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The Study of Surface Defects of Carbon Fibre Reinforced Polymer (CFRP) under Minimum Quantity Lubricant (MQL) in the Milling Process: A Literature Review

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Abstract: In recent years, the applications of composite materials are expanding widely due to the excellent physical and chemical properties which can replace the metal material. One of the commonly used composites are Carbon Fiber Reinforced Polymer (CFRP) due to its superior mechanical properties such as high strength-to-weight ratio, high stiffness-to-weight ratio and high corrosion resistance when compared to metal-based material. CFRP are frequently used in many areas, include the aerospace, military, automotive, construction, sport and even household appliances. However, machining of CFRP are always the challenging tasks due to its anisotropic, inhomogeneous, and abrasive nature which increase the difficulty of machining. Generally, the lower machined quality of CFRP is obtained during dry machining condition due to the induced defects caused by high cutting temperature. In this study, we are focusing on the investigation of the induced surface defects on CFRPs after end milling process by implementing Minimum Quantity Lubricant (MQL) and cutting tools with different geometries. In addition, the determination of proper cutting parameters and cutting tool geometries in achieving optimum machining performance on CFRP workpieces also been conducted. Machining performance was evaluated based on cutting force, surface roughness, effects of different cutting tool geometries, induced damages, and delamination factors. Cutting parameters with lower feed rate and higher spindle speed were effective in enhancing the machining performance due to the reduction of cutting forces, material removal rate, and tool wear. In addition, lower helix angled end mills with high number of flutes were recommended to prevent the delamination on CFRPs. Although, high cutting temperature occurred by increasing spindle speed due to plastic deformation of matrix material once it surpasses the glass-transition temperature, Tg (114-122℃). Implementation of MQL is proved to be effective to overcome these issues without providing excessive cooling effects when compared to cryogenic conditions.

Keywords: Carbon Fibre Reinforced Polymer (CFRP), Minimum Quantity Lubricant (MQL), Cutting Forces, Surface Defects.

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1. Introduction

CFRPs are polymer matrix composite materials that provide superior mechanical properties such as high strength-to-weight ratio, high stiffness-to-weight ratio, low coefficient of thermal expansion, thermal conductivity, and design flexibility. CFRPs also offer excellent characteristics such as excellent corrosion resistance, load-bearing capacity, good wear resistance, and lightweight that resulted in a widely adopted in variety of industries such as mobilities, military, civil, sport, electric substrates, etc. CFRPs can withstand extremely high temperatures up to 3000℃ while retained structural integrity and provide better resistance to moisture or most solvents, acids, and bases at room temperature [1]. When the weight percentage of carbon fibres was increased from 10% to 30%, Young's modulus of the solids and foams increased by 78% and 113% respectively [2]. Moreover, CFRPs are five times lighter and five times stronger than grade 1020 steel. Also, when compared CFRPs to 6061 aluminium, it is seven times stronger, twice stiffer, and 1.5 times lighter [3]. Due to the metal-replaceable characteristics, CFRP are extensively implemented in aerospace, aeronautical, and automobiles industries to achieve the reduction of fuel consumptions and enhancing the efficiency.

Typically, drilling and milling are two major methods that were commonly used as secondary machining on near net shapes CFRP components. Drilling is required to produce the hole on CFRP for riveting and fastening structural assemblies, especially in the aeronautical and automobile industries. Precise and damage-free holes are crucial to ensure the strength of the joint and to avoid any rejection of parts due to poor hole quality. While the milling process is commonly used for achieving complex product dimensional tolerances. However, due to the anisotropic and abrasive nature of CFRP, several types of surface defects include delamination, fibre fracture and pull-out, matrix cracking, resin coating, and fibre-matrix debonding, often occur during the machining process and may reduce the load-bearing capability and lifespan of the CFRP components [4]. Therefore, precision machining processes are essential to ensure productivity, improving the tool life, and enhancing the machining performance of CFRP parts. In addition, inappropriate cutting tool geometries can lead to poor machining performance due to chip formation and discharging problems. These physical properties of CFRP lead to excessive heat generation in the machined area, resulting in poor machining performance. Identification of suitable cooling method, such as Minimum Quantity Lubricant (MQL) during machining CFRPs are essential in reducing the cutting temperatures as conventional flood lubrication has the risk to causes serious defects and reduce its lifespan due to chemical penetration.

1.2 End Milling on CFRP

In the milling process, the workpieces are machined into a three-dimensional shape by using a rotating cylindrical tool with multiple cutting edges. The axis of rotation of the tools is perpendicular to the feed direction and these tools can be programmed to move in almost any direction against a fixed workpiece. The milling cutter removes material through its movement in the machine and from its shape [5]. After the prepreg preparation of CRFPs such as the lay-up and autoclave processes, milling techniques were used to machine the material in order to obtain the net-shaped parts with low tolerances and high surface quality. Milling action subjects the teeth to a cycle of impact force and thermal shock during each rotation. This nature is resulted in various cutting temperature, wear mechanisms, and dynamic stability compared to the continuous cutting process [6]. The tool materials and cutter geometries must be well designed to withstand these conditions [7].

End milling, as one of the milling operations, is widely used in machining industries due to the versatility and flexibility of its machining. It can permit end cutting and peripheral cutting with the cylindrical milling cutters that have multiple cutting edges on both of its periphery and tips. Figure 1 shows the concept of end milling process. However, due to the anisotropic and inhomogeneous elements of the CFRP affected by the carbon fibre orientations, identification of appropriate cutting tools, and cutting parameters become the largest issues to overcome in milling operations to avoid the occurrence of failure mechanisms such as delamination, tool wear issues and other surface defects. According to Wang et al., pointed that the influences of feed rate on cutting forces are higher than cutting speed as it increases the material removal rate of cutting edge [8]. However, higher cutting temperature are resulted by the increasing cutting speed. In conclusion, a low cutting temperature which is lower than the glass transition temperature, T_g, minimum cutting force and maximum machining efficiency are crucial in achieving maximal machining quality. Ultrasonic assisted milling (UAM) is an alternative method suggested by Halim et al. due to the effective reduction of cutting force and cutting temperature when compared to conventional milling [9]. However, the surface roughness was not as expected as ultrasonic vibration was applied perpendicular to the feed direction and improvement in surface roughness may achieved when applied in the same direction as the feed direction.

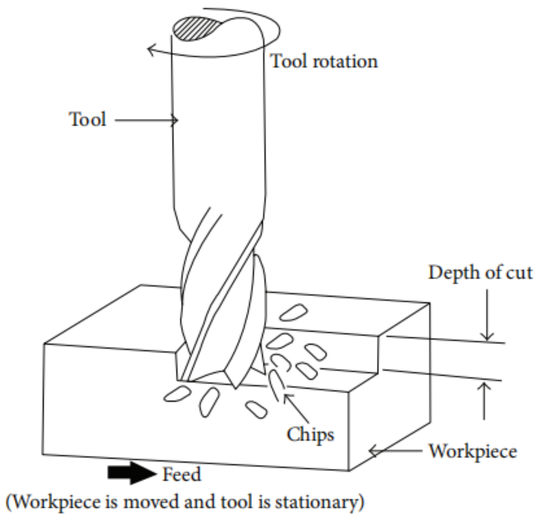

Figure 1: End Milling Process [10]

1.3 Minimum Quantity Lubricant (MQL)

Minimum Quantity Lubrication (MQL), also known as Near Dry Machining (NDM), has proven to be an adequate solution when dry machining is not feasible, as it contributes to significantly reducing the application of cutting fluids, while the tool-life and performance requirements have remained uncompromised. It has been found that under specific conditions, the MQL procedures can result better machining performance in terms of grinding operation, energy consumption, surface quality, and leftover stress, with lesser lubricant than the flood cooling condition [11].

