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MACHINABILITY EVALUATION OF CARBON FIBER REINFORCED POLYMER UNDER DRY AND CHILLED AIR CUTTING CONDITION

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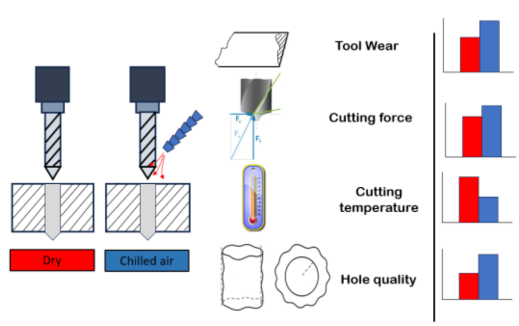
Graphical abstract



Abstract

Carbon Fiber Reinforced Polymer (CFRP) is widely used composite material known for its exceptional strength-to-weight ratio and versatility in aerospace, automotive, and military applications. However, there are significant challenges associated with drilling CFRP, including issues such as burr, delamination and tool wear. In addition, environmental and health concerns associated with traditional cutting fluids further complicate the machining process. This study explores few alternatives to conventional cutting fluids, namely dry and chilled air cutting conditions in drilling CFRP. Key performance indicators, including tool wear, delamination, burr formation, cutting forces, cutting temperature, and hole quality, were analyzed to evaluate their interrelations and overall influence on drilling performance. The findings indicate that dry cutting produced approximately 24% lower flank wear compared to chilled air cutting, while chilled air achieved better delamination control. Although chilled air increased the cutting force by about 20%, it reduced the cutting temperature by nearly 40% and improved dimensional accuracy by minimizing deviations in hole diameter, circularity, and cylindricity. Overall, the results suggest that both cutting conditions offer distinct advantages depending on the targeted performance criteria. The findings also demonstrate the potential of dry and chilled air machining as eco-friendly alternatives for achieving efficient and high-quality CFRP drilling.

Keywords: CFRP, chilled air, tool wear, delamination, cutting force

Abstrak

Polimer Bertelulang Gantian Fiber (CFRP) ialah bahan komposit yang digunakan secara meluas kerana terkenal dengan nisbah kekuatan terhadap berat yang luar biasa dan serba boleh dalam aplikasi aeroangkasa, automotf dan ketenteraan. Bagaimanapun, terdapat cabaran yang ketara dalam proses penggerudian CFRP, termasuk isu-isu seperti burr, delaminasi dan kehausan mata alat. Tambahan pula, kebimbangan terhadap aspek alam sekitar dan kesihatan yang dikaitkan dengan penggunaan bendalir pemotongan konvensional turut menambahkan lagi kerumitan dalam proses pemesinan. Kajian ini meneroka beberapa alternatif kepada bendalir pemotongan tradisional, iaitu pemotongan kering dan pemotongan menggunakan udara sejuk dalam proses penggerudian bahan CFRP. Petunjuk prestasi utama seperti kehausan alat, delaminasi, pembentukan burr, daya pemotongan, suhu pemotongan, dan kualiti lubang telah dianalisis bagi menilai hubungan antara parameter tersebut serta pengaruh keseluruhan terhadap prestasi penggerudian. Hasil kajian menunjukkan bahawa pemotongan kering menghasilkan kira-kira 24% kehausan sisi alat yang lebih rendah berbanding pemotongan udara sejuk, manakala udara sejuk menunjukkan kawalan delaminasi yang lebih baik. Walaupun pemotongan menggunakan udara sejuk meningkatkan daya pemotongan sekitar 20%, ia berjaya menurunkan suhu pemotongan hampir 40% dan meningkatkan ketepatan dimensi dengan mengurangkan sisihan pada diameter lubang, kebulatan, dan keselindiran. Secara keseluruhannya, keputusan menunjukkan bahawa kedua-dua keadaan pemotongan mempunyai kelebihan tersendiri bergantung kepada kriteria prestasi yang disasarkan. Penemuan ini membuktikan potensi keadaan pemotongan kering dan udara sejuk sebagai alternatif mesra alam untuk mencapai proses penggerudian CFRP yang cekap dan berkualiti tinggi.

Kata kunci: Please Provide

1.0 INTRODUCTION

Carbon Fiber Reinforced Polymer (CFRP) is characterized by its strength and durability and widely use in aerospace, automotive, military, and recreational sectors. This material showcases resilience and robustness while demonstrating a notable resistance to corrosion. In assembly requirements of engineering components, particularly those involving riveted and bolted joints, drilling has emerged as the predominant cutting method for CFRP composites. CFRP composes of two phases with significantly distinct mechanical and thermal properties, leading to intricate interactions between the matrix and the reinforcement during machining. The machining of CFRP composites presents challenges and expenses attributed to various factors. These include the material's distinctive properties, such as high strength and stiffness, along with the presence of uncut fibers that can contribute to the formation of burrs [1]. The machining of CFRP poses substantial challenges, particularly in the drilling process, where issues such as excessive tool wear, undesirable surface roughness, delamination, and heightened cutting forces significantly impact the quality and efficiency of the manufacturing process [2]. These problems contribute to increased production costs, reduced tool lifespan, and compromised structural integrity of the CFRP components [3].

