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RESEARCH ARTICLE

Milling-Induced Surface Roughness in Carbon Fiber Reinforced Polymer: A Diagnostic Study between R_a and S_a

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ABSTRACT - Carbon Fiber Reinforced Polymer or CFRP is among the composite with high utilisation especially in the high-end industrial sectors such as automotive, aviation and architecture. This is due to its superior characteristics such as excellent strength-to-weight ratio, high stiffness and corrosion, and can be manufactured near its end shape. However, the abrasive nature originated from the carbon fiber impregnated in the epoxy resin creates an anisotropic and inhomogeneous material. It is a challenge to machine the CFRP as the carbon fiber abraded the cutting edges. This implicated in the tool wear progression, thus affecting the surface quality of the CFRP. Since the CFRP is impregnated in the epoxy resin, machining must be conducted below the glass transitional temperature (Tg), to avoid degradation of the polymer to occur. This study investigates the influence of different cutting environments (dry, coolant and chilled air) on the surface evaluation of the CFRP during the milling process with a constant V_c = 150 m/min and V_f = 2100 mm/min. The surface roughness was evaluated by both R_a and S_a. There is a minimal contrast in the R_a values along the milling process, whereas the S_a value shows significant increases across the machining process for all the conditions of dry, coolant, and chilled air. It is indicated that milling in dry conditions produced S_a values that were 28.23 % and 14.48 % higher compared to coolant and chilled air, respectively. These values highlight the efficiency of coolant and chilled air in reducing the heat generation. This reduction minimizes the thermal effects thus improving the surface quality. Flooding the cutting zone with coolant prominently helps in reducing the heat produced from the friction between the CFRP and the mill tool. It is evidently supported and visualised by the pseudo-color depth maps of the areal surface roughness analysis. The areal surface roughness, S_a proven to be beneficial in understanding the surface topography and condition for inhomogeneous materials like CFRP. It justifies the occurrences of surface damages such as delamination, matrix smearing, and fiber pull out when observed under the scanning electron microscope. This study emphasizes the importance of suitable cooling method to maintain the integrity of the CFRP surfaces.

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1. INTRODUCTION

Carbon fiber reinforced polymer or CFRP is a polymer matrix composite (PMC) globally known for its superior strength-to-weight ratio, high stiffness and high resistance to corrosion [1]. Possessing these remarkable attributes make CFRP highly advantageous over metallic materials. The versatility of this composite has been demonstrated through its applications across advanced sectors such as aerospace, automotive and architecture. In the automotive industry, CFRP has been integrated as part of the materials components such as bumper and roof panel. This integration aims to optimize the fuel consumption by reducing the weight of the vehicle thus improving the performances of the automobile while upholding the standard safety requirements. The durability and lightweight of the CFRP also being manifested through the airframe structure such as the vertical stabiliser, tailplane, flaps and wings skin of the aircraft which reduces up to 25% of its initial weight. This is also aligned with the four pillar strategies introduced by International Air Transport Association (IATA) encompassing the enhanced technologies, streamlined aircraft operations, infrastructure enhancements and economic uplift initiatives. A review by Ahmad et al. [2] on the applicability of CFRP suggested that replacing the steel with CFRP potentially reduces the vehicle weight by 60%. This advantage is also agreed by Atescan-Yuksek et al. [3] during comparing the life cycle assessment of aluminium and CFRP in aerospace manufacturing in their study on the aircraft wing skin panels features. They supported their study with the break-even analysis which indicates the non-crimp fabric (NCF) carbon fiber stands out as the most eco-conscious material capable of covering 100,000km flight distance when compared to aluminium.

