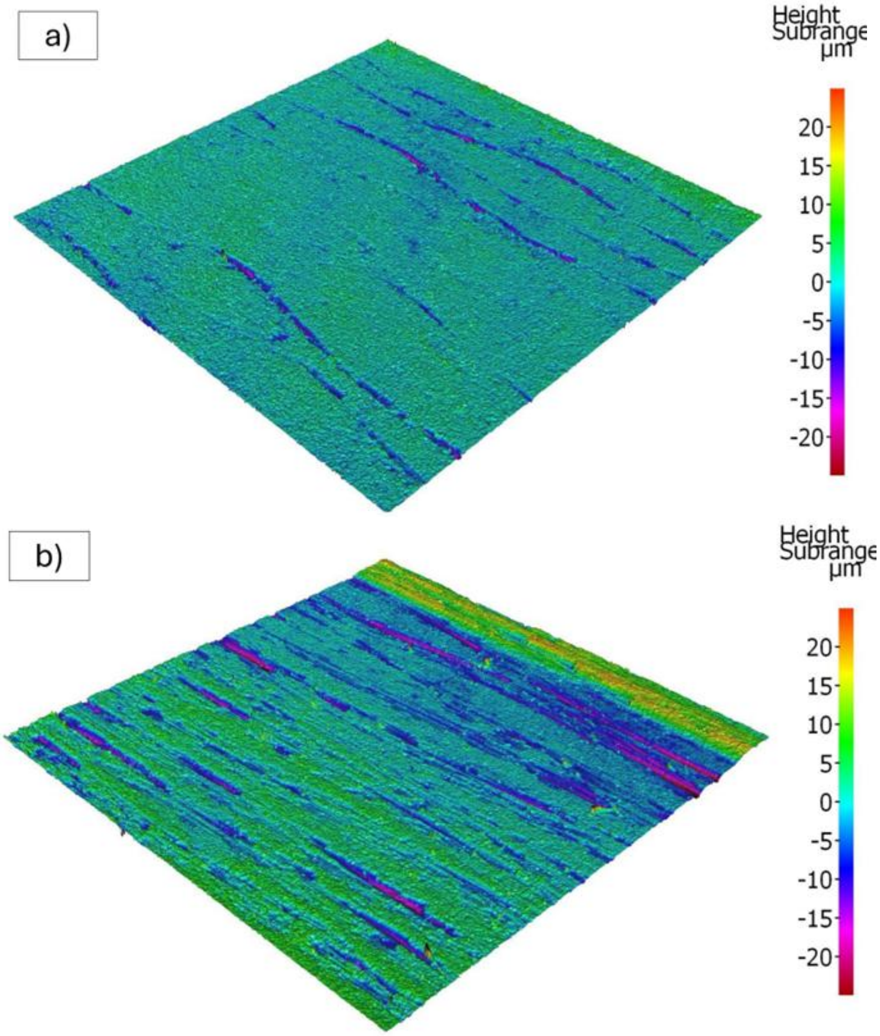


Figure 17: Machined surface topography of the CFRP after milling 3000 mm in dry cutting condition with a cutting speed of (a) 75 m/min (b) 100 m/min.

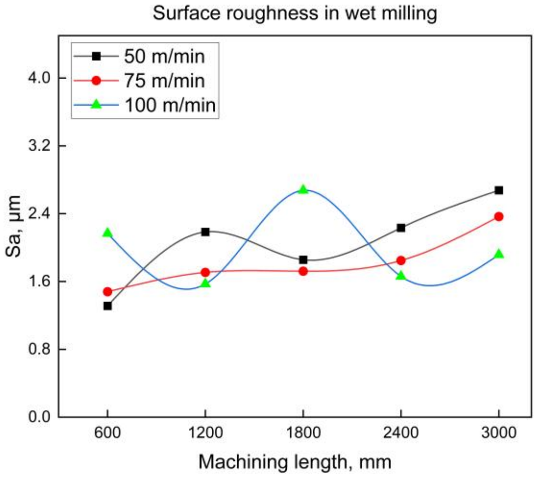


Figure 18: Areal surface roughness value, Sa, in wet milling over 3000 mm length.

