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INVESTIGATION OF DRILLING PERFORMANCE IN CRYOGENIC DRILLING ON CFRP COMPOSITE LAMINATES

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THESIS

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering in the College of Engineering at the University of Kentucky

By

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ABSTRACT OF THESIS

INVESTIGATION OF DRILLING PERFORMANCE IN CRYOGENIC DRILLING ON CFRP COMPOSITE LAMINATES

In recent years, there has been a substantial growth in the application of carbon fiber reinforced plastic (CFRP) composite materials in automobile and aerospace industries due to their superior properties such as lightweight, high strength, excellent corrosion resistance, and minimal fatigue concerns. The present study evaluates the drilling performance of woven carbon fiber reinforced plastics under both dry and cryogenic cooling conditions using uncoated solid carbide drill with a through-hole for coolant application.

The effects of the cooling conditions and the cutting parameters on drilling performance in drilling CFRP were evaluated in terms of generated thrust force, torque, cutting edge radius, outer corner flank wear, hole quality (including surface roughness, diameter error, roundness, delamination, burr formation, sub-surface quality). Both cooling conditions and cutting parameters were found to influence the thrust force and torque at different levels. The thrust force and the torque are higher in cryogenic cooling under all cutting parameters. In most of the cases, cryogenic drilling gives better bore-hole quality with lower surface roughness, more accurate diameter, less burr generation, better sub-surface quality, etc. Also, the tool-wear rates measured in drilling shows that cryogenic drilling produces less tool-wear than dry drilling does.

KEYWORDS: CFRP, Cryogenic drilling, Hole quality, Tool-wear, Thrust force

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CHAPTER 1: INTRODUCTION

Composite materials form a material system composed of a mixture or a combination of two or more macro constituents that differ in form and chemical composition. They are developed specifically to meet the challenge of modern industry [1]. In recent years, there has been a substantial growth in the application of carbon fiber reinforced plastic (CFRP) composite materials in automobile and aerospace areas due to their superior properties such as lightweight, high strength, excellent corrosion resistance, and minimal fatigue concerns.

Among all manufacturing processes, hole-making operations are essential for the functionality of machined components. The use of CFRP (carbon fiber reinforced plastics) frequently involves drilling of a large number of holes for structural joints. For example, over 100,000 holes are made for a small single engine aircraft [2]; in a large transport aircraft millions of holes are made, mostly for fasteners such as rivets, bolts and nuts [2]. In these cases, drilling becomes one of the most widely needed operations in machining of CFRP composite laminates.

However, problems exist, such as high rejection ratio of the product and severe tool-wear usually due to the mechanical and thermal properties of this fiber- reinforced material. The abrasive nature of CFRP material often leads to a high tool-wear rate and some related defects such as delamination; cutting temperature is an another problem that causes defects due to the low thermal conductivity of this material. Many factors influence the borehole quality, which can lead to rejection of the products. These factors are cutting parameters, type of cutting tools and cooling conditions, etc. [3].

Achieving a lower thrust force is the first priority during drilling process since thrust force is highly related to delamination. Delamination is a mode of failure, which happens in drilling of laminate material, and when thrust force exceeds a certain value, it would cause layers of multilayer material such as CFRP to become separated. This failure would cause the material a significant loss of mechanical toughness, and would extremely diminish inter-laminar strength. Avoiding delamination becomes the main objective of drilling CFRP material since the CFRP material continues to grow in the aerospace and automobile industries, and the safety issue has become the most cared-for aspect. Structures and parts with delamination would very likely reduce the reliability of the product and endanger the safety of the passengers. The optimum cutting parameters should be determined in order to reach a lower thrust force, and for achieving a delamination-free borehole. A relatively low feed rate (lower than 0.1 mm/rev) and a high cutting speed (lager than 800 rpm) are recommended for drilling CFRP material [3].

On the other hand, thermally-induced damage is another aspect of defect that cannot be ignored. Low thermal conductivity of CFRP would lead to an extremely high cutting temperature and make the expansion of the drill bit, which would influence the dimensional accuracy of the boreholes. Also, degradation would occur in matrix due to the high temperature. Traditionally there are two cooling conditions for use, i.e., dry and flood cooling, and recently the usage of MQL (minimum quantity lubrication) has emerged. Applying cooling would, to some degree, reduce the cutting temperature, and then reduce the defect related to thermal damage. But, a chemical reaction might happen between the coolant liquid and the CFRP material, which would diminish the properties of the material. This factor should also be considered when drilling CFRP material.

Meanwhile, to the best of our knowledge, the influence of cryogenic cooling in drilling performance has not yet been studied. High cutting temperatures can negatively affect the structure of CFRP and the shape of machined surfaces. Applying cryogenic cooling might significantly influence the hole quality by reducing the cutting temperature, thus preventing pyrolysis and material-softening, and thermally–induced defects from happening.