MQL machining applies Metal Working Fluid (MWF) in the form of mist (together with compressed air) which then delivered through the spindle to the interface of tool-workpiece to provide lubrication and cooling. When compared to conventional wet machining, MQL requires only 50-500 mL/h as the flow rate of cutting fluid, depending on the particular cutting operations, and is nearly 10,000 times lesser than the ordinary flood cooling [12]. Figure 2 shows the schematic of MQL system. MQL employs the lubricant aerosols delivered in the proximity of the cutting zone have shown significant potential in reducing the tool–chip friction coefficient and friction between the cutting tool-workpiece, thus improving machining performance. MQL also greatly reduces the forces and specific energy for all of the steels explored, likely due to reduced ductility of the material, retained grit-sharpness, ideal chip formation mechanism, and shorter chips [11]. In addition, MQL provides a positive effect on the environment when compared to conventional flood lubricant due to its limitation in the utilization of coolant and lubrication. In this study, the effects of MQL on machining performance of CFRP were investigated and discussed.

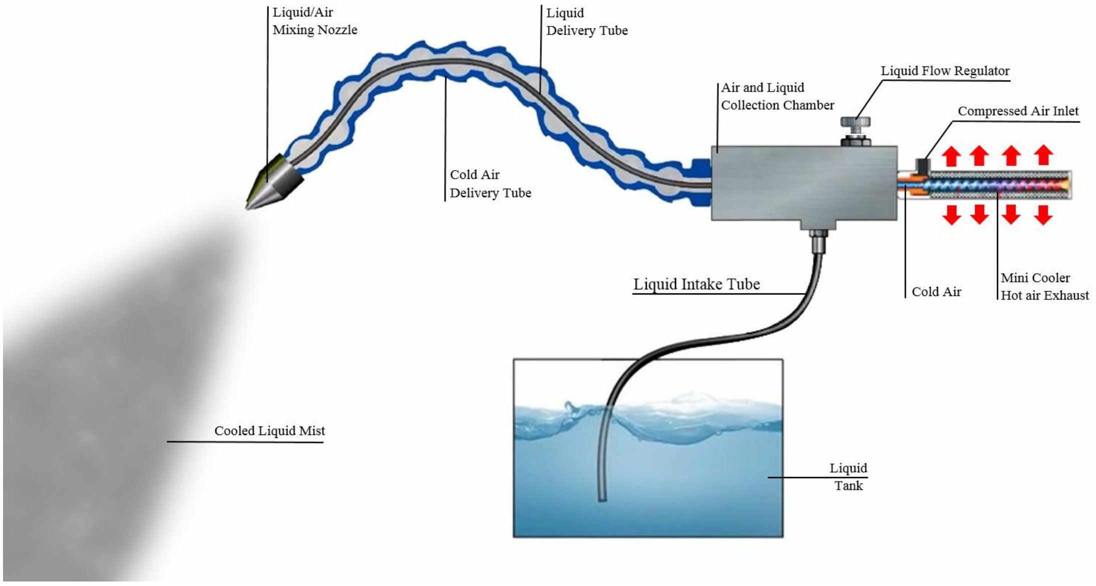

Figure 2: Schematic of Minimum Quantity Lubricant (MQL) system component [13]

2. Materials and Methods

In establishing a comprehensive overview, the selection of research papers and journal articles that related on the machining performance of CFRP and the effects of MQL cooling techniques were systematically analysed. The searching process were conducted mainly on two well establish journal articles searching engines, which is ScienceDirect and ResearchGate, however other data bases also been used for further searching. Keywords such as “CFRP end milling”, “machining CFRP with MQL”, “Effects of machining parameters on CFRP”, “Surface defects of CFRP” and “Surface morphologies of CFRP” were included during the searching process, and the scope was restricted for recent publications from year 2001 to 2021.

By roughly read through the title, abstract, and conclusion of the articles, the main points and findings are summarized and checked. Then, the filtration of these journal papers is conduct based on the relatability of the papers with the objectives and scope of study of this study. Then, more related papers were searched through the citations and references on selected papers and repeated the same process. After done with filtering the related journals, detailed literature review is carried out to provide deeper understanding on the findings. Later on, the results and findings of the journal papers will be compared and categorized based on different induced effects by various machining parameters in machining CFRP. These effects on machined surface of CFRP during end milling are included with cutting forces, surface roughness, effects of different cutting tool parameters, effects of MQL implementation, induced damage, and occurrence of delamination. The effects are then discussed to identify the best machining parameters in order to achieve the improvement of CFRP machined performance and provide better surface quality.

3. Results and Discussion

Effects of various machining parameters during machining CFRP from selected journals were identified. The discussion was mainly focusing on the variation of machining performance on CFRP in terms of cutting forces, surface roughness, and surface defects together with the effects of different cutting tool geometries and implementation of MQL.

3.1 Result and Analysis of Cutting Forces

The resultant cutting forces were found to be significantly influenced by the feed rates implemented during the milling on CFRP, where increases of feed rate results as increase in cutting forces, due to the increasing chip loads and material removal at higher speeds. However, increasing spindle speed also causes an increase in the resultant cutting forces. This may be due to the higher thermal softening and deformation of epoxy resin that increases the difficulty of machining, especially when the machining temperature surpasses the glass transition temperature, Tg (114-122℃ for resin) and the inter-laminar strength reduced [14]. Figure 3 shows the variation of cutting force along with the change of feed rate at a constant spindle speed (5000rpm) while Figure 4**Error! Reference source not found.** shows the effects of different spindle speed on the cutting force at a constant feed rate (0.02mm/rev). On the other hand, in the aspect of cutting tool geometries, the axial forces, Fz or upward forces increases when the helix angle of end mill was larger as shown in Figure 5. This may result in the deeper fluffing mechanisms on CFRP machined surface. Thus, with 0° and 30° of helix angled end mills resulted better surface roughness when compared to 45° helix angle end mills. In addition, end mills with higher number of flutes were found to reduce the milling cutting forces on CFRP. The TiAl coated carbide end mills with the greatest flute number (4 flutes) and the highest helical angles (45°) obtained the lowest cutting forces [15].