Different observations on the effect of cutting speed on the Sa values were found as machined in wet cutting conditions as seen in Figure 18. The lowest cutting speed of 50 m/min gives the highest Sa value of 2.676 µm, 28.4% higher than the Sa value produces by the highest cutting speed of 100 m/min (1.916 µm). It can be seen that the highest cutting speed of 100 m/min produces the lowest Sa value, which can be caused by the high temperature generated during the process, that created smearing of the material which smoothen the surface of CFRP (Kumar et al., 2020). This can be confirmed by the green indication in the pseudo-colouring of the height subrange displayed on the surface topography in Figure 19(a). The high Sa value produced by the cutting speed of 50 m/min is to be due to the poor condition of the cutting tool, which has begun to wear out at the machining distance of 3000 mm as illustrated in Figure 9. Figure 19(b) shows the damages on the surface that are displayed by the blue indication in the pseudo-colouring of the height subrange. This shows the occurrence of damage, such as fiber pull-out and delamination caused by the cutting tool, that leads to the high Ra and Sa values.

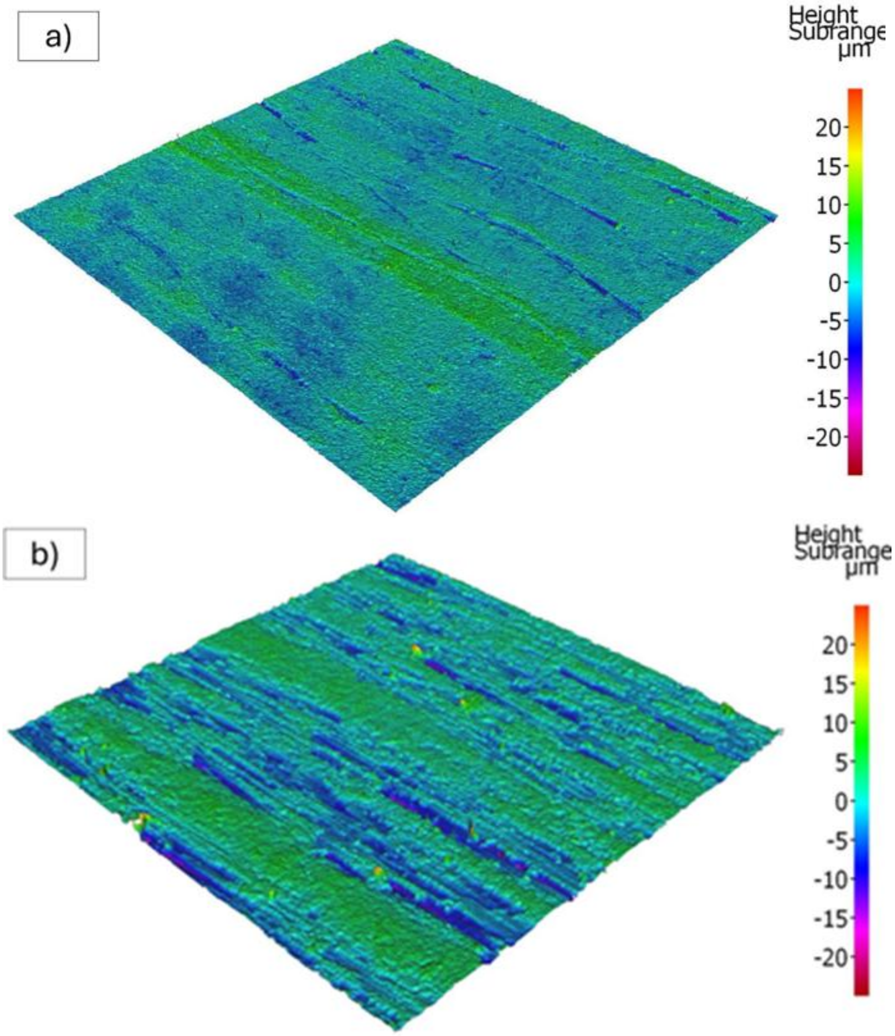


Figure 19: Machined surface topography of the CFRP after milling 3000 mm in wet cutting condition with a cutting speed of (a) 100 m/min (b) 50 m/min.