The purpose of this project is to investigate the influences of cryogenic cooling on drilling CFRP plate. An assumption has been made that the hole quality can be enhanced by lowering the cutting temperature through cryogenic cooling. Different aspects of the drilling performance, such as the torque, the thrust force, the hole quality, and the tool-wear, have been studied under different cutting parameters and cooling conditions. Besides, analytical models are also used in this project for the purpose of establishing the relationship between thrust force and delamination.

The innovative part of this thesis lies in the experiment setup: the drilling test is carried out with a fixed drill bit and a rotating cylinder-shaped CFRP composite specimen, in order to apply cryogenic cooling. Liquid nitrogen goes through the internal coolant hole of a coolant-fed drill during the drilling operation. During the whole course of the experiment, the workpiece was processed under dry and cryogenic cooling conditions. A range of feed rates and cutting speeds are also applied to enable the optimum conditions for drilling CFRP composites. The rest of this thesis is organized as follows:

Chapter 2 presents an introduction on drilling carbon fiber reinforced plastics. Also presented is a review of some of the previous work that has been done in the field.

Chapter 3 presents the experimental setup for machining and the drilling experiments performed under different cooling conditions: dry and cryogenic cooling. It also gives a brief description of the specimen preparation method used for drilling test.

Chapter 4 presents trust force and torque results obtained under each cooling condition at different cutting parameters of cutting speed and feed rate. It also includes analytical models for drilling CFRP laminates in order to establish a relationship between the thrust force and delamination. By studying the analytical models, one can have a better understanding of delamination, one of the most deleterious damage processes associated with drilling carbon fiber reinforced plastics.

Chapter 5 discusses the surface integrity and delamination results of the machined samples. The surface integrity parameters such as diameter error, roundness, surface roughness of the internal surface of the borehole and the quality of the internal surface of the borehole are studied for the specimens.

Chapter 6 presents a summary of findings from this project with a short discussion on future work.

CHAPTER 2: LITERATURE REVIEW ON DRILLING OF CFRP MATERIALS

This chapter begins with an overview of current issues in the drilling of CFRP materials. Then, several specific aspects involved in the drilling of CFRP materials will be discussed in detail presenting the current state-of-the-art, and this includes current knowledge on delamination, thrust force and torque, cutting temperature, cooling methods, and cutting tool selection in drilling of CFRP materials.

2.1 Current Issues in the Drilling of CFRP Composite Materials

Machining CFRP composite materials raise some specific problems due to their unique nature of inhomogeneous and anisotropic properties [4]. It has been observed improper cutting parameters or tool-wear lead to damages such as delamination, cracks, fiber/matrix debonding, fiber breakage and matrix thermal melting [4]. Since they are very abrasive, fibers used as reinforcement rapidly increase the tool-wear rate, and therefore the drill is worn quickly and can no longer maintain the edge sharpness. Researchers also found that if the cutting edge radius increases to a certain level, the thrust force will surpass a critical value, when delamination is most likely to happen at the exit side of the machined surfaces [5]. Not only does tool-wear bring the problem of delamination, the blunt drill also causes the problem of excessive burr generation. According to Teti [3], the main reason for burr generation is outer corner wear.

Meanwhile, as a consequence of low thermal conductivity of CFRP, the heat generated during the cutting process could not be effectively transferred. This leads to an extremely high cutting temperature generation during the machining process, resulting in more severe expansion of cutting tool diameter during drilling CFRP, compared with drilling metallic materials. This overheating problem causes matrix material of carbon fiber reinforced composite to get burned, as well as with a larger deviation on the diameter of the bored holes [6]. These quality control problems, which severely and negatively affect the mechanical properties of parts, are the reasons for a significant rejection rate of machined composite parts [1]. In order to eliminate defects in drilling CFRP and to achieve boreholes with acceptable hole quality and surface integrity, many researchers have tried to establish correlations between cutting conditions and problems occurring during drilling CFRP in order to achieve optimized results. Figure 2.1 summaries these attempted correlations.