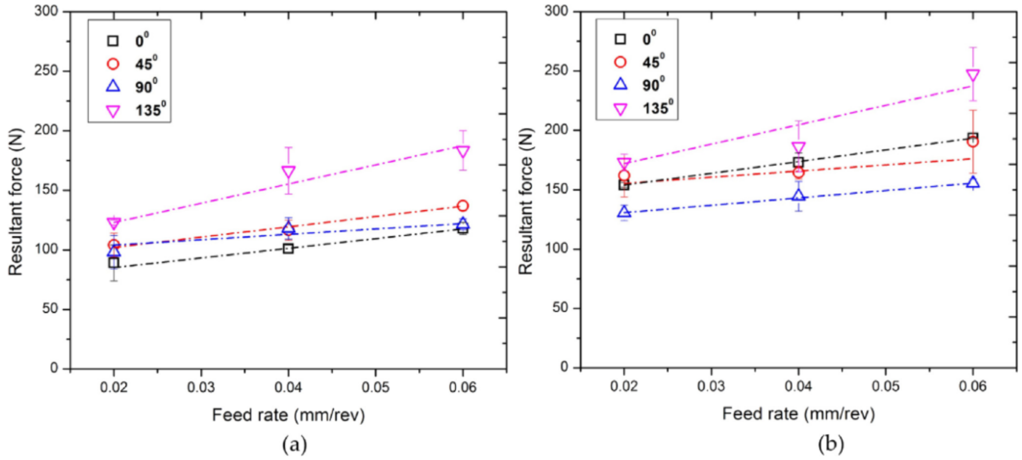

Figure 3: Effect of different feed rate on resultant force for all fiber orientation at spindle speed of 5000rpm: (a) dry and (b) cryogenic condition [14]

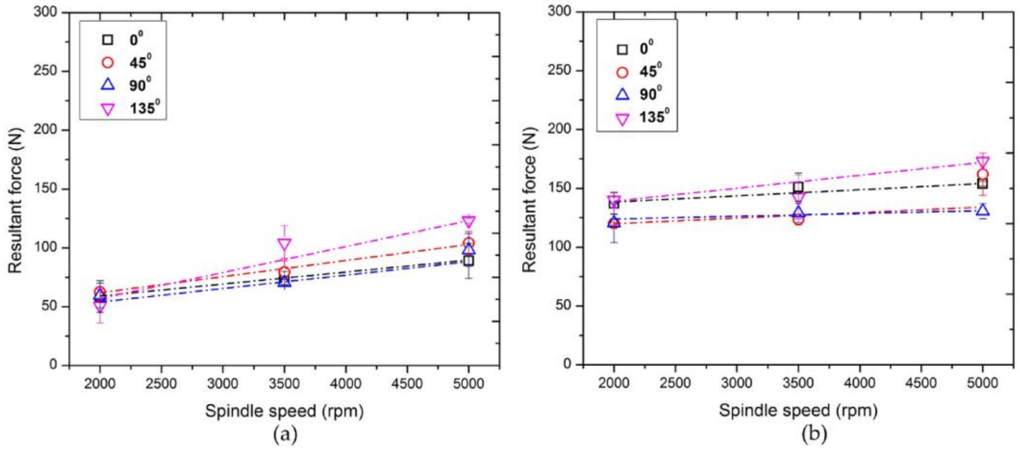

Figure 4: Effect of different spindle speed on resultant force for all fiber orientation at feed rate of 0.02mm/rev: (a) dry and (b) cryogenic condition [14]

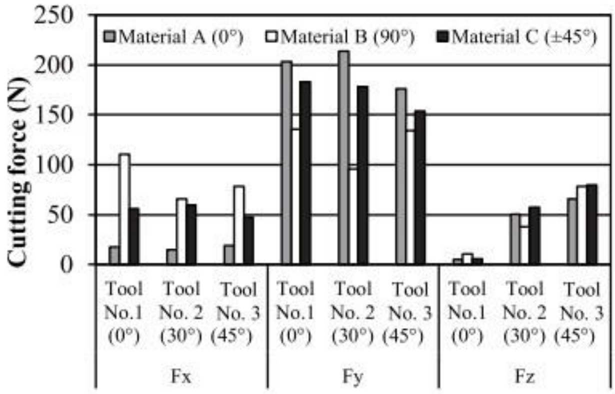

Figure 5: Relationship between cutting force, fiber direction and helix angle [16]

While the results of milling tests on UD-CFRP showed that higher fibre orientations lead to higher magnitude of resultant cutting force, thus increased tool wear in term of high edge rounding radius. This may be due to shear fracture that occurs during CFRP chip formation when cutting at 90° fibre orientation [17]. The highest resultant forces were observed in UD-CFRP with 135° of carbon fibre orientation, due to thicker chips and more prominent fibres bending when the tool interacted with workpieces with fibre orientation greater than 90° [18]. While 0° fibre orientation showed lowest resultant forces because the main mechanism of chip formation was the delamination of the fibres, therefore the interaction of the fibres with the cutting edge was limited.

The resultant cutting forces during milling the UD-CFRP increased at cryogenic condition, were the whole milling process were conducted under an extremely low temperature. Zhenyuan Jia et al. found that reducing the cutting-area temperature using cryogenic coolant resulted in increased cutting forces due to the sharply increase in tensile modulus and impact strength of CFRP, and it is recommended that the cutting-area temperature be controlled above -25℃ to avoid extremely large cutting forces [19]. This may be due to the strengthened properties of the fibres and the different thermal expansion of the matrix and fibres resulting in an increase in the Young’s modulus and tensile strength of the CFRP laminates. However, decreasing resultant forces was observed with the use of atomization-based vegetable oil spray, which are one of the minimum quantity lubricants (MQL) as shown in Figure 6. When using an atomized cutting fluid (ACF), friction coefficient at the interfaces between tool/chip and tool/workpiece was reduced, effectively reducing the resultant forces without increasing the properties and characteristics of the CFRPs.

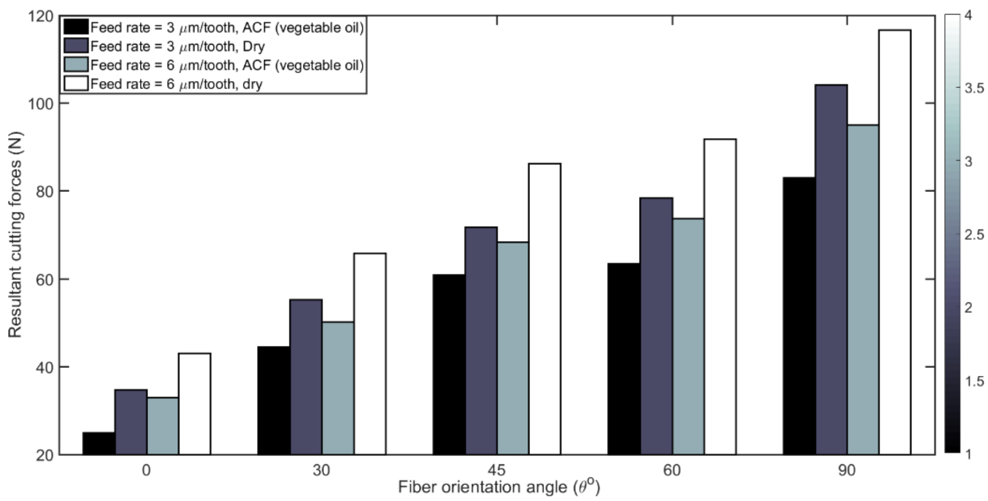

Figure 6: Resultant cutting forces for all fiber orientations at feed rates of 3 and 6 μm/tooth and different cutting conditions [17]

3.2 Result and Analysis of Surface Roughness of CFRP

Greater surface roughness was obtained with higher feed rates due to the increased heat generated, tool wear, and reduced chip ejection rates. Moreover, the fibre removal rate was increased and the spring-back effect of the carbon fibres were enhanced, therefore resulting in more machining defects. While surface roughness values decreased as the spindle speed increased due to the coating of deformed resin on the machined surface and shortened cutting time which reducing fibre deformation and providing sufficient fiber cutting. Wang et al. stated that feed rate was crucial in varying the cutting force in milling of CFRP composites, followed by cutting speed and radial depth of cut [8]. Luca Sorrentino and Turchetta found that higher surface roughness was induced with the increasing axial cutting depth and the decreasing cutting speed [20]. However, the increases of the delamination factor on the top layer of CFRP workpieces were often occurred due to the plastic deformation of resin materials that resulted by increasing of cutting temperature, especially when exceed the glass-transition temperature, Tg (114-122℃ for resin) where the inter-laminar strength reduced [14].