3.3 Damage Mechanism and Surface Quality

The surface roughness is affected by the damage that happens to the machined surface of CFRP during the milling process from the wear of the cutting tool. Figure 20(a), Figure 20(b), and Figure 18 show the Scanning Electron Microscopic image observed on the machined surface of CFRP after machining through a 3000 mm machining distance. A few defects were observed in SEM on the machined surface, such as delamination and fractured fiber, as shown in Figure 20(a), Figure 20(b), and Figure 21. It was observed that the damage mechanism was severe during milling in a dry cutting condition as compared with the present of coolant during machining. The abrasive properties of CFRP cause the fiber to break into dust-like chips while machining, causing the cutting force to increase and leading to more fiber breakage. Cracks and delamination happen as a result of the breaking of fiber, affecting the structural durability of the laminated surface during the edge trimming (Elgnemi, Songmene, et al., 2021; Kumar et al., 2020). This shows that milling at all cutting speeds with worn-out tools increases the cutting force due to the increase in the force for removal of the material and the friction produced from the contact of the tool and the abrasive surface of the material, hence the deterioration of surface condition (Zhang et al., 2020). Besides, the chips formed during the material removal processes influence the increase in the cutting force as well as the cutting temperature (Shahruddin et al., 2021). Additionally, milling at a higher cutting speed somehow induces a high cutting temperature, causing the smearing of matrix resin by the cutting tool on the machined surface due to the softening of matrix resin at a high temperature (Kumar et al., 2020).

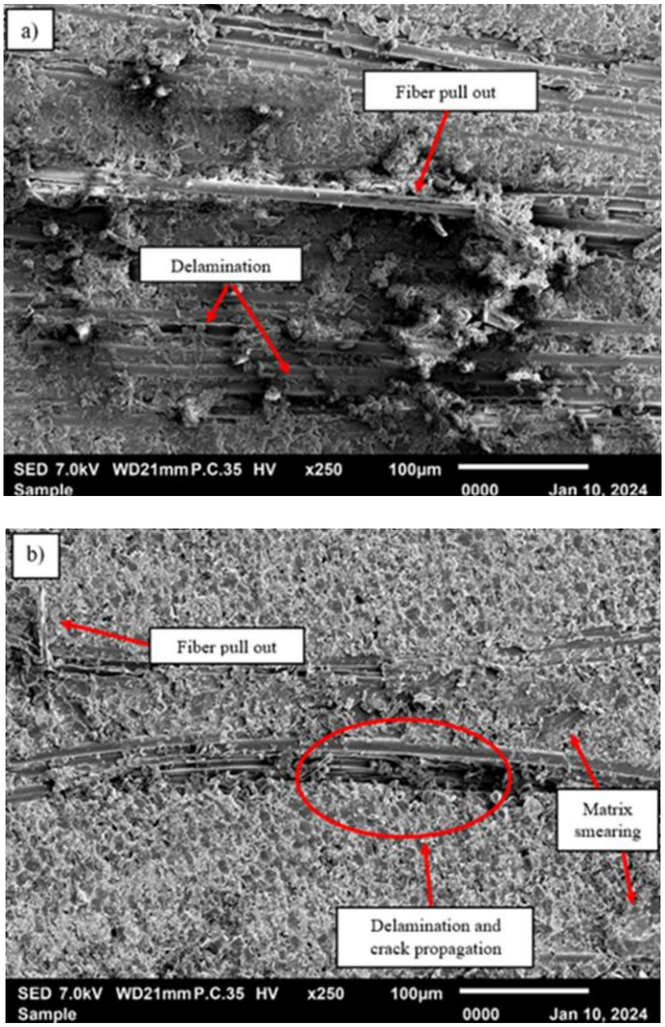


Figure 20: Defects observed under SEM microscope for CFRP machined with cutting speed of 100 m/min in (a) dry cutting condition (b) wet cutting condition.