Besides its properties, CFRP offers the advantage of near-net-shape manufacturing, reducing or eliminating extensive machining [4]. However, secondary machining such as drilling and edge milling is inevitable to ensure that the composite meets the product dimensional requirement and the geometrical structure [5]. CFRP displays an abrasive nature

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originated from the anisotropic and inhomogeneous characteristic that stems from the distinct physical and mechanical characteristic of the carbon fiber and matrix resin [6]. These characteristics of CFRP affects the tool wear and surface quality during the machining process. It complicates the material removal process which results in the shortening of the tool life caused by the abrasiveness of the carbon fiber and inducing the surface damage on the machined surface of CFRP to occur [7]. Fabricating CFRP is also known to be an intricate process, as machining the composite above the matrix resin's glass transition temperature (Tg) exposes significant risks to its structural and thermal integrity. It is the temperature where the resin transforms from rigid solid to soft rubbery state. Machining with high cutting speed potentially leads to high cutting temperature that exceeds the Tg therefore soften the matrix resin [8]. This condition will contribute to the degradation of the matrix resin that will alter the mechanical and physical properties of the CFRP and affect the quality of the composite. It prompts defects such as fiber pull-out, delamination and matrix cracking [9]. The application of coolant has been a common practice in effectively reducing the heat produced especially on the machining zone during the machining process [10]. It also aids in flushing the material removal in the forms of chips away from the cutting zone, thus preventing disruption on the cutting edge and improving the surface quality [11]. However, in processing polymeric material, absorption of moisture can occur between the laminate thus distorting the adhesion between the layer of the composite [12]. Therefore, chilled air has been an alternative cooling method in reducing the cutting temperature during the material removal process. Studies show machining with the assistance of chilled air or cryogenic decreases the progression of tool wear and improves the surface quality of CFRP in contrast to dry condition [10]. It clarifies the influence of cutting conditions on the machining performance of the CFRP.

The evaluation of the surface roughness is one of the analyses that are normally performed to evaluate the machinability of the CFRP. It interprets the interaction between the cutting tool and the work materials during the machining process. The examination of the surface roughness illustrates the effect of the machining parameters such as the cutting speed, feed rate and cutting condition on the CFRP. Among the commonly used metrics, R_a (arithmetic mean height of profile line) is a two-dimensional parameter of surface roughness measured along a single line across a surface [13]. It is widely applied for the analysis of flat or cylindrical surface where a single value from the line measurement sufficiently characterizes the surface texture. R_a commonly used to examine the surface of the work material with isotropic and homogenous characteristics such as metals. In contrast, S_a (arithmetic mean height of the surface area) is the extension of R_a with three-dimensional parameter quantified over a defined surface area as illustrated in Figure 1.

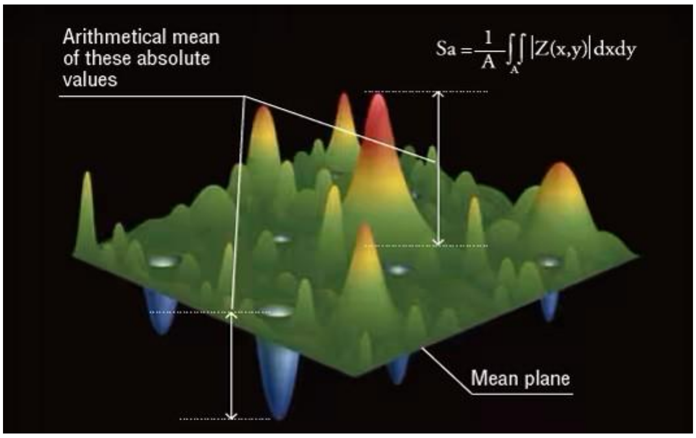

Figure 1. Illustration of Sa measuring principle (areal scanning measurement) [14]

S_a provides three-dimensional evaluation of the entire defined surface area by including its waviness and uniformity into its measuring principles. The dimensionality of S_a provides extensive comprehension of the areal surface texture especially in cases where line measurement such as R_a, inadequately defines the surface characteristics. This is because defects formed in composite materials differ from those in metals where it sufficiently presented only by R_a. S_a is proficient in examining material with anisotropic and inhomogeneous characteristics such as the non-uniform texture between the laminate of the carbon fiber and the matrix resin. Therefore, S_a serves as an extensive parameter to R_a, which is incapable of accurately describing the surface topography of anisotropic and inhomogeneous surfaces, particularly CFRP [15].

Therefore, the application of S_a as an extension of R_a is appropriate to measure and analyse the surface of CFRP with damages such as matrix smearing, fiber cracking and fiber pull out. He et al. [16] critically compares the concept, development and applications of the measuring parameters for R_a and S_a. They agreed on the dominance of the profile roughness in surface roughness as the standard surface evaluation method in the industry. However, the capability of areal surface roughness in analysing the complexity of surface roughness is undeniably equally significant.