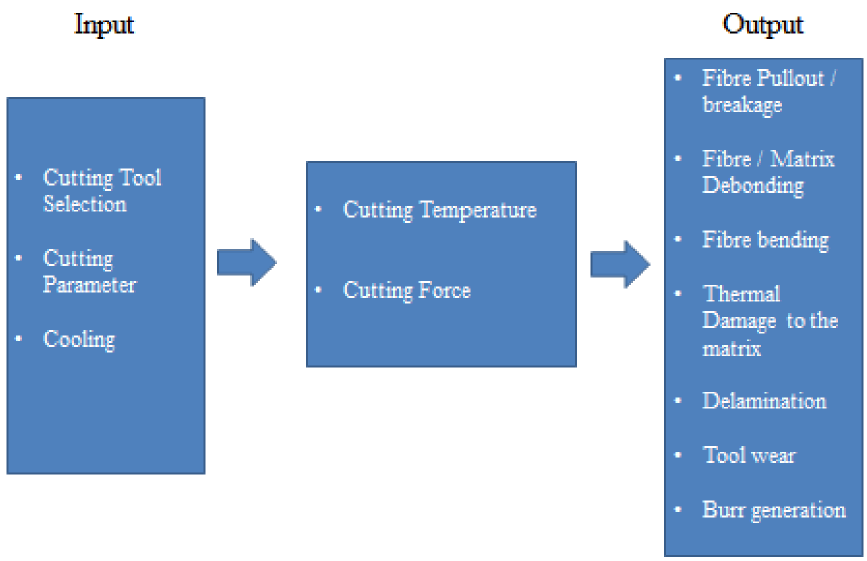


Figure 2.1: Attempted correlations between cutting conditions and quality issues in drilling of CFRP materials.

2.2 Analysis of Delamination

Delamination in the drilling of CFRP composite materials became one of the major problems for almost all researchers. It is an inter-laminar or inter-ply failure phenomenon [1]. According to ASTM standard, delamination refers to the separation of plies in a laminate. This may be local or may cover a large area in the laminate [7]. When occurring at the top surface around the drilled borehole, it is known as "peel-up delamination" or "hole entry delamination". It is more severe at the bottom surface around the drilled borehole known as "push-out delamination" or "hole exit delamination" [8]. Hole entry delamination and hole exit delamination are schematically illustrated in Figure 2. 2.

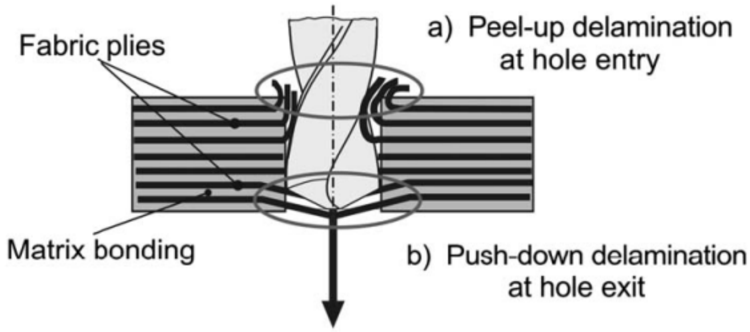


Figure 2.2: Peel-up and Push-down delamination [8].

Delamination has been recognized as the major concern in drilling of CFRP materials since it induces the structural damage to the laminates and results in poor assembly tolerance, and thus causes long-term performance deterioration [3]. Ho-Cheng and Dharan [9] investigated the delamination during drilling in composite laminates. By using fracture mechanics, they analyzed the problem and found an optimal thrust force as a function of drilled borehole depth. Their analytical model correlates thrust force to delamination and they concluded that the maximum thrust force for no delamination can be used in cutting parameter selection to improve productivity. Analytical models for drilling carbon fiber reinforced plastics would be discussed in later sections of this thesis.

Several methods have been developed for measuring and evaluating delamination, of which the ultrasonic C-Scan proves to be the most accurate and precise approach for quantifying the phenomenon [10]. However, other techniques, such as “dye-penetration” (DP) testing and “direct visualization” (the usage of a conventional “Tool Makers” microscope), have also been frequently utilized by various researchers [11]. Khashaba [12] claims that a precise and economical technique for measuring the delamination resolution has been developed. Equipment required for this technique includes: PC, color flatbed scanner, and image software (CorelDraw). The drilled specimen is to be placed directly on the scanner in such a manner that the damage areas in the borehole could be recorded. This technique is calibrated by measuring several dimensions on a standard steel ruler. The error lies in the range from 0.3% to 0.8%, which is totally acceptable when compared with the measurements carried out using the CCD sensor.

Because of the importance of achieving delamination-free or nearly delamination-free boreholes, researchers have made quite a few attempts. The most obvious way to reduce delamination is to reduce the feed rate, but it in turn brings another problem: lower feed rate means lower productivity. Considering that the recommended highest feed rate for drilling carbon fiber is less than 0.1 mm/rev [13], which is already a relatively low value for drilling approach, a lower feed rate seems an unpractical option for industry.

Instead of lowering the feed rate, many authors have come up with ideas of using different kinds of drill bits in the drilling of CFRP materials. Tsao and Hocheng [14] investigated the effect of special drill bits on drilling-induced delamination of CFRP materials. Several specially designed drills including saw drill, candle stick drill, and core drill were studied. They also compared the theoretical critical thrust force with the experimental critical force for each type of drill bit [15]. Most of the special drill bits have a higher critical thrust force than conventional twist drills, which makes them more difficult to cause delamination. Fernandes and Cook [16] studied the effects of drilling carbon composite using one-shot drills. This specially designed drill bit has two cutting edges, which allow the drill bit to drill and to ream at the same time. The tip of this drill has a smaller diameter compared with the rest of the drill, and this design allows the drill bit to create a pilot hole before achieving the desired diameter, which will reduce the thrust force. With an extremely thin web of the drill, this drill bit significantly reduces the thrust force during drilling process, thus contributing to reducing delamination.