CFRP demonstrate relatively low machinability, proving more challenging to drill than traditional homogeneous materials owing to their inherent anisotropy and heterogeneity [4]. The distinct removal mechanisms of fibers and polymers, coupled with continuous changes in fiber layup, make these composites susceptible to significant defects, including delamination, burrs, tearing, surface cavities, fiber pullout, and glass transition failure. Consequently, the occurrence of such defects significantly degrades the quality of machined CFRP parts. Delamination is a common problem that occurs when the layers of the composite material separate, causing the material to weaken and become more susceptible to damage [5]. Delamination can be caused by several factors, including the drill bit's speed, feed rate, and angle of entry [6]. Fiber pullout is another problem that can occur when drilling CFRP. Fiber pullout can be caused by several factors, including the drill bit's sharpness, feed rate, and angle of entry [7]. Besides that, burr also the common problem which may be caused by tool wear and high abrasiveness and hardness. Excessive tool wear poses the risk of inducing undesirable interlaminar delamination, exit burrs, and surface tearing, thereby contributing significantly to the rejection of composite parts [8]. Furthermore, the exceptionally high abrasiveness and hardness of the reinforcing fibers and the rubbery matrix base present additional challenges in drilling CFRP materials while maintaining satisfactory quality [9].

Dry cutting of CFRP refers to the machining process without the use of cutting fluids, relying instead on the natural cooling and lubrication properties of the material. This method is often used in situations where the use of cutting fluids is not allowed or not recommended, such as in the secondary process of aircraft CFRP part machining [10]. This is because CFRP is sensitive to fluid intrusion due to several factors which is CFRP composites are made of a matrix material (such as epoxy or polymer) that holds the carbon fibers in place. The matrix material is typically porous, which allows it to absorb and retain fluid [11]. This porous nature makes it susceptible to damage from fluid intrusion, which can lead to delamination and other forms of damage [12]. Besides that, fluid intrusion can occur due to capillary action, which is the movement of fluid through small pores or capillaries in the composite material. The small diameter of these pores and the surface tension of the fluid can cause the fluid to spread rapidly throughout the composite, leading to damage [13].

During the drilling of carbon fiber reinforced polymer (CFRP), cutting fluid is employed to enhance the machining process's performance, mitigate heat, and prolong tool life. Merino-Pérez *et al.,* 2019 [10] carried out an experiment to compare the efficacy of flood and through-tool cutting fluid delivery methods during the drilling of CFRP composite panels against a dry baseline condition. The cutting process involved the use of a water-based composite-specific fluid and a diamond-coated drill bit as the cutting tool. The results indicated that the utilization of cutting fluid successfully reduced delamination while improving both tool wear and hole quality. In another study, Kerrigan *et al*., 2018 [14] investigated the influence of cutting fluid on tool performance in both wet and dry conditions. Under general wet conditions, the study noted a decrease in tool performance with the use of cutting fluid, possibly due to the heat introduced during the drilling process, causing changes in the properties of the CFRP polymer.

Chilled air cutting, also known as cold air machining, is a technique that involves the use of compressed air, which is cooled to lower temperatures, to provide cooling during the cutting or drilling process. This environmentally friendly method aims to reduce heat generation, minimize thermal damage to the workpiece, and improve the overall efficiency of the machining operation [15]. Khairusshima *et al*., 2013 [16] assessed the quality and tool wear while milling carbon fiber-reinforced plastic under cooling air conditions at -10 °C. Their findings indicated that tool wear and delamination factors improved at higher cutting speeds. In the context of carbon fiber-reinforced polymer (CFRP) drilling, chilled air drilling has been studied for its potential benefits, such as reduced heat generation, improved tool performance, cost savings, environmental benefits and reduced health risks.

Machining CFRP composites proves to be more challenging and intricate compared to typical metals and alloys due to their distinctive structural properties [17]. This research addresses two critical problem statements in machining processes. Firstly, the conventional practice of utilizing cutting fluids in machining processes has given rise to growing adverse effects on human health, most notably an elevated risk of skin cancer among those exposed to these substances [18]. Secondly, the machining of CFRP itself poses inherent challenges due to its heterogeneous and anisotropic nature. Thus, this study endeavours to delve into alternative machining approaches, specifically exploring the efficacy of dry and chilled air cutting conditions. Despite extensive research machining CFRP, the potential of dry and chilled air cutting as sustainable alternatives has not been thoroughly explored. This study seeks to bridge this gap by investigating their applicability in achieving efficient and eco-friendly CFRP machining.