1.1 Effect of Cutting Conditions on Surface Roughness

Machining at higher cutting speed potentially leads to higher cutting temperature which soften the matrix resin. This condition will contribute to the degradation of the matrix resin which alters the mechanical and physical attributes of the CFRP and affect the quality of the composite. It prompts irregularities such as matrix cracking, fiber pull-out and delamination to occur. The application of coolant has been a common practice in effectively reducing the heat generated especially on the cutting zone during the machining process [17]. It also aids in removing the material removal in the forms of chips, away from the cutting zone, thus preventing disruption on the cutting zoon and improving the surface quality [18]. However, in processing polymeric material, absorption of moisture can occur between the laminate thus distorting the adhesion between the layer of the composite. Consequently, chilled air has been an alternative cooling method in reducing the cutting temperature during the material removal process [19]. Studies show that machining with the assistance of chilled air or cryogenic decreases the progression of tool wear and improves the surface roughness of CFRP in contrast to machining the CFRP in dry condition. Rodriguez et al. [20] evaluated the effect of different cutting conditions such as dry, flood of fluid, optimized lubricants and minimum quantity lubrication (MQL) on surface roughness of CFRP. Their findings revealed that the highest surface roughness of 2.2 µm was recorded when milling in MQL while the lowest surface roughness of 0.5 µm was measured when employing optimized lubricants. It is believed that grinding CFRP with MQL offers a little or no cooling effect, similar with dry conditions [20]. In another study, Danish et al. [21] compares the efficiency between sustainable cooling conditions in the milling performance of the CFRP. This study is pertinent due to the minimal resistance to heat of the polymer matrix and the absorption of moisture that will threatening the composite stability. Carbon dioxide (CO_{2ice}) proven to produce the lowest surface roughness of 0.77 µm in contrast to 0.85 µm, 0.97 µm and 2.12 µm of cryogenic-liquid nitrogen ($N_{2liquid}$), minimum quantity lubrication (MQL) and dry condition, respectively [21].

Therefore, the objective of this paper is to investigate the influence of different cutting conditions on surface evaluation of the CFRP by comparing the value of R_a and S_a as the surface texture evaluation. The experiment was designed to be in full factorial method to explore the effects of the cutting parameters and cutting conditions on the surface roughness of the CFRP. This paper aims to highlight the critical role of cutting environment in milling CFRP and the evaluation method of the surface roughness.

2. METHODS AND MATERIAL

Carbon fiber reinforced polymer (CFRP) was selected as the primary workpiece in these experiments with its properties tabulated in Table 1. End mill tool made of uncoated tungsten carbide (WC-Co) with specifications of 6 mm diameter and 30° helix angle displayed in Figure 2(a) served as the main cutting tool in this experimental work. A new cutting tool was used for each condition, totalling to three end mill tools. The properties of the cutting tool were displayed in Table 2. The end milling of the CFRP was performed using Nexus 410A-II Vertical Machining Centre by Mazak as illustrated in Figure 2. The CFRP panel with a dimension of 200 x 200 x 5 mm and CFRP strip with a dimension of 200 x 50 x 5 mm have been securely clamped separately on the machine table as shown in Figure 2(b). The CFRP panel was used to monitor the distance travelled by the end mill tool during the milling while the CFRP strip was utilized for the surface roughness measurement. The milling of the CFRP was repeated with the same cutting speed in different environments which are dry, coolant and chilled air as tabulated in Table 3 to analyse the effect of the cutting conditions on the surface evaluation of the CFRP. For the coolant cutting condition, fully synthetic fluid of Belling X-Ten C82 specifically formulated for tool bit cooling and lubrications was utilized. The coolant was supplied through the nozzle that already installed in the machine tool. The cold air was delivered through external nozzle which is the Vortec Cold Air Gun when milling in chilled air condition. To maintain the - 9° C temperature of the cold air exiting from the nozzle, the pressure of the air was maintained constant at 6.9 bar pressure throughout the experimental work. The nozzle was located 10 mm from the cutting tool throughout the experiment to maintain the consistency of the cooling effect as displayed in Figure 2(c).