Another way to solve delamination is using back-up materials. This method has been widely used in industry. Tsao and Hocheng [17] reported that delamination can be effectively reduced or even eliminated by using back-up materials to support and counteract the deflection of the composite laminate, which causes exit side delamination. They also mention that the use of the back-up materials is very common in practice and it is extremely effective, but no analytical study has been done regarding this effect. In their work, they explained it both mathematically and physically. From the analytical viewpoint, the critical drilling thrust force for material with back up is calculated and compared with the critical drilling thrust force for material without backup. The results show that the critical thrust force is higher when a back-up support is applied. The effect could also be physically explained by the counteraction of back-up material to the drilling-induced downward bending deflection of the laminate. Although the deflection of the last layer of the laminate could not be avoided, the back-up material has a much higher stiffness than the single layer being bent, and thus will effectively reduce the laminate deflection. As seen in Figure 2.3, critical thrust forces for drilling with and without backup plate were calculated, and it is clear that critical thrust force with back-up plate is larger, and meanwhile measured thrust force exceeded estimated thrust force for drilling without a back-up plate. This shows the advantage of using a back-up plate..

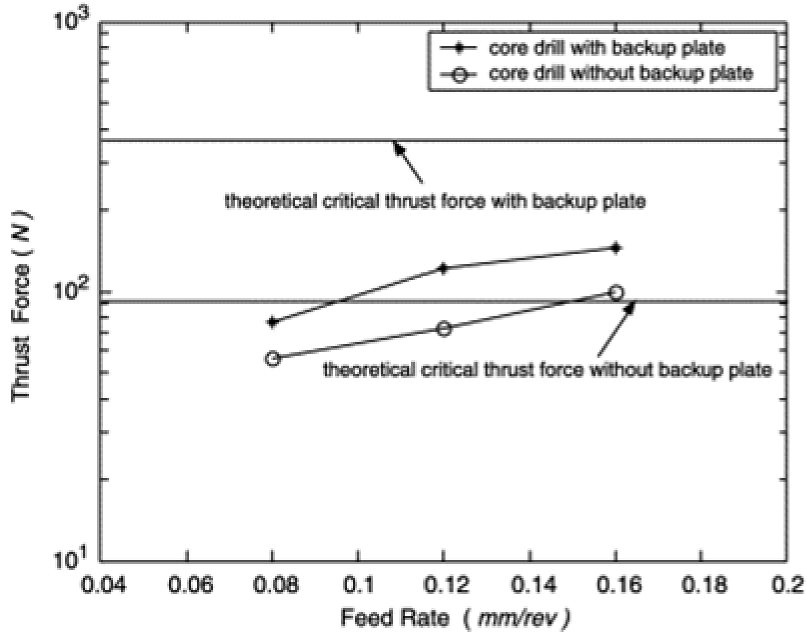


Figure 2.3: Correlation between measured thrust force and feed rate during drilling [17].

Another attempt has been made by Shyha et al. [18] to reduce the delamination. They applied peel ply layers (0.1 mm thick nylon sheet attached on both sides of 3 mm thick laminates) on hole entry and exit delamination. The hole quality was significantly improved, because remarkable reduction in damages relating to fiber breakage, matrix melting, and delamination was observed during the drilling of the nylon-backed CFRP material. The reason for the improvement in hole quality after applying peel ply layers is that peel ply layers support the CFRP material during the drilling process as back-up materials. As discussed in the previous section, using back-up material would effectively reduce or even eliminate delamination.

Another strategy is the use of pilot holes. Won and Dharan [19] conducted a series of experiments to evaluate thrust force under various feeds, and drilling experiments were carried out on laminates with and without pilot holes. They investigated the effects of chisel edge and pilot hole on thrust force. Experimental results show that thrust force measurements were much smaller when using a smaller chisel edge and drilling laminates with pilot holes. The results indicate that the thrust force contribution from the chisel edge is a significant component of the total thrust force, suggesting that the potential for delamination in composite laminates can be significantly reduced through the use of pilot holes.

Other strategies such as utilization of non-conventional vibration-assisted drilling techniques [20], laser machining, ultrasonic machining [21], and active back-up force [22] have also been used by various researchers in order to reduce or eliminate delamination.

2.3 Cutting Tool Selection and Tool-wear Measurements

Carbon fibers used as reinforcement in the CFRP feature high hardness and abrasiveness, and therefore the tool materials recommended for cutting CFRP laminates include carbides (both coated and uncoated) and diamond [23]. However, uncoated carbide is the most commonly used tool material.