2.0 METHODOLOGY

2.1 Experimental Setup and Machining conditions

This study investigated the effects of dry and chilled air cutting conditions on the machining performance of Carbon Fiber Reinforced Polymer (CFRP) during drilling process. The workpiece material was CFRP, with dimensions of 90 mm in length, 75 mm in width, and 4 mm in thickness. The CFRP specimens used in this study were commercially available composite plates produced by a high-temperature hot-pressing process. A 6 mm, 2-flute, uncoated High-Speed Steel (HSS) drill bit was used as the cutting tool, chosen for its compatibility with CFRP drilling due to its durability against wear and efficient chip removal capability. Figure 1 shows distances between the holes on the CFRP. The experiments were conducted on Akira-Seiki Perfoma SR3 XP CNC milling machine. Machining was performed at a spindle speed of 1500 rpm and a feed rate of 0.07 mm/rev under two distinct cutting conditions: dry cutting, in which no additional cooling or lubrication was applied. A VORTEX adjustable cold air gun, with dual nozzle, as shown in Figure 2 was utilized in the chilled air system to convert filtered compressed air into a cold air stream as low as -14.4°C at flow velocity of 14 m/s velocity using cooling capacity values at 6.9 bar operation pressure under room temperature around 28.7 °C. It has a magnetic mounting base that allows it to be simply mounted to any metal-based equipment. The vortex tube was mounted on the machine and the nozzle which supplied the chilled air to the cutting tool was located parallel to the feed motion and behind the cutting tool. Another nozzle was pointing to the CFRP workpiece to ensure that the cooling effect was effectively applied as shown in Figure 2. The nozzle exit was positioned 15 mm away from the workpiece and directed at 60° angle to the spindle and tool axes. The temperature of the air exiting the nozzle was measured using a UNI-T UT320D Mini Contact Type Thermometer Temperature Type K/J Thermocouple prior to drilling to ensure consistent chilled air conditions. For each cutting condition, 35 drilling operations were conducted with identical parameters, and this process was repeated twice to ensure consistency and reliability in the experimental results. Measurements of all response variables, including tool wear, cutting temperature, and hole quality (diameter, circularity, and cylindricity), were taken after each drilled hole. For data analysis and presentation, the results were expressed as the average values obtained from all 35 drilled holes for each cutting condition.

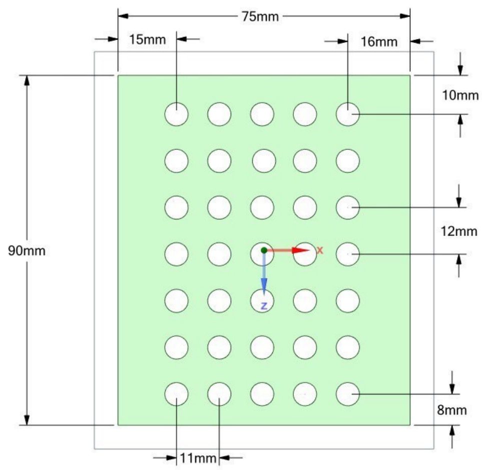


Figure 1 Workpiece dimension and distance between the holes

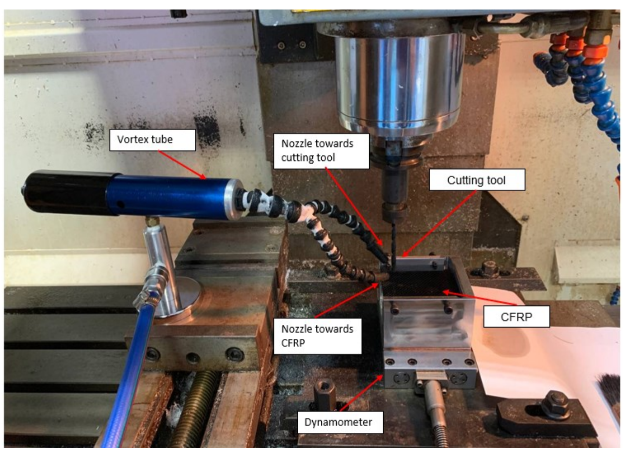


Figure 2 Experimental setup for drilling with chilled air

2.2 Cutting Force and Cutting Temperature

Cutting force and cutting temperature were measured to evaluate the mechanical loads and thermal during the drilling process. Cutting force measurements were recorded using a Type 9256C2 Kistler Dynamometer, which provided precise force data under each cutting condition, offering insights into the mechanical demands placed on the tool and workpiece. Simultaneously, cutting temperature was monitored using a FLIR 440 thermal imaging infrared camera, which captured real-time thermal images of the cutting zone. To ensure accurate and unobstructed temperature readings, the thermal camera was positioned outside the machine enclosure with a direct line of sight to the cutting area as shown in Figure 3. The distance to the cutting zone is about 1 meter. The camera setup allowed it to capture thermal images through the machine's viewing window, providing real-time data on the temperature fluctuations within the cutting zone.

