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The Impact of Cutting Speed and Feed Rate on Tool Wear and Surface Damage During the Milling of CFRP Composites

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ABSTRACT
Renowned for their high specific stiffness and exceptional structural integrity, carbon fibre reinforced polymer (CFRP) has become indispensable in advanced aerospace and automotive engineering. However, the machining of these composites presents significant difficulties due to their abrasive constituents and anisotropic architecture. During milling, common problems such as rapid tool degradation, delamination of fibres, matrix debonding, and compromised surface finish are frequently observed. This study investigates the extent of tool deterioration and associated surface impairments during the dry milling of CFRP using an uncoated 8 mm tungsten carbide end mill. A selection of cutting parameters which is cutting speeds (100, 150, and 200 m/min) and feed rates (450, 600, and 850 mm/min) were examined during milling of CFRP. The results reveal that cutting speed predominantly affects tool degradation, accounting for a 62.1% increase in wear, while feed rate contributed to 42.7% of the variation. Microscopic analysis of the machined surfaces highlighted defects such as fibre rupture, resin smearing, interlaminar separation, and cracking-phenomena intensified by elevated thermal loading at higher cutting speeds. Based on the outcomes, employing moderate feed rates and lower cutting velocities is recommended to enhance surface integrity and prolong tool usability under dry machining conditions.
Keywords: CFRP; milling; tool wear; tool damage

1 INTRODUCTION

In recent years, carbon fiber-reinforced polymer (CFRP) composites have gained widespread application across various sectors, including aerospace, transportation, sports equipment, and civil infrastructure. This adoption is largely due to their superior mechanical performance-specifically, high stiffness, tensile strength, and fatigue resistance—combined with low density. These advantages have led to CFRPs constituting over half of the structural components in advanced aircraft such as the Airbus A350, where they are used in fuselage sections, wing assemblies, doors, and tail structures. The integration of CFRP materials enhances aircraft capacity, improves fuel economy by up to 20%, and extends flight range, demonstrating their effectiveness over traditional metallic materials.

Typically, CFRPs are fabricated near net-shape by stacking multiple layers of fiber-resin sheets in a laminate form. Despite this near-finished state, secondary machining processes like milling and drilling remain necessary to achieve dimensional precision and remove excess material. However, machining CFRP presents several complications due to its heterogeneous composition. The brittle nature of carbon fibers, coupled with the abrasive characteristics of the polymer matrix, makes tool selection and cutting parameter optimization particularly critical in conventional machining operations. If not appropriately managed, the machining process can result in severe tool wear, elevated cutting forces, and suboptimal surface quality, potentially leading to part rejection during final inspection.

A significant volume of scholarly work has analysed the influence of key machining parameters—namely cutting speed, feed rate, and depth of cut—on tool degradation and the resulting surface integrity. For example, Ozkan et al. [5] reported reduced tool wear at higher cutting speeds, whereas Mustafa et al. [6] observed increased tool deterioration under similar conditions when using uncoated solid carbide end mills. Their findings noted wear values of 0.072 mm at 132 m/min compared to 0.061 mm at 94 m/min, attributing the difference to the softening of the composite under thermal stress. Similarly, Rashid et al. [7] indicated extended tool life at higher speeds, noting a

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35.88-minute lifespan at 160 m/min, compared to only 14.4 minutes at 17 m/min, likely due to decreased mechanical resistance in the composite at elevated temperatures. Shahruddin et al. [8] recorded a 27% decrease in tool wear when operating at 132 m/min instead of 170 m/min, attributing this improvement to reduced frictional forces and slower cutting edge degradation. In contrast, increasing cutting speeds can also raise chip thickness and cutting forces, amplifying surface damage. Erkan et al. [9] demonstrated that a rise in cutting speed from 62 to 113 m/min correlated with a 7.8% increase in surface damage, likely caused by enhanced plastic deformation of the polymer matrix. Nguyen-Dinh et al. [10] further noted that higher feed rates exacerbate surface defects by exceeding the shear limits of the material, contributing to crack propagation between laminate layers. To mitigate such damage, several studies advocate for lower feed rates to reduce delamination, although Voss et al. [11] presented an opposing view, suggesting that increased feed rates can limit contact time, thus minimizing workpiece damage.