High speed steel (HSS) tools are also used in some cases, but they have a lower heat resistance and a high tool-wear rate. This proves to be the case when drilling FRP using the high speed steel (HSS) drill. A HSS drill does not possess the same capability in terms of wear resistance as a carbide drill does. The sharpness of the cutting edge could only be kept at a certain level until sometimes in drilling practice, and afterwards it rises rapidly, as does the thrust force. For experimental work, the HSS drill bit may be an option, but it is not a practical choice for the industry. On the other hand, many researchers recommend the uncoated cemented carbide drill, since its cutting edge radius is smaller compared with coated carbide and it has a higher wear resistance compared with the HSS drill bit. Also, the carbide drill is much more economical than the diamond tool. Davim and Reis [24], in their experimental work, found that the carbide tool yielded better results than the HSS drill bit did.

Diamond tools (PCD or CVD) have been gaining popularity over the past few years because their tool-life equals 10 to 20 times of that of uncoated carbides, even though diamond tools are much more expensive compared with solid carbide drills. Apart from extending the tool-life, it also lowers the tool changing frequency, and in turn increases the productivity. Although tool changing takes less than five minutes, a disruption of the working process still influences the efficiency, and thus leads to loss of productivity with increased cost of manufacture. Ramulu et al. [23] investigated drilling of a graphite-epoxy composite with PCD tools. The wear behavior was characterized by small cracks and flank wear. They also found that the tool-wear resistance increase with the increase of the size of diamond grain. In another study, based on the their experiment results, Ramulu et al. [25] claimed that with abrasive nature of carbon fiber, harder tools are required. They tested different drill bit and thrust force of PCD drill is the smallest among the drill bits they used. Figure 6 shows the thrust force result in drilling. Increase rate of thrust force is significantly higher for the HSS tool than increase rate of thrust force in PCD tool. The excessive thrust force in HSS tool indicates that PCD is superior in terms of tool-wear resistance.

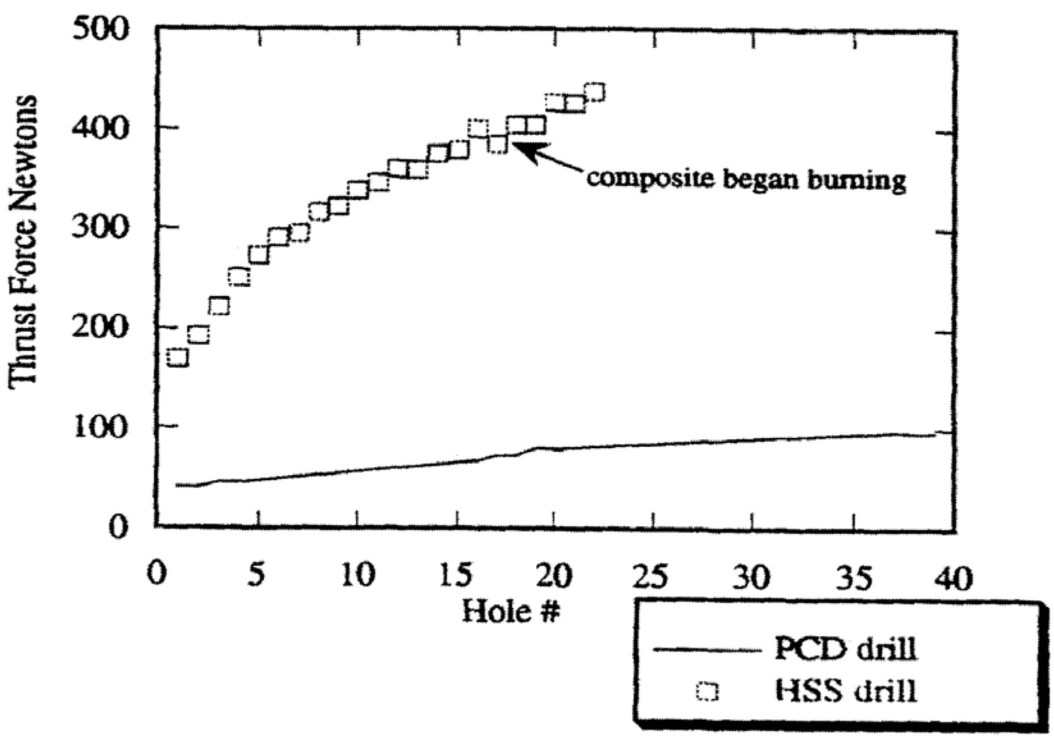


Figure 2.4: Thrust force versus number of holes drilled, 2720 rpm and 0.028 mm/rev [25].