Significant effects on surface roughness were also observed in the aspect of carbon fibre orientation. Milling at 0° fibre orientation were found to result a better surface integrity when compared to at 45° and 135° fibre orientation [4]. In fact, at 0° fibre orientation, the cutting direction was parallel to the fibres orientation, where the main mechanism of chip formation was delamination which resulted minimum interaction between fibres and cutting edge. While cutting direction were perpendicular to fibres orientation at 90°, resulting the greater interaction between fibres and cutting edge. For 45° fibre orientation, fibres are dragged and sheared that causes uneven fracture of fibre and matrix, thus resulted the highest magnitude of surface roughness, Ra. This phenomenon was caused by variation of fibre cutting angle (ϕ), as delamination tend to occur in the actual critical fibre cutting angle range at $0° \leqslant \phi \leqslant 90°$, while under fibre cutting angle at $\phi > 90°$, nearly no damages induced [21]. Bending in laminate plane is predominant for $\phi < 90°$, while $\phi > 90°$ tend to induce the bending mechanism that perpendicular to the laminate plane. However, exceptional presence of delamination in non-critical fibre cutting range at $90° \leqslant \phi \leqslant 135°$, also known as the propagation of delamination could occur due to the progressing feed motion of the tool from cutting angle of pre-damaged fibre changes to the non-critical range. Hence, down milling on 0° of carbon fibre orientation or up milling on 90° of carbon fibre orientation are suggested to achieve optimum machined quality of CFRP.

Influences of implementation of cooling method also found to be significantly on machining performance of CFRP. Although the Implementation of cryogenic coolant enhanced the chip breakability and decreased the thermal damages on CFRP surface significantly, the high resultant cutting force under cryogenic condition could result high occurrence of cutting tool wear which increases the surface roughness value of CFRP. While, Zhenyuan Jia et al. found that decreasing of surface roughness values were resulted as the cutting temperature decreases where Ra value reaches 1.6 μm by cutting temperature below -25℃ [19]. Thus, it is recommended to control the cutting temperature above -25℃ to avoid extremely large cutting force. MQL condition, on the other hand, provided smoother fibre cross-section failure when compared to dry machining condition. Not only MQL performed milling in low temperature and reduce friction of tool/chip, but also reduce the cutting forces and tool wear. Figure 14 shows the effects of fibre orientation angle at feed rates 3 and 6 μm/tooth and different lubrication conditions on the delamination percentage. Percentage of damaged surface of CFRP were significantly reduced when milling by using atomized cutting fluid, ACF (vegetable oil) as low temperature increases the properties of CFRP in terms of tensile strength, shear modulus and stiffness, hence provide greater resistance to delamination [17].

3.3 Effect of Cutting Tool Geometries on Machining CFRP

There are various uncertainties on the effects of end mills with different cutting tool geometries on milling performance of CFRP as the effects of number of flutes, helix angle, clearance and rake angle of end mill varies in different journals. Voss et al. found that larger clearance angles of 21° instead of 14° provided better resistance on CFRP top-layer damages, include reducing the uncut fibres and delamination due to shorter tool-workpiece interaction length [21]. Increasing clearance angle not only reduce the friction, but also reduce the cutting forces and tool wear. While higher rake angle was effective in improving the discharge of chips from the cutting edge and increases machining quality of the milled edge. Furthermore, Chen et al. conducted milling tests on UD-CFRP with different micro-textured end mill which found to be no significant influences on the surface roughness values of CFRP machined surface [4]. However, surface texture on the rake face of end mills were effective in preventing the slippage of fiber ship.

Moreover, higher helix angles of end mills were effective in lowering the cutting force and tool wear when milling on CFRP. However, the axial forces, Fz or upward forces were increase when milling with high helix angled end mills which resulted the delamination and fluffing mechanisms on the top layer of machined CFRP [16]. End mill with helix angle of 45° resulted more fluffed carbon fibre than with helix angle of 30°, while 0° helix angled end mill provided almost zero fluffing mechanism on finished CFRP surface. But in the case of milling with 60° of high helix angled end mill provide a different result, as smooth CFRP machined surface without visible damage were obtained. On the other hand, the flute numbers of end mills also show some exception on the machinability of CFRP. Bayraktar and Turgut pointed out that higher number of flutes were found to increase the surface roughness value compared to end mill with lower flute numbers, as 4-flute end mill provided greater surface roughness magnitude than 2-flute end mill when the feed rate increased [15]. While 4-flute end mill were found to provide lower surface roughness values when compared with 3-flute end mill by [22]. However, both agreed on that lowest cutting force and plastic deformation factors were obtained for cutting tools with highest number of flutes, hence reduce the occurrence of tool wear. In addition, the cutting tool geometries also found to have effect on surface roughness of CFRP machined quality.

Higher number of flutes with lower feed rate are recommended to achieve a better machining performance in terms of lower surface roughness on CFRP. While higher helix angle end mills are inappropriate in achieving lower surface roughness during milling, due to the increasing axial force, Fz that resulted deeper fluffing and delamination of CFRP machined surface.

3.4 Effect of MQL on Machinability of CFRP

MQL are one of the effective cooling techniques which penetrating the atomized coolant fluid upon the interaction between tool/chip and tool/workpiece to reduce the friction, improve chip ejection rate and provide better cooling performance during milling the CFRP. During end milling, MQL with the condition of highest air flow rate, AFR (31 l/min) and lowest oil flow rate, OFR (10 ml/min) were found to provide optimal machining performance in terms of machining stability and accuracy of machined geometries [23]. Lower droplet size, lower vorticity, and higher droplet velocity were the main reasons for reduction of flank wear by 17% when milling by applying optimum MQL condition. Implementation of MQL condition also reduce the tool wear by 20% to 30% when compared to the dry, pressurized air, and flood cooling condition, also provides the longest tool life and the lowest machining error.

Moreover, the resultant cutting forces when applied MQL during helical milling were much lower than at dry and cryogenic conditions [24]. Higher resultant forces in cryogenic condition may lead to slightly higher tool deflection during helical milling of stacks and reduce the hole diameter. This may be due to friction reduction effect of chips and cutting tool upon the machined surface at MQL condition by increasing the physical properties (tensile strength, shear modulus, and stiffness) of carbon fibers and resin without applying excessive cooling effects. Not only providing better cylindricity of holes machined, but also reducing the occurrence of tool wear when compared to dry and cryogenic conditions. In the case of drilling test under MQL condition, better hole quality than dry cutting condition were obtained with the reduced quantities of surface grooves and cavities [25]. This may be due to effective reduction of friction coefficient between the interaction of drill bit, chip, and hole wall by the use of MQL. In addition, atomized cutting fluid, ACF (Vegetable oil) which have the same concept with the MQL was also found to improve the machining performance of CFRP, reduce the delamination factors, cutting forces and tool wear.