These findings underscore the complex relationship between machining parameters and the machinability of CFRPs. The current study aims to evaluate the influence of cutting speed and feed rate on tool wear progression and the resultant damage mechanisms on CFRP surfaces during milling with uncoated carbide tools under dry cutting conditions

2 EXPERIMENTAL SET UP AND RESEARCH METHODOLOGY

All milling trials were conducted in a dry cutting environment utilizing an uncoated solid tungsten carbide end mill with a diameter of 8 mm, manufactured by Precisetech Sdn Bhd. The machining was carried out on a Mazak Nexus 410A-II vertical machining center. Two distinct carbon fiber-reinforced polymer (CFRP) sample types were prepared for this investigation: 200 mm-wide panels and 50 mm-wide strips, both with a consistent thickness of 3 mm. The CFRP materials were supplied by PiCarbon Sdn Bhd. The larger panel specimens were used to evaluate tool wear over extended machining distances, whereas the narrower strips were designated for analyzing surface integrity after each cutting trial. The selected cutting tool was a three-fluted uncoated tungsten carbide bit, 8 mm in diameter, as illustrated in Figure 2 and detailed in Table 1. The CFRP workpieces, shown in Figure 3 and specified in Table 2, were sectioned into 3 mm-thick pieces with two widths: 200 mm panels for tool wear studies and 50 mm strips for surface damage inspections. Each new strip was replaced after every 1-meter pass to ensure consistent evaluation of surface condition. Cutting parameters—namely, cutting speed and feed rate—were varied across three levels as summarized in Table 3, while the depth of cut was held constant throughout all tests.

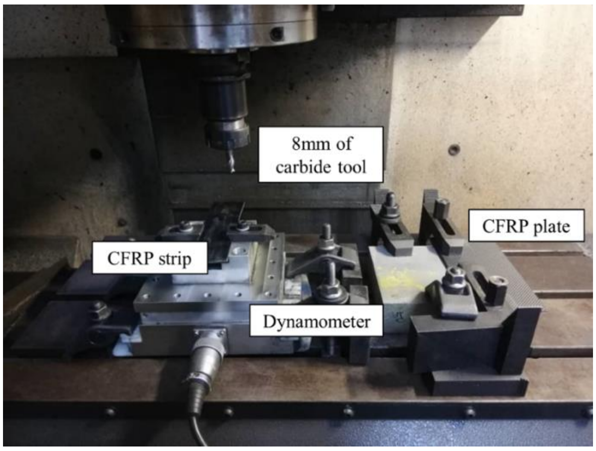

Figure 1: Experimental setup

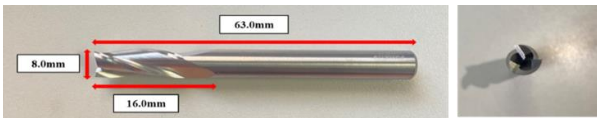

Figure 2: 8 mm of uncoated tungsten carbide tool

Table 1: K3EPEN 080U tool supplied by Precisetech specification

Specification	Number of flutes	Tool Diameter (mm)	Shank (mm)	Length of cutting (mm)	Helix Angle
Value	Three	8	8	14	30

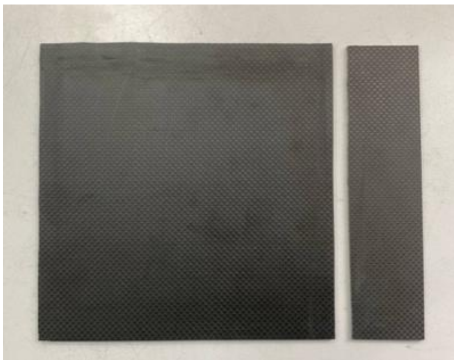

Figure 3: CFRP plate and strip

Table 2: The specification of CFRP workpiece

Specification	Density (g/cm3)	Tensile strength (MPa)	Tensile modulus (GPa)	Fibre mass per unit area	Fabric type	Fiber volume fraction
Value	2.0	4000	430	281	ABR 1-0006	40/60

Table 3: Combination of cutting parameters employed in milling of CFRP

Parameters	**Value**
Cutting speed (*V*), m/min	100, 150, 200
Feed rate (*f*), mm/min	450, 600, 850
Depth of cut, mm	3 mm
Cutting condition	Dry

Tool wear was monitored at 1-meter intervals up to a total cutting length of 20 meters. Measurements were performed using a Dino-Lite handheld digital microscope at 95x magnification, which was linked to DinoCapture 2.0 software for capturing and measuring the wear on each of the tool's flutes. For each flute, flank wear was quantified at three different points, and the average value was recorded for analysis. Surface damage mechanisms were investigated using scanning electron microscopy (SEM). Before SEM examination, the machined surfaces were cleaned using an ultrasonic bath. To facilitate SEM conductivity, a thin layer of gold was sputtered onto the CFRP surfaces prior to imaging. This allowed for detailed visualization of the machining-induced defects such as delamination, matrix degradation, and fiber breakage.