Geometry of the drill bit has a huge impact in the drilling of CFRP. Durão et al. reported thrust force results from conventional twist drills with different point angle [26]. They found that a drill bit with lower point angle gives lower thrust force, which leads to a less severe delamination. The numbers of flutes also influences experiment results. In his study, Davim [24] used three different types of drill bits (diameter of 5mm, 118 degrees point angle): (a) helical flute HSS drill, (b) four-flute K 10 cemented carbide drill, and (c) helical flute K 10 carbide drill. He reported that the helical flute K 10 drill produced less damage on the composite laminate than the four-flute carbide (K 10) drill did in his research. Tsao and Hocheng [27] recommended using drill bits with short chisel edge length since it would reduce the thrust force effectively. As shown in Figure 2.5, thrust forces were significantly smaller with pilot hole when comparing with thrust forces without pilot hole at any feed rate, and were lower than the critical thrust force at the feed rate of 0.15 mm/rev. Shyha et al. [28] reported that productivity in terms of the number of holes drilled per tool increased significantly (up to 50%) when uncoated tungsten carbide stepped drills were used at a higher feed rate (0.2 mm/rev rather than 0.1 mm/rev). Stepped drill geometry leads to lower chisel edge/workpiece material interaction, while the increase in the feed rate reduced the time of drilling operation, thus reducing the abrasive action and cutting temperature. On the other hand, both conventional (diameter of 1.5 mm) and stepped drills with TiN coated suffer low tool life which have resulted from a possible chemical reaction between the CFRP and coating, and also from the lower cutting edge radius of the uncoated drill.

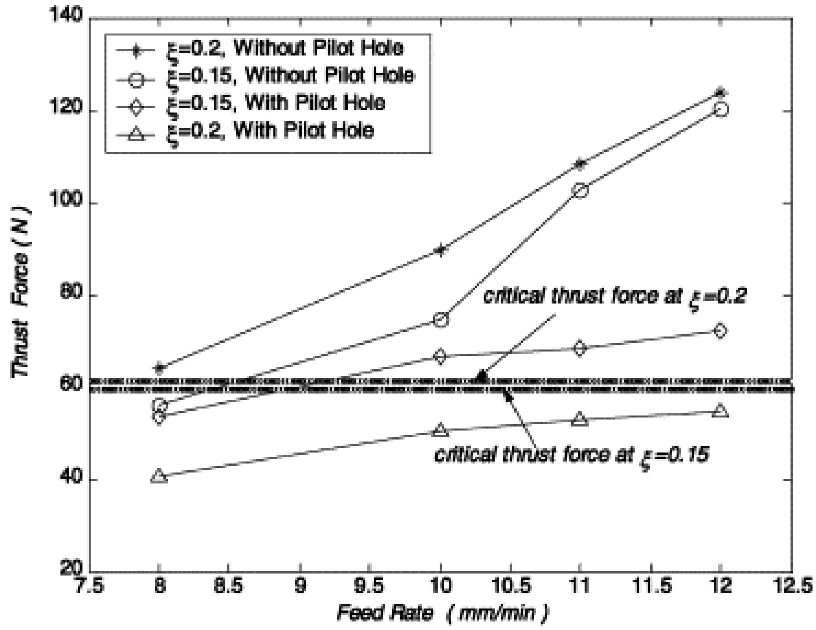


Figure 2.5: Effects of pilot hole on thrust forces (drill diameter, 10 mm; $\xi = 0.15$ and 0.2) [27].

The cutting edge also has a large influence on the drilling performance in drilling of fiber reinforced plastics. Franke [5] pointed out that the cutting edge radius influences the feed force as well as the drilled hole quality. The flank pressure of the tool increases with the increase of the cutting edge radius. In this case the tool has to generate a larger force to penetrate the workpiece, which leads to an increase in thrust force. Furthermore, the increase in the cutting edge radius causes the workpiece material to deform more and more severely, until it can no longer cut.

The elastically-deformed workpiece matrix material will return to its former shape when the tool is drawn back from the hole. Therefore, the hole will prove to be undersized. The borehole diameter is also influenced by the corner radius (also known as the tool nose radius) and the minor cutting edge. The increasing roundness of the corner and the minor cutting edge of drill bit together lead to a rise in borehole roundness as well as borehole cylindricity deviation. Fiber separation is impeded as the cutting edge radius is larger than the fiber diameter. In this case the fibers are deformed rather than sheared, at entry and exit. Improper cutting of fiber causes fiber pullout and delamination. As seen in Figure 2.6, exit delamination becomes more severe with the increase in cutting edge radius.