Figure 3 Thermal camera setup

2.3 Tool wear, burr, delamination and hole measurement

The machining performance was evaluated based on several key factors. Tool wear (flank wear & chisel edge wear), burr formation, and delamination were analyzed using a Xoptron XST60 stereomicroscopy system, allowing close examination of wear patterns, burr characteristics, and the extent of delamination around the drilled holes. Additionally, the hole quality was assessed by measuring average hole diameter, circularity, and cylindricity using a Coordinate Measuring Machine (CMM), which helped evaluate the geometric integrity of the drilled holes. For each hole, six points were probed on the circumference of cross-sectional diameters to obtain average diameters of holes. Figure 4 shows sample images of chisel edge wear and flank wear observed using microscope.

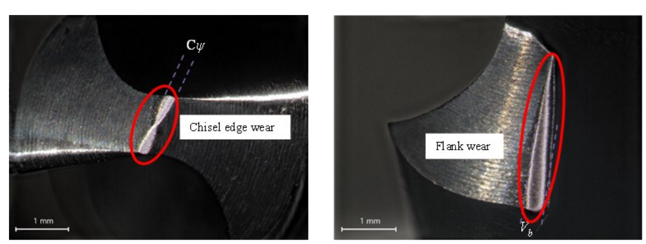


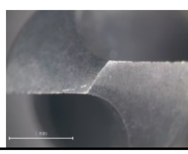
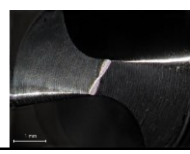
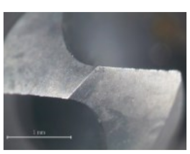
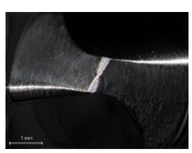
Figure 4 Chisel edge and flank wear images using microscope

3.0 RESULTS AND DISCUSSION

3.1 Chisel edge wear

The chisel edge is the central part of a drill bit where the two cutting lips meet. It is a non-cutting edge that primarily serves to push material aside rather than cut it, creating high thrust forces during drilling. Table 1 presents the chisel edge condition of the drill bit before drilling and after 35 holes under two machining conditions: dry cutting and chilled air cooling. Initially, the chisel edge was well-defined with no visible signs of wear. However, after 35 drilled holes, clear differences in wear progression were observed between the dry and chilled air cutting conditions. Figure 5 indicates that the wear is higher for chilled air cutting (0.26 mm) compared to dry drilling (0.23 mm). This result against the studies which have shown that chilled air can aid in decreasing tool wear during milling of CFRP panels [19]. The wear under chilled air conditions were higher than dry cutting conditions can be attributed to several factors. This can be primarily attributed to the material behavior influenced by temperature variations. Previous researcher reported that chilled air cooling tends to make the CFRP material more brittle [20]. This brittleness increases the material's abrasiveness, causing it to interact more harshly with the cutting tool. As a result, the chisel edge of the cold tool experiences greater wear and degradation. In contrast, dry drilling does not alter the material properties of CFRP as drastically, maintaining a more consistent and less abrasive interaction with the cutting tool. Consequently, the chisel edge wear is less pronounced under dry drilling conditions.

Table 1 Chisel edge wear

Cutting Conditions	Before Drilling	After 35 holes
Test A (Dry)		
Test D (Chilled air)		

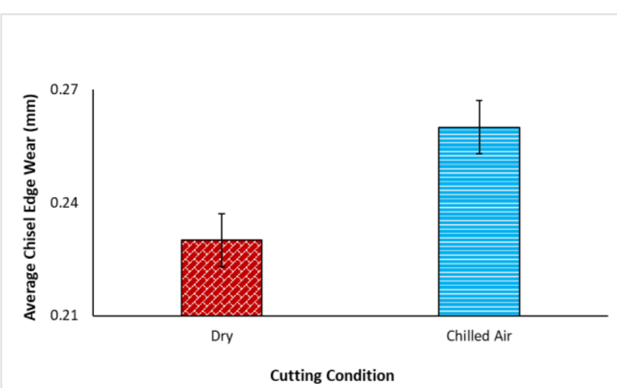


Figure 5 Average chisel edge wear under different cutting conditions

Another significant factor causes the higher tool wear under chilled air is the insufficient lubrication and cooling provided by chilled air during the cutting process. While chilled air is effective at reducing the temperature, it does not offer the same level of lubrication as other cooling methods, such as liquid coolants. This lack of lubrication increases friction between the cutting tool and the CFRP material. Higher friction leads to increased heat generation at the cutting interface, which can exacerbate tool wear. In dry drilling, although there is no external cooling, the friction-induced heat is more evenly distributed and may be partially mitigated by the material's inherent properties, reducing the overall wear on the chisel edge.