Table 1. CFRP material properties

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

Table 2. Cutting parameters of milling CFRP

Cutting speed (V_c), m/min	Feed rate (V_f), mm/min	Radial depth of cut, mm	Machining distance, mm	Machining environments
150	2100	2	6000	Dry, coolant, chilled air

Prior to the analysis, each of the milled CFRP strips was cut into 10 mm width to facilitate the measurement process and were cleaned before the surface roughness and damage observation. Surface roughness was measured using an Alicona SL 3D profiler with 5x magnification lens, cut off length of 4.0 mm and 0.8 mm evaluation length, in accordance with ISO 4288. Both R_a and S_a values were recorded with supported surface topography images for comprehensive surface assessment. The surface roughness measurements were taken at 600 mm intervals along the machining distance with a total of 10 intervals, equivalent to 6000 mm machining distance. Three different points were taken at each CFRP machined surface and the average for the R_a and S_a was measured. For damage mechanism observation under scanning electron microscopy, the CFRP strips were coated with gold palladium by Quorum SC7620 Mini Sputter Coater. To observe the surface condition and damages that formed on the machined surface, Jeol JSM-5600 Schottky Field Emission scanning electron microscope was employed. The machined surfaces were further analysed using EDX analysis to determine the elemental composition on the surface. These procedures were repeated for all CFRP strips for all cutting conditions.

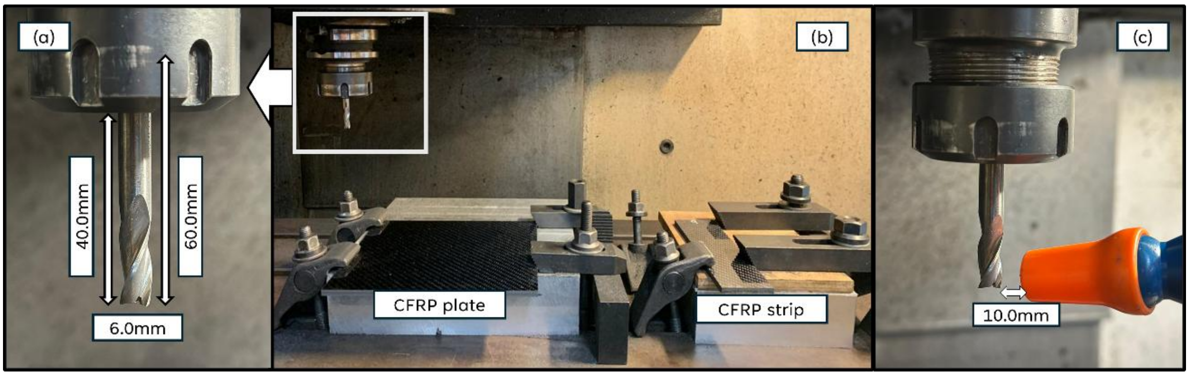

Figure 2. (a) The cutting tool that employed in this study, (b) the experimental setup in milling the CFRP and (c) the distance of the cold air gun nozzle from the cutting tool for chilled air cutting conditions

3. RESULTS AND DISCUSSION

Figure 3(a) and Figure 3(b) display and compare the progression of surface roughness in R_a and S_a when milling the CFRP at V_c = 150 m/min in dry, coolant and chilled air. The results indicate that the highest average surface roughness, R_a of 2.018 µm was recorded when milling the CFRP in dry condition after milling for 4800 mm. It is noticeable that dry cutting condition produced highest value of R_a compared to coolant and chilled air and the trend remains nearly consistent across all the cutting distance. Employing high V_c = 150 m/min has yielded in the increasing of the heat produced due to the friction between the tool edge and the work surface. It leads to the deterioration of the matrix resin that softens the matrix resin which eases the material removal process. It weakens the bond between the polymeric resin and carbon fiber laminates, resulting in damages like matrix smearing, fiber breakage and fiber pull-out. Therefore, alternatives such as coolant and chilled air have been introduced in reducing the heat generated during machining. Milling with the presence of coolant and chilled air has proven to lower the heat generated especially at the cutting zone therefore produced the lowest R_a of 1.429 µm and 1.179 µm respectively after 6000 mm machining length as agreed by Rodriguez et al. [20]. The gradual increase in R_a and S_a throughout the milling is attributed to the rounding of the cutting edges that occur during machining. It reduces the efficiency of removing the machined surface, leading to higher surface roughness values. This condition also subjected the CFRP machined surface to shearing and tensile fractures which resulted in the formation of defects especially fiber pull out and matrix smearing [22].