3.5 Induced Damage Analysis

Machining CFRP are challenging due to its anisotropic and inhomogeneous mechanical properties, include with abrasive nature and low thermal conductivity. Appropriate machining parameters were required in order to achieve better machining performance and greater machined quality; hence the study of surface defect patterns was conducted to identify the optimal machining parameters. To determine the theory of anisotropic mechanism of multidirectional CFRP, the material removal mechanisms in different fibre cutting angles, which are the interaction angle between the cutting tool edge and fiber directions that varies as the cutting tool rotates during milling were studied. **Figure 7** shows the schematic of fibre orientation, fibre cutting and engagement angles during milling on UD-CFRP.

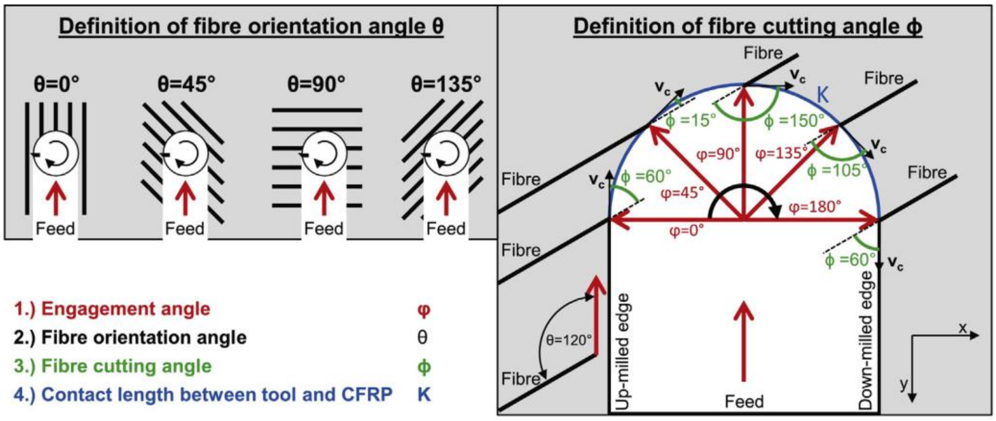

Figure 7: Schematic of fibre orientation, fibre cutting and engagement angles [21]

Chen et al. found out that in the case of 0° carbon fibre cutting angle, the applied pressure in the cutting direction created the bending stresses and resulted peeling off of fibre from matrix [4]. **Figure 8**(a) shows the fibre bending formed by bending stresses and obvious fibre tearing and shearing were shown at the fracture morphologies. The fracture face of the carbon fibres is very elliptic and rough striated area are observed. While for 45° carbon fibre cutting angle, bending induced fracture and interlaminar failure was the dominant mechanism which caused fibres peel up as shown in **Figure 8**(c). These peeled up fibres will interact with the tool rake and flank face. For 90° carbon fibre cutting angle, the fracture of chips along fibre-matrix interface were occurred due to high interlaminar shear stress as shown in **Figure 8**(b). Lastly for 135° carbon fibre cutting angle, crushing of the fibres were caused by the compressive stresses at the contact points of tool/fibres. Cracks were then formed and gradually coarsening until resulting into a distinct shear of the fiber ends. **Figure 8**(d) shows compressive induced fracture which consists of severe small crushed and disordered debris embedded into the machined surface.

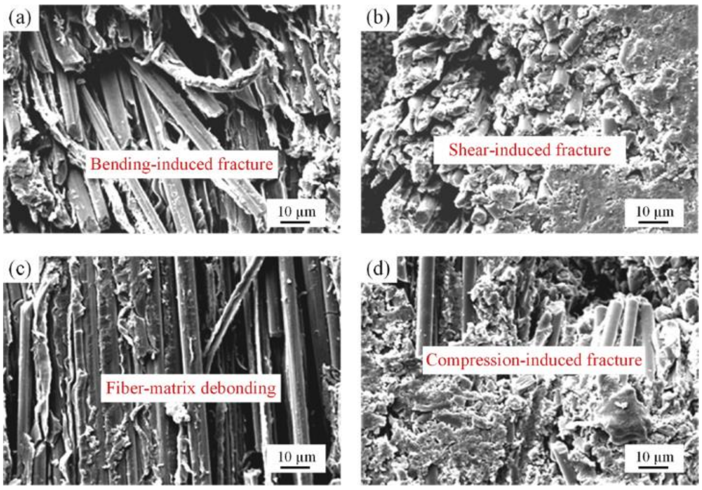

Figure 8: Typical surface morphologies observed in milling of UD-CFRP [4]

Figure 9 shows that comparison of the machined surface morphologies of different laminated UD-CFRP by conventional end mills. For CFRP machined surface of 0° of carbon fibre orientation as shown in **Figure 9**(a), the fibre fracture was observed along the longitudinal and transverse directions due to the compression action by the cutting edges. Bending induced fibre fractures and ploughing action of the cutting edges also resulted severe furrows on the machined surface. While for the machined surface of 45° fibre orientation as shown in **Figure 9**(b), the fibre-matrix debonding and fibre fractures caused by bending were also occurred. At the same time, the compression induced fibre fractures caused the rough fracture morphology and exposure of fibres due to little plastic deformation of resin also observed. As for surface morphology of machined CFRP with 90° fibre orientation as shown in **Figure 9**(c), small segments of fibre chips were formed by the severe buckling of fibres at the tip of cutting edges and embedded into the machined surface due to the compression action of cutting edges. For the surface morphology of machined CFRP with 135° fibre orientation as shown in **Figure 9**(d), a relatively smooth surface with few shallow pits that resulted by the fracture and pulling out of carbon fibres were observed.

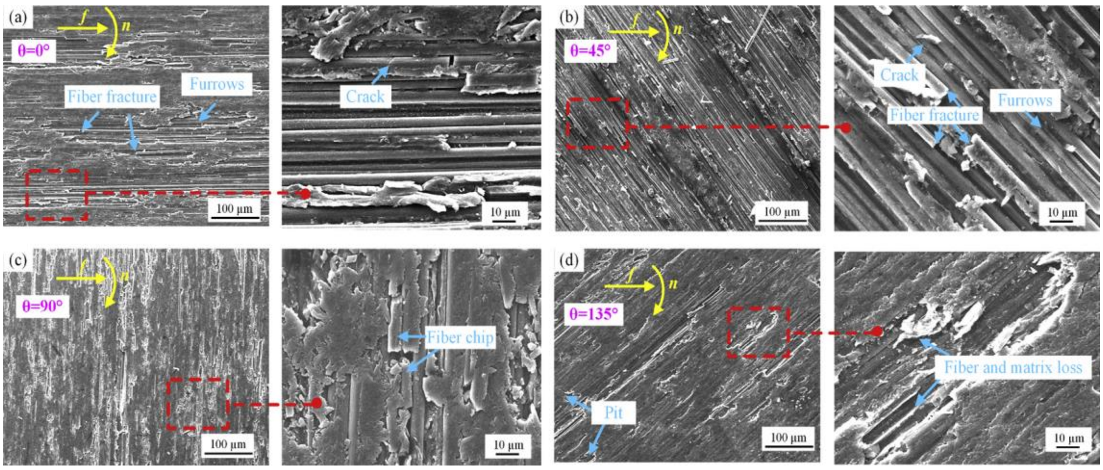

Figure 9: Machined surface morphologies of UD-CFRP with different fiber orientation by conventional end mills [4]