The matrix smearing observed on the surface as shown in Figure 20(a), Figure 20(b), and Figure 21 indicates the generation of high cutting temperature during milling process (Mustafa et al., 2021). From Figure 21 it was observed that the fibre was fractured, and the matrix was smeared on the CFRP machined surface. It can be concluded that the matrix resin softens as the temperature of the cutting tool and machining environment reaching and exceeds the material glass transition temperature (Tg), causing the burning of the resin and smearing of matrix resin by the movement of cutting tool (Mustafa et al., 2021; Ni et al., 2023). The degradation of the matrix resin contributing to more damages on the machined surface such as the cracking due to the poor bonding between the fiber and matrix resin, resulting in the poor strength and performance of the CFRP material (Elgnemi, Songmene, et al., 2021; Yiwen et al., 2022).

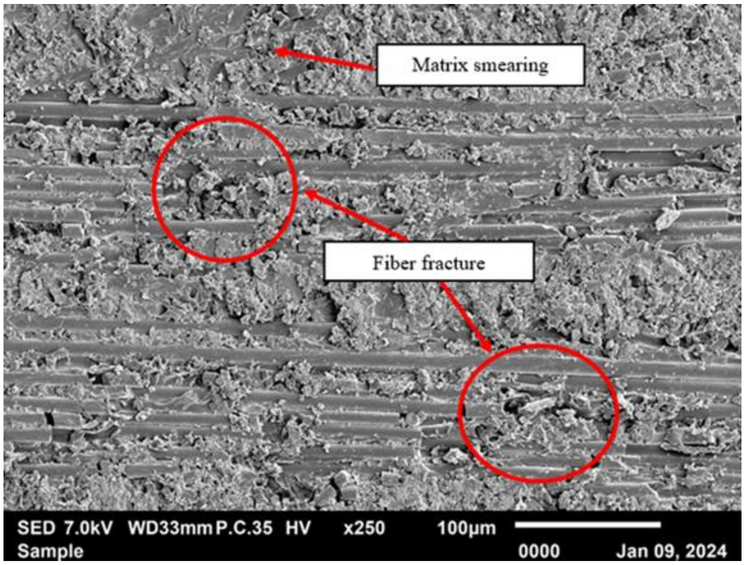


Figure 21: Defects observe under SEM microscope for CFRP machined with cutting speed of 50 m/min in wet cutting condition.

CONCLUSIONS

Based on the analysis done after milling of CFRP with an 8 mm diameter uncoated tungsten carbide tool, with cutting speeds of 50, 75, and 100 m/min, at a constant feed rate (475 mm/min) and depth of cut (1 mm) in dry and wet cutting environments, several conclusions can be drawn:

(a) The tool wear increases with the increase in cutting speeds, where the highest cutting speeds of 100 m/min in both cutting conditions give the highest wear of 0.051 mm and 0.044 mm, respectively.

(b) Milling in dry cutting conditions at a high cutting speed of 100 m/min results in 13.7% higher tool wear rates than milling in wet cutting conditions. This is due to the higher heat generation in dry milling from the constant rubbing between the cutting tool and the workpiece material, which increases the tool wear value.

(c) In dry cutting conditions, the highest cutting speed of 100 m/min produces a poor surface roughness value, Ra of 2.116 µm and Sa of 4.419 µm. This happens as the increase in cutting temperature during milling at high cutting speeds causes tool wear and results in poor surface roughness.

(d) Wet milling shows different observations, where the lowest cutting speed (50 m/min) shows the highest surface roughness value (Ra=1.825 µm, Sa=2.676 µm). The smearing of the matrix resin due to the high temperature causes the machined surface to be smoother.

(e) The machined surface topography of CFRP in dry milling at the highest cutting speed of 100 m/min exhibits poor surface roughness and texture, as proven by the varied colours in the pseudo-colouring of the height subrange. Those colours also indicate the occurrence of fiber pull-out, matrix smearing and delamination.

(f) In wet milling, the highest cutting speed (100 m/min) highly affected the machined surface, as obvious damage such as fiber pull-out, fiber fracture and delamination were significantly observed under the SEM. This is due to the higher rate of tool wear that causes the material to fracture and results in degradation of surface quality.

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