As discussed previously, areal surface roughness, S_a as an extension of R_a is vital to further understand the anisotropic and inhomogeneous characteristic of CFRP. The areal measurement, S_a is more reliable in understanding the non-uniform surface of carbon fiber laminates impregnated with epoxy resin [15]. It is observed in Figure 3 that the reading of S_a measured was consistently higher than the value of R_a. This phenomenon can be clarified by the difference in measuring principles between R_a and S_a. While R_a was measured over a cut of length, S_a was obtained by scanning a definite area of the machined surface for absolute peak-to valley values. Figure 4 illustrates the difference in measuring mechanisms between profile line of R_a and areal parameter of S_a. R_a measures the profile of the line across the machining feed while the S_a evaluates through the defined measuring area. This condition explains the higher value of S_a of 4.526 µm when compared to R_a of 2.505 µm after milling the CFRP at 150 m/min in dry condition for 6000 mm. The higher value in S_a also reflects the surface texture of the CFRP which is supported by the interpretation of the pseudo-color depth maps of surface topography.

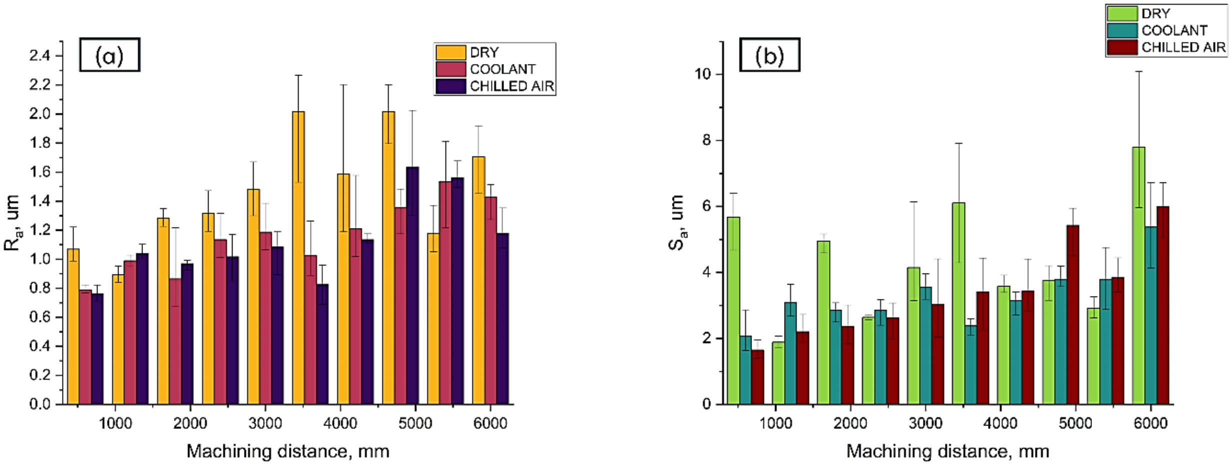

Figure 3. The average surface roughness after milling the CFRP in dry, coolant and chilled air measured in (a) R_a and (b) S_a

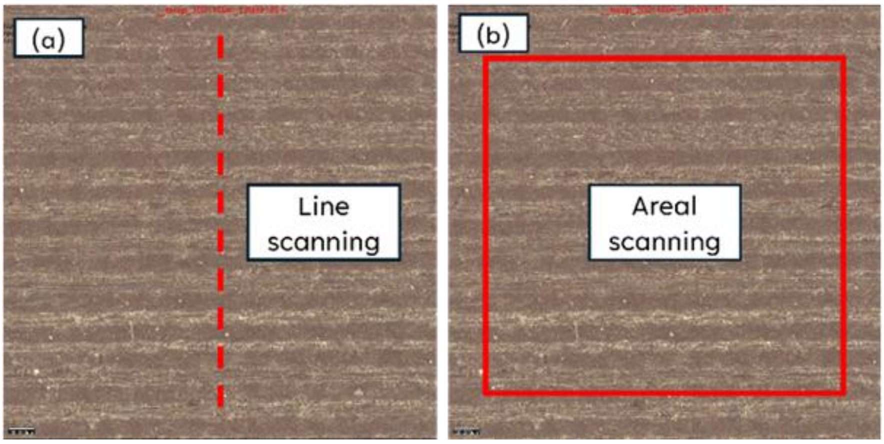

Figure 4. The difference between the profile line measurement of R_a and the areal scanning measurement of S_a