Surface morphologies of the first drilled CFRP hole wall by applying constant feed rate at 0.025 mm/rev and spindle speed at 15 m/min under dry and MQL conditions are shown in **Figure 10** and **Figure 11**. Under dry machining, many surface defects on drilled hole wall are observed due to the scratching effects of insufficient ejection of chips which resulted severe rubbing and ploughing actions between the cutting tool and the machined surface. While the MQL conditions provided much smoother morphologies of the CFRP machined hole and greatly reducing the amounts of surface grooves and cavities when compared to dry machining condition. In addition, the surface defects of CFRP drilled hole wall are mainly determined by the fibre fracture mechanisms, which means that damage induced by mechanical action was substantially controlled. These results indicate the effectiveness of MQL condition in chip ejection and sufficient reduction of friction coefficient between the interaction of the tool/chip and tool/workpiece, thus resulting the improvement of machined quality and energy efficiency.

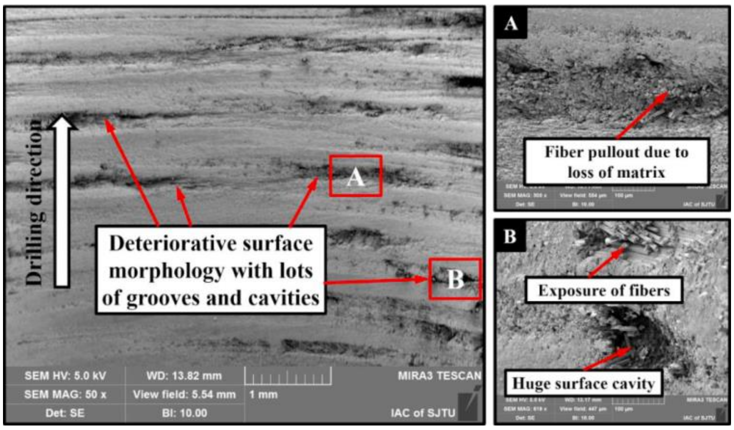

Figure 10: Surface morphologies of the drilled CFRP phase under the dry conditions [25]

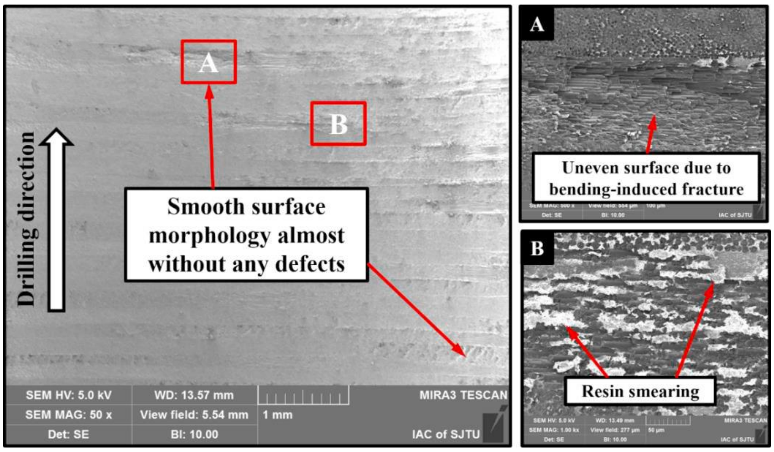

Figure 11: Surface morphologies of the drilled CFRP phase under the MQL conditions [25]

4.6 Delamination from End Milling CFRP

Occurrence of delamination of CFRP are strongly depends on variation of cutting parameters, cutting tool geometries and cooling methods. Kilickap et al. found that the delamination factor of CFRP machined surface increases as the spindle speed increases due to the increases of plastic deformation rate [22]. Plastic deformation rate of resin even accelerating once the cutting temperature exceed the glass transition temperature, Tg which are 114-122℃ for resin of CFRP [14]. The increasing feed rate also one of the main reasons for the increasing of delamination factors due to the effects of higher cutting forces and material removal rate.

In the aspect of cutting tool geometries, lower helix angled end mill provided better machining performance on CFRP in terms of reducing the delamination and fluffing mechanisms on the top layer of CFRP workpiece. As Masahiro and Takashi discovered that 30° helix angled end mill resulted less fluffed carbon fibres than 45° helix angled end mill, while end mill with 0° of helix angle provided nearly zero fluffing mechanism on finished surface [16]. **Error! Reference source not found.** shows the variation of CFRP machined surface with different helix angled end mills on different carbon fibre orientation. This may be due to the increasing of axial force, Fz as the helix angle of end mills increase. However, better machined quality was observed when milling using 60° high helix angled end mills due to the significant reduction of normal force, Fx and tangential force, Fy [26]. Moreover, when milling the CFRP with end mill with higher number of flutes could reduce the delamination factors, as the 4-flute end mill provided lower value of delamination factors than 3-flute end mill. This is attributed in the reduction of the delamination factor due to participation of more cutting edges per revolution. Figure 13 shows the variation of the delamination factor with different cutting parameters on at different flute number.

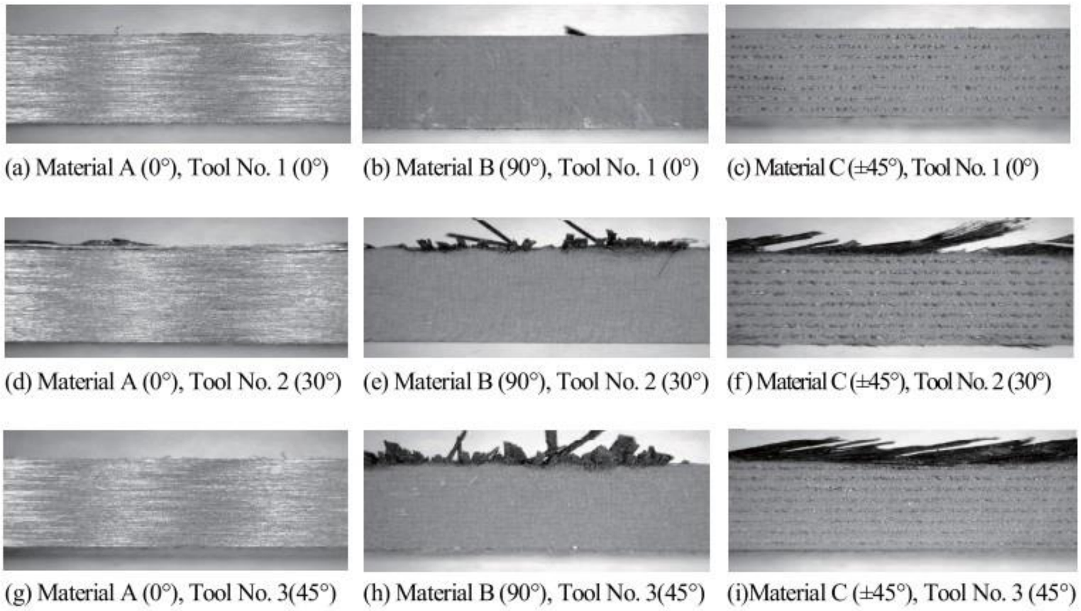

Figure 12: Finish surface condition with different helix angle end mills on different carbon fiber orientation [16]