3 RESULTS AND DISCUSSIONS

3.1 Effect of Cutting Speed on Tool Wear Development

Figure 5 illustrates how tool wear evolves over a 20-meter machining distance under varying cutting speeds, while maintaining a constant feed rate. The results indicate a direct relationship between cutting speed and tool degradation. The greatest wear, measured at 0.107 mm, was observed when machining at 200 m/min with a feed rate of 850 mm/min. Conversely, the lowest wear recorded was 0.063 mm, corresponding to 100 m/min and 450 mm/min.

This increase in wear with higher cutting speeds can be attributed to elevated frictional forces at the tool–workpiece interface. Given the abrasive nature of CFRP, greater cutting speeds accelerate tool abrasion and thermal buildup. As noted by Ghafarizadeh et al. [17], increased sliding interaction contributes significantly to heat generation, especially when the cutting temperature nears the glass transition temperature (Tg) of the matrix resin. Once this threshold is approached, both thermal and mechanical stress intensify, further hastening tool degradation [18].

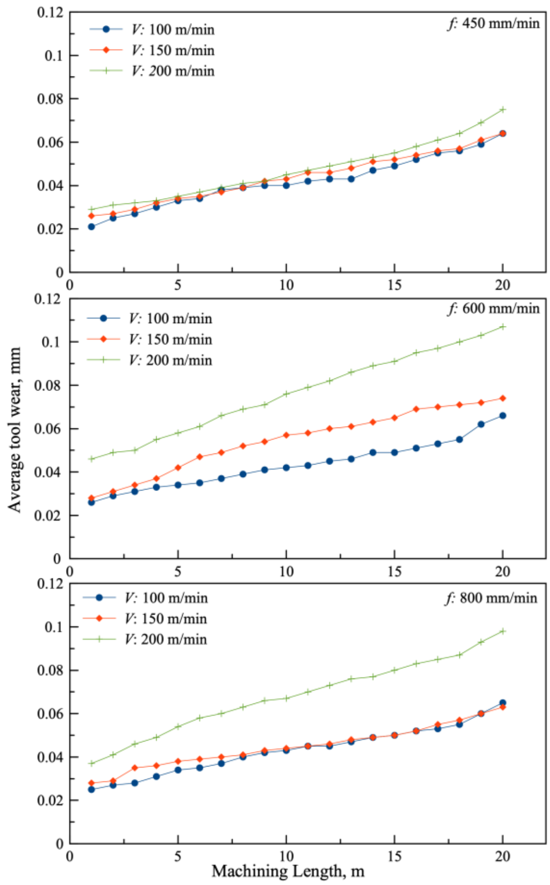

Figure 5: Progression of tool wear of WC-Co uncoated end mill over 20 m machining length

3.2 The Effect of Feed Rate on Progression of Tool Wear

Figure 6 displays the impact of different feed rates—450, 600, and 850 mm/min—on tool wear progression at three constant cutting speeds (100, 150, and 200 m/min). A general increase in wear was observed as machining distance extended. The most severe tool degradation, again reaching 0.107 mm, was seen at the highest feed rate (850 mm/min). As depicted in Figure 6, average tool wear exhibited a progressive increase with machining distance across all cutting speed conditions. Similar pattern was observed when cutting speed had remained constant where highest tool wear (0.107mm) was observed at higher feed rate, 850 mm/min. This can be explained by the development of high cutting forces during the machining process to produce higher tool wear. Higher feed rate increased in friction forces due to an increase in the contact area of tool-workpiece interfaces cause increasing of thickness the chip load which required more energy to remove unnecessary material when machining CFRP [19] . The generation of cutting forces as the feed rate increased also prompted instability in the cutting process due to vibration in machining which contributed to higher tool wear of the carbide tool [20]. The influence of feed rate on tool wears progression having a minor effect as the highest percentage difference give only 42.7 % compared to 62.1% given by the effect of cutting speed. As shown in Figure 6, varying the feed rate while maintaining a constant cutting speed resulted in no significant difference in average tool wear.