In summary, the combination of increased brittleness of the CFRP material, inadequate lubrication, and the thermal effects of rapid cooling contribute to the higher mean chisel edge wear observed under chilled air cutting conditions. These factors collectively make chilled air less effective in preserving the tool's integrity compared to dry drilling, despite its cooling benefits. Understanding these mechanisms is crucial for optimizing cutting processes and selecting appropriate cooling strategies to minimize tool wear and enhance machining performance.

3.2 Flank wear

Figure 6 shows the average flank wear under different cutting conditions. It illustrates a significant difference in the mean flank wear (V_B) when drilling Carbon Fiber Reinforced Polymer (CFRP) under dry conditions versus chilled air conditions. The data indicates that dry drilling results in a mean flank wear of 0.38 mm, while chilled air drilling results in a higher mean flank wear of 0.5 mm. Figure 7 shows the flank wear developed in cutting flute for a) dry cutting condition and b) chilled air condition, respectively. One of the primary reasons for the higher flank wear under chilled air conditions is thermal shock [21]. Chilled air causes rapid cooling, leading to sudden temperature changes during the drilling process. These extreme temperature fluctuations can induce thermal shock in the cutting tool, causing micro-cracks and structural weaknesses [22]. These micro-cracks can propagate under the stresses of cutting, leading to increased wear on the tool's flank. In contrast, dry drilling avoids such rapid temperature changes, resulting in a more stable thermal environment and consequently less wear. Material properties and chip evacuation further contribute to the higher flank wear observed with chilled air. The CFRP material can become harder and more brittle when exposed to chilled air, making it more abrasive against the cutting tool. This behavior is attributed to the reduced matrix ductility and increased stiffness of the polymer resin at low temperatures, which limit energy absorption during cutting and increase tool-fiber interaction. Similar findings were reported by researchers who observed that cryogenic conditions can increase the brittleness and hardness of CFRP composites [23]. This increased abrasiveness accelerates tool wear. Additionally, chilled air can affect chip evacuation, resulting in poor chip removal efficiency from the cutting zone [24]. These hardened chips can further abrade the tool's flank, leading to increased wear.

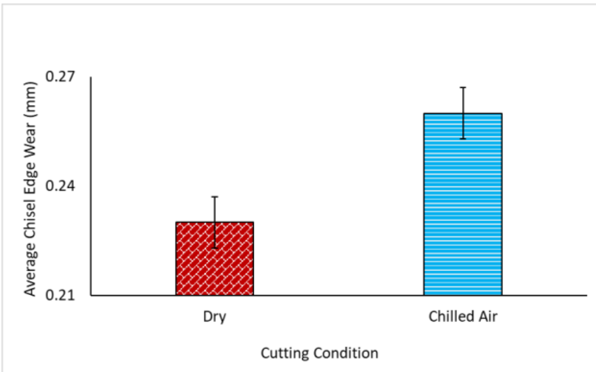


Figure 6 Mean of Flank Wear under Different Cutting Condition

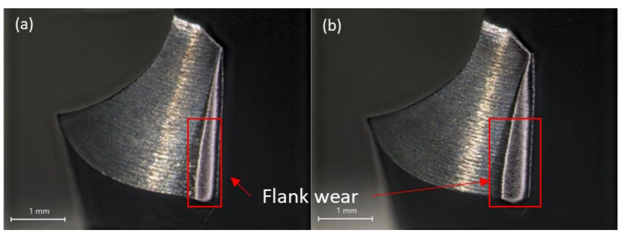


Figure 7 Flank wear (a) dry machining (b) machining with chilled air

3.3 Burr and Delamination

Figure 8 shows the comparison of burr and delamination formation between dry and chilled air. The entry and exit point of the hole were observed during this experiment. During dry drilling at 1st hole, the tool is relatively new, and the initial holes may exhibit moderate delamination and burr formation while the initial holes drilled under chilled air cutting are likely to show minimal delamination and burr formation. Burr and delamination are lower when drilling CFRP with chilled air compared to dry air, despite the greater tool wear, due to the stabilizing effect of the chilled air on the material and the drilling process [25]. Chilled air cooling can help maintain the structural integrity of the CFRP by reducing the thermal degradation of the matrix material, which is more prone to occur under dry cutting conditions. The cooling effect of chilled air reduces the local temperature in the drilling zone, preventing excessive softening and weakening of the polymer matrix, thus minimizing the risk of delamination.

The results clearly show that delamination increases progressively under dry drilling. Starting from 1st, significant delamination is evident in dry drilling, whereas the holes drilled with chilled air exhibit minimal burrs. By 35th hole, the dry drilling holes are filled with uncut fibres and a substantial number of burrs, while the holes drilled with chilled air show only a slight increase in burrs compared to 1st hole. This is particularly evident which show the more effective result at exit point of the holes. Chilled air helps to harden the matrix around the carbon fibres, making it less likely for the fibres to pull out or for cracks to propagate between the layers. This results in cleaner cuts and better preservation of the laminate structure. The cooling effect also minimizes the heat-affected zone, reducing the extent of thermal damage and thereby contributing to lower delamination [26].