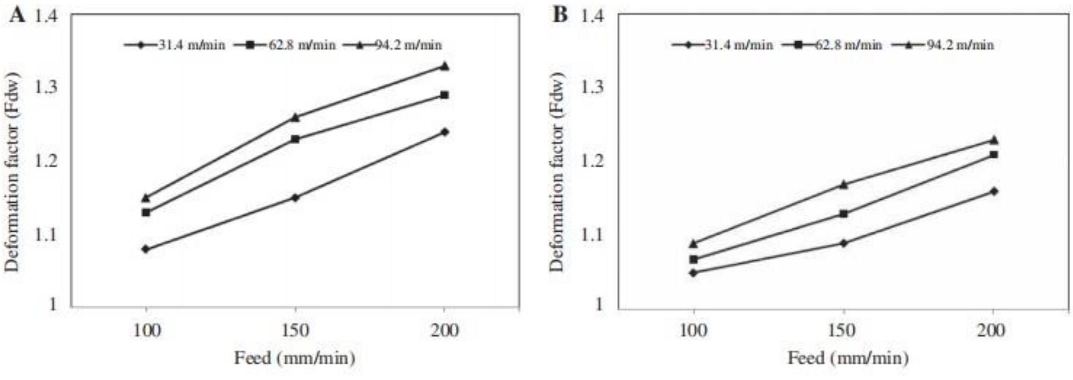

Figure 13: Variation of delamination factor with different cutting parameters and different number of flutes: (A) 3 flutes and (B) 4 flutes [22]

Additionally, the fibre cutting angle also influences the occurrence of delamination on CFRP machined surface. As the delamination are generated in the fibre cutting angle range of $0° \leqslant \phi \leqslant 90°$, where carbon fibres tend to evade the cutting edge. The propagation of delamination could then occur in an actual non-critical range of $90° \leqslant \phi \leqslant 180°$ due to the progressing feed rate once the carbon fibres initially delaminated [21]. Furthermore, the atomized cutting fluid, ACF (vegetable fluid) which have same concept with MQL cooling method has proven to provide greater resistance to delamination due to the improvement of physical properties of CFRP under low temperature [17]. Figure 14 shows the variation in delamination percentage with fibre orientation angle at different feed rates of 3 and 6 μm/tooth and different lubricant conditions, which are dry machining and ACF condition.

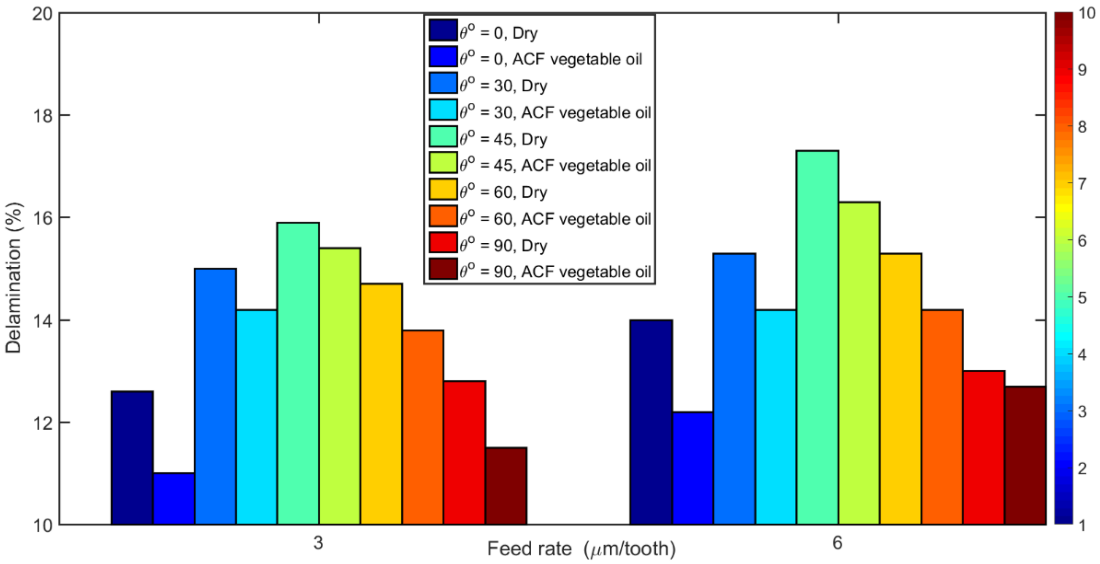

Figure 14: Variation in delamination percentage with fiber orientation angle at feed rates 3 and 6 μm/tooth and different lubrication conditions [17]

4. Conclusion

As conclusion for this review study, the objectives are achieved as appropriate cutting parameters and cutting tool geometries in achieving optimum machining performance are identified by determine the induced damages of CFRP machined surface that varying with the machining parameters. Furthermore, MQL conditions also prove to be effective in improving the machining performance during end milling CFRP. The following key findings are the appropriate machining parameters that allow enhancement of machining performance on CFRP applications:

- Lower feed rate and higher spindle speed are recommended in order to achieve better machined quality of CFRP in terms of low surface roughness due to the reduction of cutting forces and tool wear of end mills and improve the machining performance.
- For cutting tool geometries, although higher helix angled (45°) end mill provides lower resultant cutting forces during milling CFRP, the lower helix angled (30°) end mill is suggested to obtain the smoother machined surface. As high axial forces, Fz or upward forces are obtained when applying high helix angled and resulted the delamination and deeper fluffing mechanisms of CFRP machined surface.
- Higher number of flutes (4-flute) end mills were recommended to provide higher rigidity and lower cutting forces during machining CFRP. The feed direction of end milling on CFRP is suggested to start with down milling on 0° of carbon fiber orientation in order to enhance the stability of machining and achieve optimal machined quality.
- MQL condition were proven to be the effective cooling methods to improve the machinability of CFRP. Reduction of cutting force, cutting temperature, and tool wear without changing much of the physical properties of CFRP excessive cooling effects that lower than -25℃, are the main reason for implementation of MQL in order to achieve better surface quality in a long-term machining.
- MQL condition with higher air flow rate (AFR) and lower oil or lubricant flow rate (OFR) are recommended as the optimum MQL parameters during end milling CFRP. This may be due to lower droplet size, higher droplet velocity and lower vorticity which resulted the reduction of flank wear by 17%. Not only it could improve the machining stability, but also increase the accuracy of

machined geometries. The application of MQL also reduce the tool wear by 20%-30% when compared to the dry, pressurized air and flood cooling condition.

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References

[1] D. Ozkan, M. S. Gok, and A. C. Karaoglanli, 'Carbon Fiber Reinforced Polymer (CFRP) Composite Materials, Their Characteristic Properties, Industrial Application Areas and Their Machinability', *Adv. Struct. Mater.*, vol. 124, no. March, pp. 235–253, 2020, doi: 10.1007/978-3-030-39062-4_20.