Figure 7 shows the cutting tool condition observed under Scanning Electron Microscopy (SEM). Figure 7(a) indicates fresh cutting tool whereas, Figure 7 (b) and (c) indicate the condition of cutting tool after 20 metre machining length. It was observed that the cutting tool edge becomes rounded after the machining stop. The fresh carbide tool displayed clear, well-defined lines prior to milling CFRP. In contrast, Figures 7 (b) and (c) reveal that these lines became blurred and the cutting edges lost their sharpness, resulting in rounded edges after edge trimming CFRP at cutting speeds ranging from 100 to 200 m/min and feed rates between 450 and 850 mm/min. This indicates that a continuous rubbing action occurred between the cutting tool edges and the hard CFRP material, causing gradual wear regardless of the cutting speed and feed rate combination when using an uncoated tungsten carbide (WC) tool. It was also observed on the cutting tool surface the voids which indicates the dislodgment or pull-out of WC-Co particles form the tool. The dislodgment of WC-Co particles from the carbide tool occurred due to abrasive interactions. Continuous abrasion between the tool and CFRP during machining gradually removed the cobalt binder that holds the harder tungsten carbide particles together. As a result, under compressive stress, WC-Co particles were pulled out because the cobalt binder could no longer adequately secure the tungsten carbide grains.

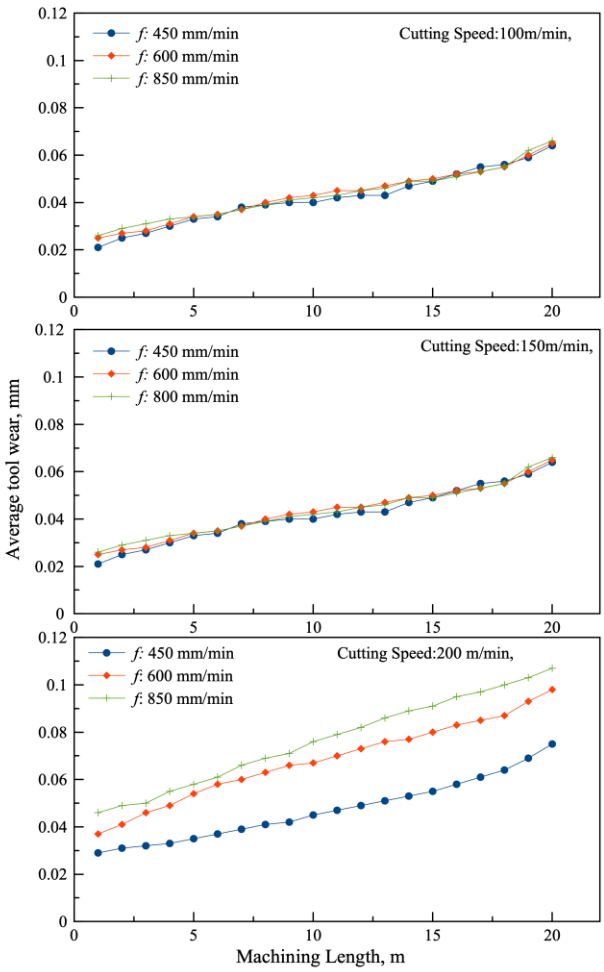

Figure 6: Comparison of the progression of tool wear at different feed rate.

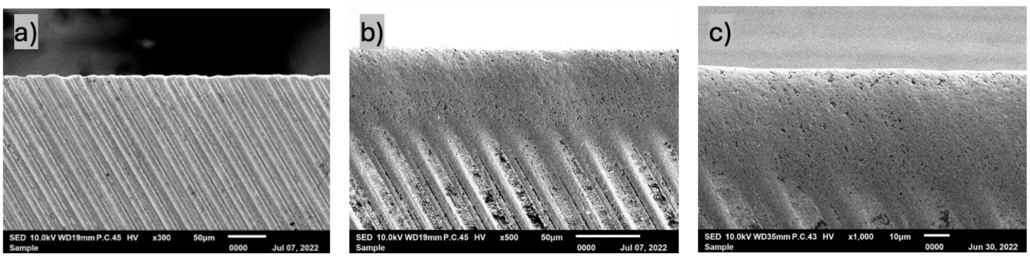

Figure 7: The tool wear mechanism observed under SEM a) new tool b) and c) cutting egdge rounding indicates the worn out tool