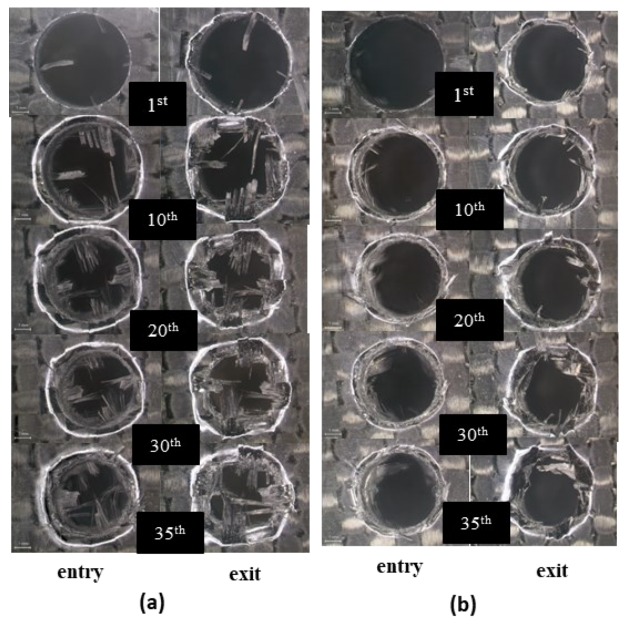


Figure 8 *The comparison of burr and delamination formation between (a) dry and (b) chilled air machining at entry point*

Moreover, the high tool wear in chilled air conditions can be managed by the cooling effect, which helps in maintaining the sharpness of the cutting edges for a longer duration compared to dry cutting. This maintains a more consistent and controlled cutting action, reducing the mechanical stresses that could lead to delamination. Thus, the benefits of reduced thermal damage and stabilized cutting conditions with chilled air outweigh the drawbacks of higher cutting force and tool wear, resulting in lower delamination.

3.4 Cutting Force and Cutting Temperature

In drilling, cutting force and cutting temperature are the key parameters that affect tool wear, hole quality, and overall machining performance. Figure 9 shows the trend cutting force of the drilling process from 1st hole to 35th hole for both cutting conditions. The cutting force is higher in the chilled air runs compared to the dry runs. Yellow line that represents chilled air condition show higher mean cutting forces compared to the dry run (grey line), particularly noticeable as the number of holes increases.

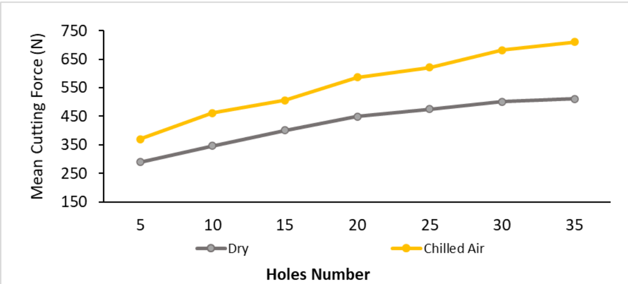


Figure 9 Cutting Force under Dry and Chilled Air

Chilled air might cause the CFRP material to become more brittle and harder due to the lower temperatures. The measured average cutting temperature under chilled air was approximately 34°C, whereas under dry cutting it reached about 56°C as shown in Figure 10. The reduced temperature increased the matrix rigidity and limited the ductile deformation of the composite, thereby requiring higher cutting forces to fracture the fibers and matrix. This observation aligns with previous findings that CFRP machining at lower temperatures can increase brittleness and subsequently the cutting forces required [27]. Figure 11 shows thermal images captured during CFRP drilling under chilled air and dry cutting conditions. The temperature distribution in the cutting zone under dry cutting is visibly higher, with maximum temperatures reaching approximately 87.7°C, whereas chilled air machining maintains a significantly lower maximum temperature around 34.2°C.

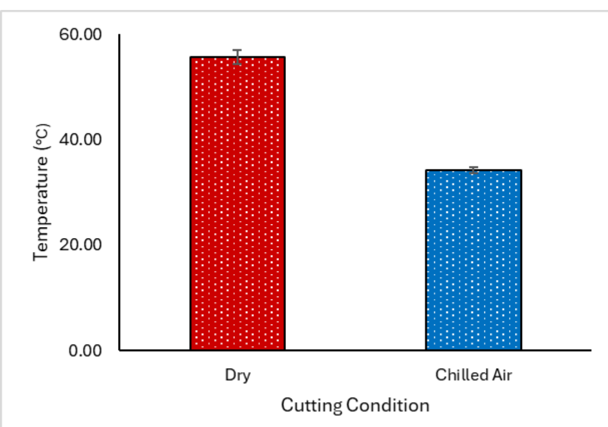


Figure 10 Average Cutting Temperature of CFRP Drilling with Different Cutting Conditions