Further insight on R_a and S_a can be developed through Figure 5 where it compares the surface topography after milling the CFRP with 150 m/min in dry, coolant and chilled air condition. The surface topography with pseudo-color depth maps reflects the condition of the scanned surface under the 3D profiler. It can be observed that the result after milling in dry, coolant and chilled air show a similarly minimal increase in R_a value from 600 mm to 6000 mm machining distance. However, the progression of S_a along the machining distance for dry, coolant and chilled air contradicted the trend in R_a due to the areal parameters of S_a. This can be exemplified with the high reading of S_a = 5.966 µm when compared to the reading of R_a = 0.988 µm in dry machining for 6000 mm. This also justified that the rounding of the cutting edges affects the efficiency of the composite removal mechanism during the cutting process.

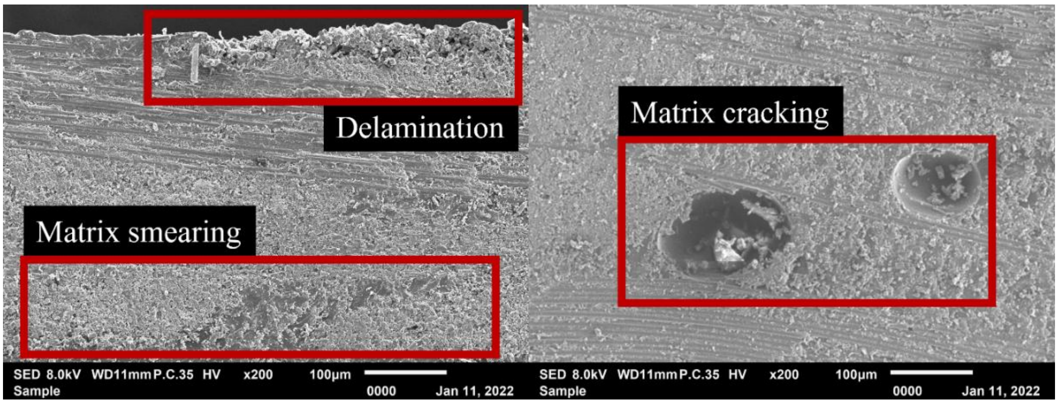

Figure 5. SEM images of delamination, matrix smearing and matrix cracking on CFRP machined surface in dry condition after 6000 mm machining length for cutting speed 150 m/min

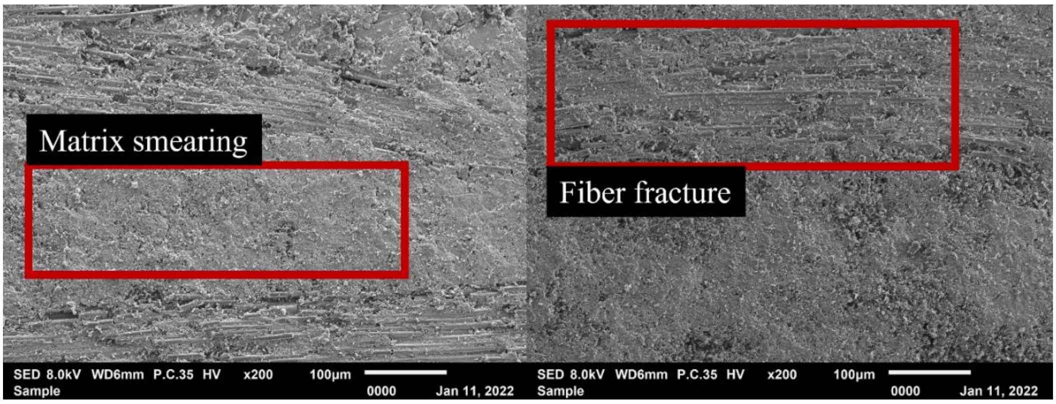

Figure 6. SEM images of delamination, matrix smearing and matrix cracking on CFRP machined surface in coolant condition after 6000 mm machining length for cutting speed 150 m/min