3.2 Observation on the Effect of Cutting Parameters on Damage Mechanism

The impact of cutting speed and feed rate variations on surface damage mechanisms of CFRP was analysed after a 20-meter machining length, as illustrated in Figures 8, 9, and 10. The machined surfaces displayed delamination along the external laminate layers. Elevated friction during milling increased the cutting temperature, approaching the epoxy matrix's glass transition point. This thermal condition softened the resin, diminishing its ability to support the carbon fibres, thus promoting fibre-matrix separation. Progressive tool wear under continued compressive stress at the tool-workpiece interface facilitated the formation of unsupported fibre layers, contributing to delamination. He et al. [23] noted that such abrasive interactions increase out-of-plane shear, causing fractures to develop in the uncut chip during cutting. In this study, delamination was particularly noticeable at higher feed rates (600 and 850 mm/min), as depicted in Figures 8(a–c), confirming that excessive force accelerates layer separation in CFRP laminates [24].

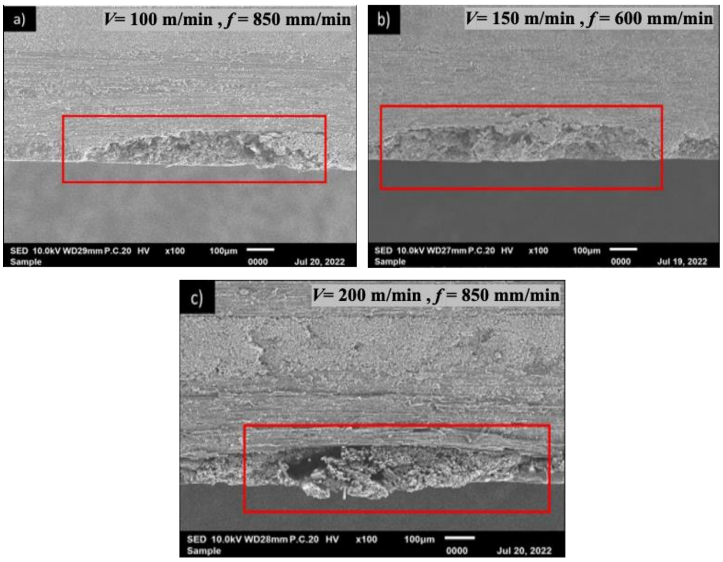

Figure 8: SEM micrograph of CFRP surface with delamination occurrence

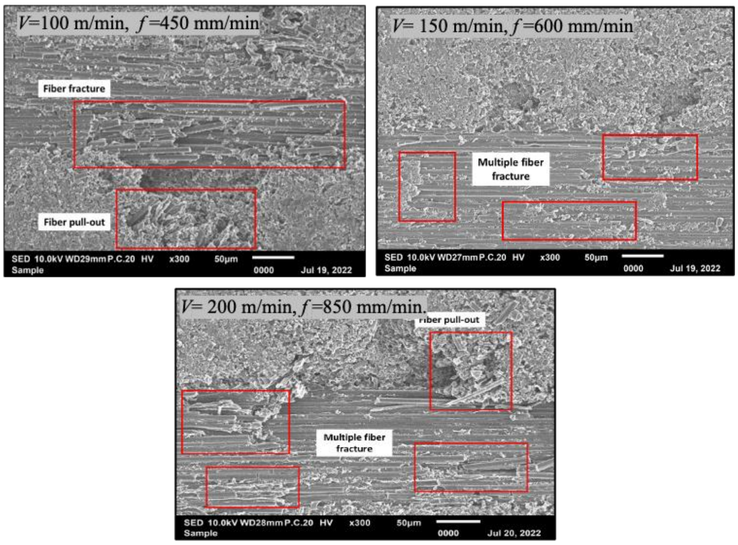

Figure 9: Fiber fracture and pull-out were identified on the CFRP surface following a machining length of 20 meters

Fiber breakage was another common defect observed. Due to the brittle nature of CFRP, fibres tended to fracture into smaller fragments under tool-induced compression during milling. These fibres lack plasticity and therefore fail under bending stress. Additionally, broken fibre debris can become trapped at the tool–workpiece interface, worsening abrasion and increasing the risk of further breakage. As flank wear developed over time, tool edges applied more stress to the fibres, pushing them beyond their bending limit and resulting in crushing-dominated failure modes [25]. Such surface degradation may further induce defects like fibre pull-out, compounding the deterioration of the machined finish [26]. These effects were most severe when using higher cutting parameters (200 m/min at 850 mm/min), where surface roughness and fibre damage were significantly amplified.