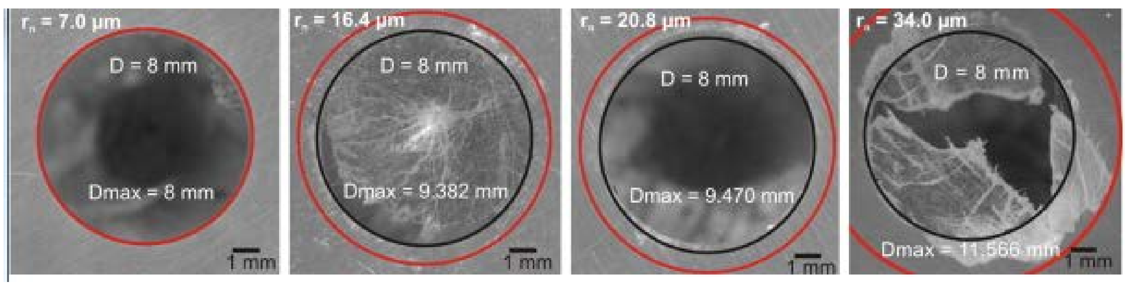


Figure 2.6: Delamination at the hole exit depending on cutting edge radius. [5].

Faraz, Biermann and Weinert [8] introduced an innovative tool-wear characteristic into the drilling of CFRP composite laminates using an uncoated carbide drill, and this resulted in the cutting edge rounding, evenly and smoothly distributed rounded abrasion wear pattern along the entire cutting edge of the uncoated carbide drill due to the abrasive nature of carbon fiber. Their study showed that satisfying correlations can clearly be seen between mechanical loads and cutting edge rounding, as well as between quantitative hole entry/exit delamination results and cutting edge rounding. As seen in Figure 2.7, it is clear that both entry and exit delamination increase with the increase in thrust force. Figure 2.8 shows that both thrust force and torque increase when the value of cutting edge rounding grows. In other words, the increase in cutting edge rounding will compromise the hole quality in terms of increasing both entry and exit delamination.

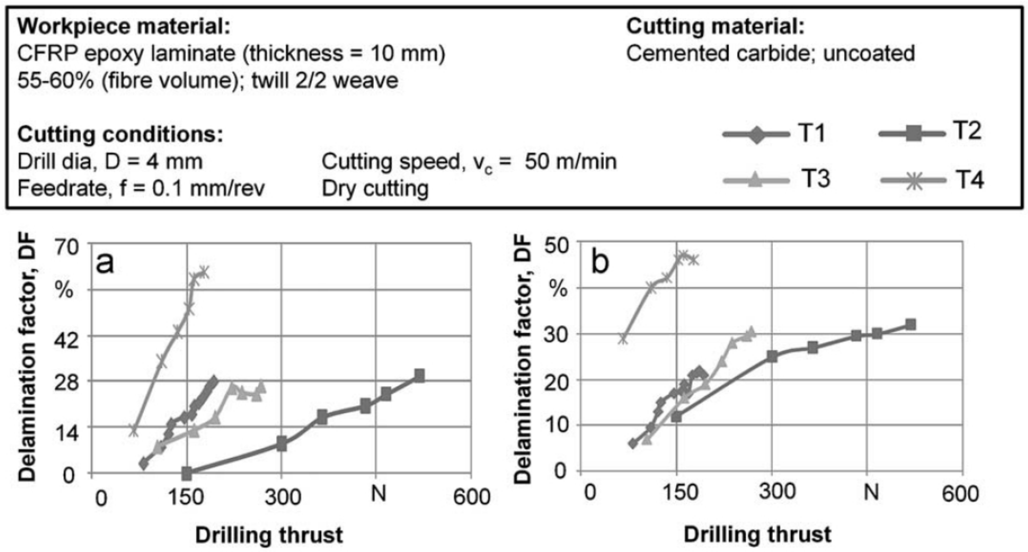


Figure 2.7: Development of (a) hole entry delamination and (b) hole exit delamination with increasing drilling thrust due to wear [8].

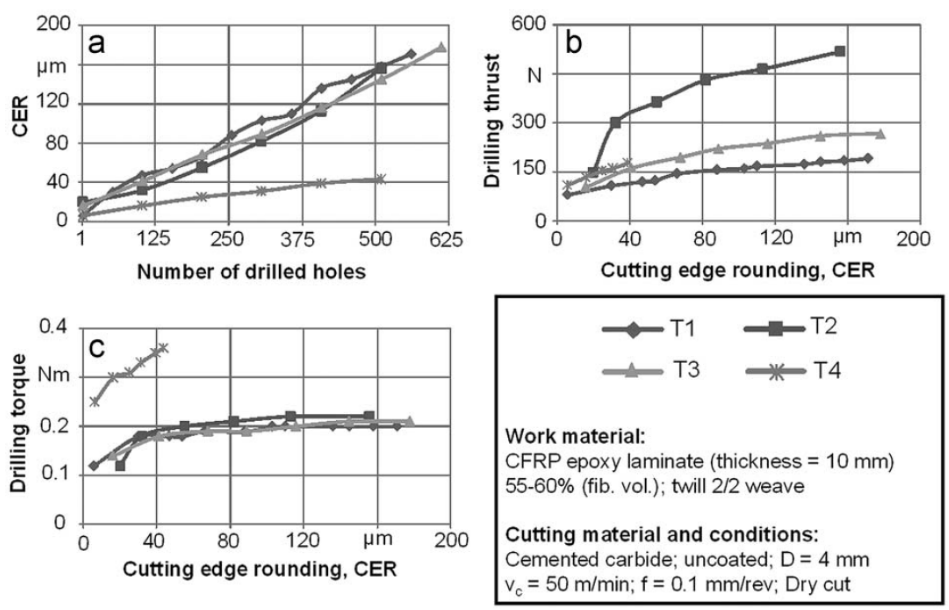


Figure 2.8: Cutting edge rounding (a) progression and its correlation with (b) thrust and (c) torque [8].