[2] D. K. Rajak, D. D. Pagar, P. L. Menezes, and E. Linul, 'Fiber-Reinforced Polymer Composites : Manufacturing, Properties, and Applications', 2019.

[3] E. G. Nawy, *Fiber-reinforced composites*. 2008.

[4] Y. Chen, X. Guo, K. Zhang, D. Guo, C. Zhou, and L. Gai, 'Study on the surface quality of CFRP machined by micro-textured milling tools', *J. Manuf. Process.*, vol. 37, no. November 2018, pp. 114–123, 2019, doi: 10.1016/j.jmapro.2018.11.021.

[5] MachiningCloud.Inc, 'Introduction to Milling Tools and their Application', p. 17, 2016, [Online]. Available: https://www.machiningcloud.com/wp-content/uploads/2016/05/MachiningCloud_MillingToolsAndTheirApplication.pdf.

[6] M. A. Hadi, J. A. Ghani, C. H. Che Haron, and M. S. Kasim, 'Comparison between up-milling and down-milling operations on tool wear in milling Inconel 718', *Procedia Eng.*, vol. 68, pp. 647–653, 2013, doi: 10.1016/j.proeng.2013.12.234.

[7] M. P. Groover, 'Fundamentals of Modern Manufacturing (4th Edition)', *Mater. Process. Syst.*, pp. 87–109, 2011, doi: 10.1007/978-94-010-9506-8_6.

[8] H. Wang, J. Sun, J. Li, L. Lu, and N. Li, 'Evaluation of cutting force and cutting temperature in milling carbon fiber-reinforced polymer composites', pp. 1517–1525, 2016, doi: 10.1007/s00170-015-7479-2.

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

[10] M. Nurhaniza, M. K. A. M. Ariffin, F. Mustapha, and B. T. H. T. Baharudin, 'Analyzing the Effect of Machining Parameters Setting to the Surface Roughness during End Milling of CFRP-Aluminium Composite Laminates', *Int. J. Manuf. Eng.*, vol. 2016, pp. 1–9, 2016, doi: 10.1155/2016/4680380.

[11] T. Tawakoli, M. J. Hadad, and M. H. Sadeghi, 'Investigation on minimum quantity lubricant-MQL grinding of 100Cr6 hardened steel using different abrasive and coolant-lubricant types', *Int. J. Mach. Tools Manuf.*, vol. 50, no. 8, pp. 698–708, 2010, doi: 10.1016/j.ijmachtools.2010.04.009.

[12] I. P. Okokpujie, C. A. Bolu, O. S. Ohunakin, E. T. Akinlabi, and D. S. Adelekan, 'A review of recent application of machining techniques, based on the phenomena of CNC machining operations', *Procedia Manuf.*, vol. 35, pp. 1054–1060, 2019, doi: 10.1016/j.promfg.2019.06.056.

[13] M. O. Helmy, M. H. El-Hofy, and H. El-Hofy, 'Influence of process parameters on the ultrasonic assisted edge trimming of aerospace CFRP laminates using MQL', *Int. J. Mach. Mach. Mater.*, vol. 22, no. 5, pp. 349–373, 2020, doi: 10.1504/IJMMM.2020.109844.

[14] D. Kumar and S. Gururaja, 'Machining damage and surface integrity evaluation during milling of UD-CFRP laminates: Dry vs. cryogenic', *Compos. Struct.*, vol. 247, no. May, p. 112504, 2020, doi: 10.1016/j.compstruct.2020.112504.

[15] S. Bayraktar and Y. Turgut, 'Investigation of the cutting forces and surface roughness in milling carbon-fiber-reinforced polymer composite material', *Mater. Tehnol.*, vol. 50, no. 4, pp. 591–600, 2016, doi: 10.17222/mit.2015.199.

[16] H. Masahiro and I. Takashi, 'Effect of carbon fiber orientation and helix angle with CFRP cutting characteristics', *10th Int. Conf. Prog. Mach. Technol. ICPMT 2012*, vol. 7, no. 3, pp. 197–200, 2013.

[17] T. S. M. Elgnemi, M. B. G. Jun, V. Songmene, and A. M. Samuel, 'Milling performance of CFRP composite and atomised vegetable oil as a function of fiber orientation', *Materials (Basel).*, vol. 14, no. 8, 2021, doi: 10.3390/ma14082062.

[18] D. Kumar, S. Gururaja, and I. S. Jawahir, 'Machinability and surface integrity of adhesively bonded Ti/CFRP/Ti hybrid composite laminates under dry and cryogenic conditions', *J. Manuf. Process.*, vol. 58, no. August 2019, pp. 1075–1087, 2020, doi: 10.1016/j.jmapro.2020.08.064.

[19] C. H. Zhenyuan Jia, Rao Fu, Fuji Wang, Baowei Qian, 'Temperature Effects in End Milling Carbon Fiber Reinforced Polymer Composites', *Polym. Polym. Compos.*, 2016, doi: 10.1002/pc.

[20] L. Sorrentino and S. Turchetta, 'Cutting Forces in Milling of Carbon Fibre Reinforced Plastics Cutting Forces in Milling of Carbon Fibre Reinforced Plastics', no. November 2014, 2016, doi: 10.1155/2014/439634.

[21] R. Voss, L. Seeholzer, F. Kuster, and K. Wegener, 'Influence of fibre orientation, tool geometry and process parameters on surface quality in milling of CFRP', *CIRP J. Manuf. Sci. Technol.*, vol. 18, pp. 75–91, 2017, doi: 10.1016/j.cirpj.2016.10.002.

[22] E. Kiliçkap, A. Yardimeden, and Y. H. Çelik, 'Investigation of experimental study of end milling of CFRP composite', *Sci. Eng. Compos. Mater.*, vol. 22, no. 1, pp. 89–95, 2015, doi: 10.1515/secm-2013-0143.

[23] Y. Iskandar, A. Tendolkar, M. H. Attia, P. Hendrick, A. Damir, and C. Diakodimitris, 'Flow visualization and characterization for optimized MQL machining of composites', *CIRP Ann. - Manuf. Technol.*, vol. 63, no. 1, pp. 77–80, 2014, doi: 10.1016/j.cirp.2014.03.078.

[24] J. GE *et al.*, 'Effect of cooling strategies on performance and mechanism of helical milling of CFRP/Ti-6Al-4 V stacks', *Chinese J. Aeronaut.*, 2020, doi: 10.1016/j.cja.2020.12.003.

[25] M. Ji, J. Xu, M. Chen, and M. E. I. Mansori, 'Effects of Different Cooling Methods on the Specific Energy Consumption when Drilling CFRP/Ti6Al4V Stacks', *Procedia Manuf.*, vol. 43, pp. 95–102, 2020, doi: 10.1016/j.promfg.2020.02.118.

[26] A. Hosokawa, N. Hirose, T. Ueda, and T. Furumoto, 'High-quality machining of CFRP with high helix end mill', *CIRP Ann. - Manuf. Technol.*, vol. 63, no. 1, pp. 89–92, 2014, doi: 10.1016/j.cirp.2014.03.084.