As shown in Figure 9, fibre pull-out appeared across all machining conditions. As the tool dulled over time, the resultant shear stress on the fibres increased. CFRP's low shear strength allows fibres to shear off and slide along the cutting edge, especially when a worn tool imposes higher bending loads, propagating cracks along the fibber's radial direction. Pull-out was detected even at low speed/feed settings (100 m/min, 450 mm/min), but became more prominent at extreme conditions (200 m/min, 850 mm/min). Matrix smearing was another recurring defect observed after 10 meters of cutting, as shown in Figure 9. Increased cutting speeds led to elevated temperatures, and once the temperature neared the matrix's glass transition point, thermal degradation of the resin occurred. This softened resin smeared across the machined surface. The combination of heat and extended contact between a worn tool and the CFRP surface caused this resin deformation. At higher cutting speeds and feed rates (200 m/min and 850 mm/min), resin smearing was far more evident than at lower parameters (100 m/min, 450 mm/min), indicating a greater risk of long-term mechanical property loss due to thermal effects. This finding was supported by the Abd Halim et al.[28] where they found that when the cutting temperature increases although not exceeded the glass transition temperature of the matrix resin, it was observed that the machined surface of the CFRP was thermally degraded. It was found that the smeared matrix covered the CFRP's machined surface that affect the value of the surface roughness.

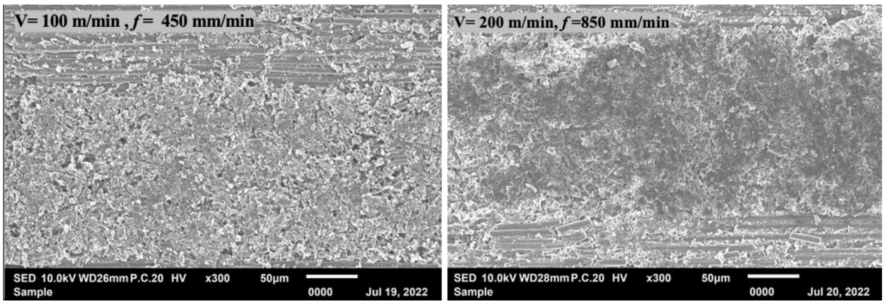

Figure 10: SEM images of matrix smearing of CFRP machined surface after 10 meters of machining traveled

4 CONCLUSIONS

This study investigated how cutting speed and feed rate influence tool wear and surface damage during the dry milling of carbon fiber-reinforced polymer (CFRP) using uncoated tungsten carbide end mills. The key findings from the experimental analysis are as follows:

- When maintaining a constant feed rate, increasing the cutting speed led to greater tool wear. The highest recorded wear value was 0.107 mm at 200 m/min with a feed rate of 850 mm/min, indicating a direct correlation between speed and tool degradation.
- A similar trend was observed for feed rate, where higher values also contributed to increased tool wear. However, the influence of feed rate was less significant than cutting speed, accounting for a 42.7% variation compared to 62.1% from speed.
- Among the two parameters, cutting speed emerged as the dominant factor in accelerating wear on uncoated carbide tools. This highlights the need to carefully manage cutting velocity to prolong tool life.
- CFRP's anisotropic and layered structure made it vulnerable to machining-induced defects such as fiber pull-out, breakage, delamination, and resin smearing. These were notably intensified under high-speed and high-feed conditions due to elevated temperatures and increased friction at the tool–workpiece interface.
- The thermal softening of the matrix resin at elevated cutting speeds contributed to resin smearing, while increased mechanical stresses led to interfacial damage and structural failure of fiber plies.

Overall, the findings suggest that to achieve optimal surface quality and extend tool longevity during dry milling of CFRP, lower cutting speeds coupled with moderate feed rates should be considered. These settings help to control heat buildup, reduce mechanical stress, and minimize the onset of damage mechanisms within the composite structure.

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