The surface topography further clarifies the effects of cutting conditions on the surface roughness of the CFRP. Through the surface topography and the value of S_a also, it is noticeable that machining in dry conditions resulted in higher S_a and supported with the pseudo-color depth maps. These establish the fact that machining in dry condition resulted in higher heat generated compared to coolant and chilled air. As discussed before, the heat generated may surpasses the glass transitional temperature (Tg) of the epoxy resin therefore causing degradation of the polymer to occur.

It reduces the adhesion between the laminates therefore initiating surface damages such as matrix cracking, matrix smearing, and delamination as illustrated in Figure 6. As mentioned before, the rounded of the cutting edges that contributes to the inefficiency of material removal process that causes damages such as fiber fracture to happen also visualised through the metallography analysis using scanning electron microscope. Even though Surface damages also occur on the surface of CFRP while milling in both coolant and chilled air, they are minimal compared to dry condition as shown in Figure 6 and Figure 7 respectively.

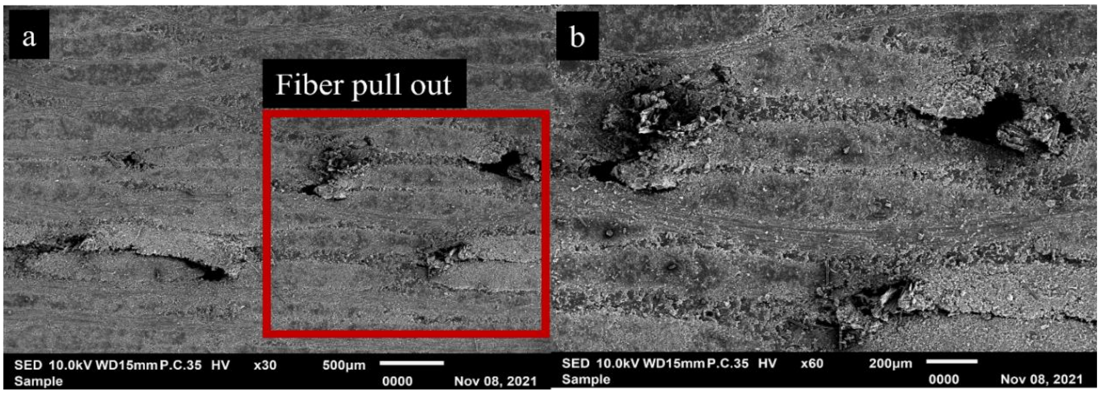

Figure 7. SEM images of delamination, matrix smearing and matrix cracking on CFRP machined surface in chilled air condition after 6000 mm machining length for cutting speed 150 m/min

4. CONCLUSION

It can be determined that milling the CFRP with V_c = 150 m/min and V_f = 2100 mm/min in dry, coolant and chilled air has resulted in:

- The inefficiency of the rounded cutting edges of the solid carbide router tool leads to increase in surface roughness value and defects along the machining length. This is due to the cutting tool inability to effectively shear the CFRP during the milling process.
- Dry cutting generates excessive heat, resulting in higher value of R_a= 1.453 μm and S_a = 7.341 μm, compared to milling in coolant and chilled air.
- Coolant and chilled air improve surface quality by reducing thermal effects, shown by lower S_a value, which are 5.269 μm and 6.278 μm after milling in coolant and chilled air, respectively.

The areal surface roughness, S_a as an extension to the profile line roughness R_a, provides more comprehensive evaluation for the anisotropic surface of CFRP. It is supported by the three-dimensional pseudo-color maps and SEM observations of damage such as matrix smearing, fiber pull out and delamination

CONFLICT OF INTEREST

The authors declare no conflicts of interest.

AUTHORS CONTRIBUTION

A.M. Mustafa (Writing – original draft, methodology, analysis)

N. F. H. A. Halim (Writing – review & editing, supervision)

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