The increased in hardness can lead to higher resistance during cutting, resulting in higher cutting forces. Besides that, while chilled air helps in cooling, it may not provide adequate lubrication. Lack of lubrication can lead to increased friction between the drill bit and the CFRP material, contributing to higher cutting forces. Another reason may be the sudden cooling effect of chilled air could introduce thermal shock in the drill bit and the CFRP material. This might cause micro-cracks or other surface anomalies, increasing the cutting resistance and thus the cutting force. This results in more cutting-edge fracture and chipping, which in turn increases the thrust force needed to drill the CFRP. Additionally, the chilled air environment can reduce the thermal softening of the CFRP material during drilling. Without the thermal softening effect, the CFRP remains harder and more resistant to deformation, leading to higher thrust forces compared to dry drilling.

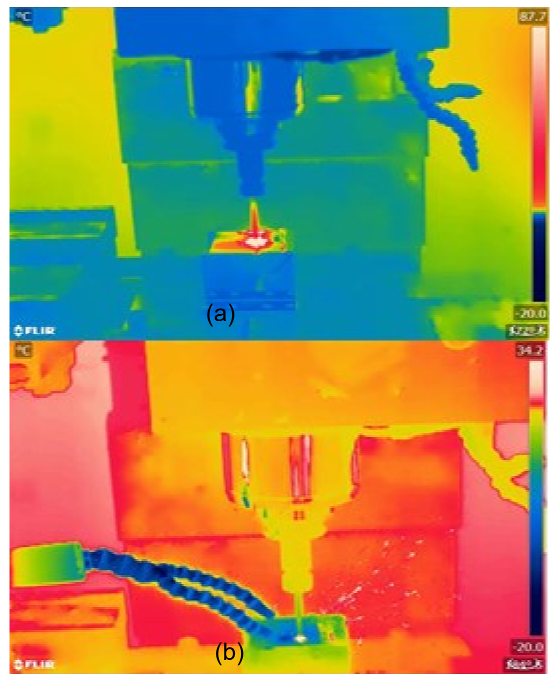


Figure 11 Thermal image comparing cutting temperature under (a) dry cutting (b) chilled air cutting condition

3.5 Hole Dimensional Accuracy

In CFRP drilling, hole accuracy is assessed using hole diameter, cylindricity, and circularity. These parameters are critical for ensuring proper fit and assembly in aerospace, automotive, and medical applications.

3.5.1 Hole Diameter

Figure 12 shows the average diameter of holes under dry and chilled air cutting. Based on the results, the average diameter of holes drilled under dry cutting conditions slightly above the target at 1st hole, then gradually decreases and stabilizes around the target diameter of 6.00 mm as more holes are drilled. But overall, still smaller than the holes under chilled air cutting condition. This behavior can be attributed to the thermal and mechanical effects on the CFRP material. Under dry cutting, higher heat generation softens the polymer matrix, allowing elastic recovery and contraction after drilling, which leads to a smaller final hole size [28]. In contrast, the chilled air condition increases the brittleness and stiffness of the composite, reducing matrix softening and deformation. As a result, the hole diameter produced under chilled air cutting remains closer to the nominal dimension, demonstrating better dimensional stability. The average diameter of holes under chilled air cutting starts higher than the target at 1st hole and shows a slight decreasing trend but remains consistently above the target diameter throughout the drilling process. Chilled air helps maintain dimensional stability during the drilling process, resulting in more consistent hole diameters throughout machining.

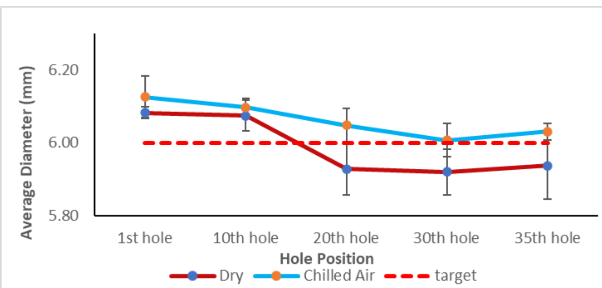


Figure 12 Average Diameter of Holes under Different Cutting Condition

3.5.2 Cylindricity

Figure 13 shows the average cylindricity of holes under dry and chilled air cutting. For the dry cutting condition, there is a noticeable variation in cylindricity across different hole positions. The cylindricity values tend to deviate more from the target diameter of 6.00 mm, especially at the entry and exit positions. This deviation is more pronounced in the earlier holes (e.g., 1st hole) and seems to stabilize somewhat in the later holes, although still exhibiting considerable variance. In the later holes, it is evident that the diameter gradually decreases at the middle and exit points. Under dry cutting, the highest value of circularity error has occurred at the entry point of first hole with the value of 0.2033 mm. This situation happened because heat effected zone formed due to the excessive force at the entry of the holes with high speed drilled and it is consequently generated higher temperature on the holes surface. This scenario causing the melting and compression on workpiece material and effected the roundness of the holes.

In contrast, the chilled air cutting condition consistently produces cylindricity values closer to the target diameter across all hole positions. The chilled air condition appears to maintain a steadier cylindricity from the entry through the middle to the exit of the holes, indicating better control over the drilling process and less deviation from the desired hole size. The error bars indicate the variability of measurements, with the chilled air condition generally showing smaller error margins, suggesting more uniform hole production. Figure 14 shows the hole shape under dry and chilled air cutting at 1st hole.

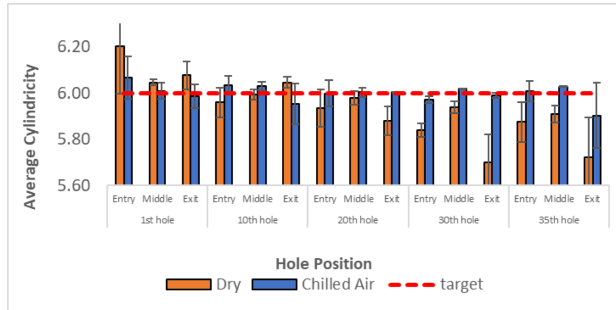


Figure 13 Average Cylindricity of Holes under Different Cutting Condition

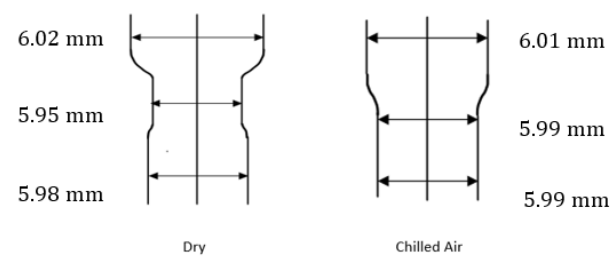


Figure 14 Hole shape under different cutting condition

3.5.3 Circularity (Roundness)

Figure 15 shows a comparative analysis of the average circularity of holes drilled under dry and chilled air cutting conditions. The results indicate that both cutting conditions maintain circularity deviations within a 0.05 mm tolerance, suggesting a high level of precision and consistency in the drilling process. Under dry cutting conditions, the result shows that the circularity of the holes remains within the 0.05 mm tolerance throughout the drilling of 35 holes. This indicates that despite the potential challenges associated with dry cutting, such as heat generation, the process can maintain acceptable circularity. The initial holes may exhibit slightly higher deviations due to the stabilization period of the tool, but as the drilling progresses, the circularity stabilizes, reflecting the tool's adaptation to the cutting conditions.

Chilled air cutting, on the other hand, demonstrates a consistent circularity within the 0.05 mm tolerance from the start. The cooling effect of chilled air helps in leading to more stable and precise hole circularity. The graph suggests that chilled air cutting provides a more controlled cutting environment, resulting in fewer deviations and better overall circularity compared to dry cutting. The cutting parameters, such as feed rate and spindle speed, are assumed to be stable and optimized for both cutting conditions, contributing to the consistent circularity observed.

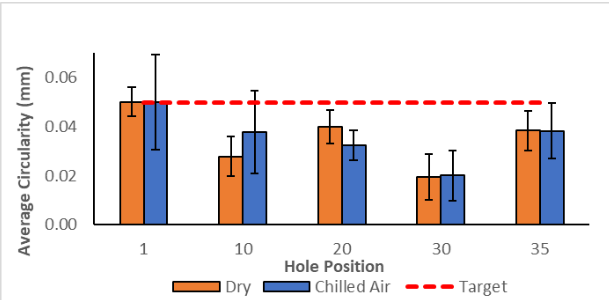


Figure 15 Average Circularity of Holes under Different Cutting Condition

4.0 CONCLUSION

This study investigated the effects of chilled air and dry cutting conditions on the drilling performance of CFRP composites, focusing on chisel edge wear, flank wear, burr and delamination formation, cutting force and temperature, and hole quality. The results showed that dry cutting produced slightly lower chisel edge wear and 24% lower flank wear than chilled air cutting. This due to the brittleness induced by chilled air, insufficient lubrication, and thermal shock effects. Although chilled air machining effectively reduced the cutting temperature compared to dry cutting, it resulted in higher cutting forces due to the increased brittleness of material. Chilled air machining offers benefits in reducing delamination and burrs and also improving dimensional accuracy, that assessed by hole diameter accuracy, circularity and cylindricity. These advantages from chilled air's ability to stabilize the material, reduce thermal degradation, and maintain sharper cutting edges for longer periods. Therefore, chilled air-assisted machining appears to be particularly suitable for applications where superior hole dimensional accuracy and reduced burr formation are more critical than maximizing tool life. For future research, it is recommended to explore the optimization of chilled air parameters (such as flow rate and temperature). Further investigation into mechanistic modelling and multi-objective optimization could also provide deeper insights into the balance between tool performance, surface integrity, and environmental impact.

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Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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