Another tool-wear criterion brought up by Teti [3] is outer corner flank wear, which has been claimed to be the main reason for burr generation in drilling fiber reinforced plastics materials. There are many researchers who have done research on this tool-wear criterion. Harris et al. [29, 30] defined outer corner wear, and also offered a method to measure the outer corner flank wear lands via optical microscope. They also mentioned that using this wear criterion, a drill can be determined as a worn tool when wear land reached more than 75% of the margin width. Abu-Mahfouz [31] also pointed out that wear on both outside corners of the drill point is due to high friction (rubbing) and the impact forces between the drill and the machined hole walls. He suggested that both feed and cutting speeds influence outer corner wear rate, and outer corner wear is the main factor for burr generation. As seen in Figure 2.9, burr height increases with the increase of cutting time, which could be easily explained since drill bits become more blunt during drilling. It is also noticeable that a higher feed rate, which leads to higher outer corner wear rate, leads to larger burr generation.

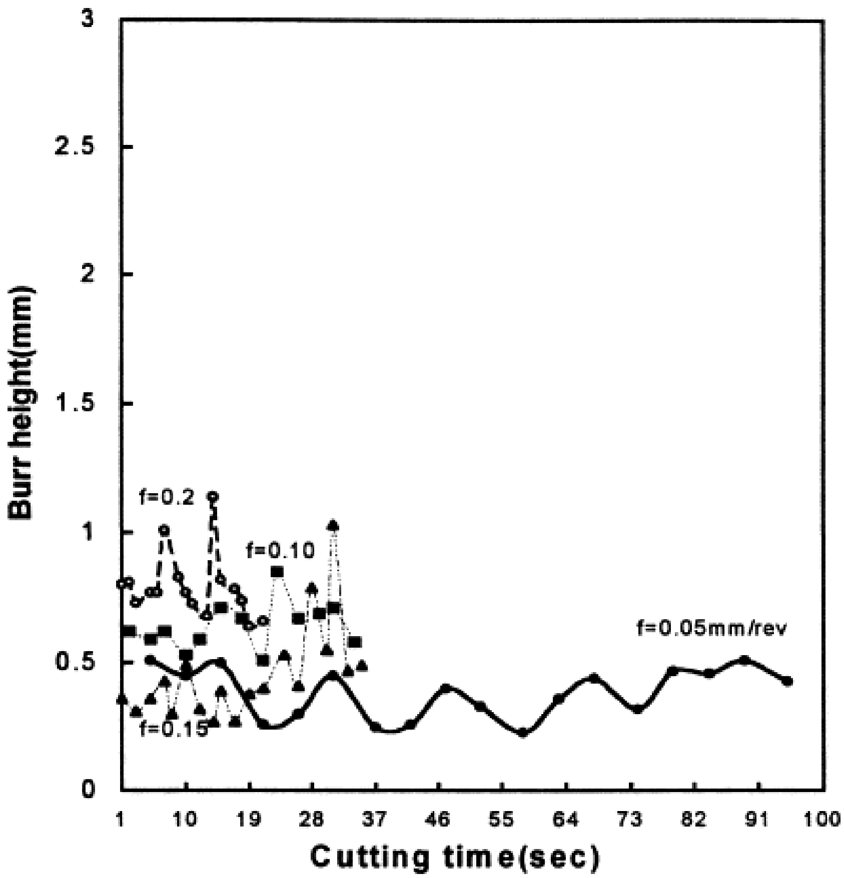


Figure 2.9: Burr height versus cutting time for different feed rates at V = 85 m/min [31].

2.4 Cutting Parameter Selection

Owing to the inhomogeneity and anisotropy of CFRP materials, the selection of cutting parameters plays a very important role. The effects of feed rates and cutting speeds on resulting torque and thrust force have been widely studied [32]. Feed rate among all the cutting parameters draws most interest from researchers [33]. Generally speaking, on one hand a greater feed rate brings in larger productivity. On the other hand, low value of feed rate ensures low thrust force, thus reducing drilling- induced delamination. Shyha et al. [34] worked on the effect of laminate configuration and the feed rate on the performance of drilling holes in carbon fibre reinforced plastic composites. The control variables considered are prepreg type (three types) and form (unidirectional (UD) and woven), together with the drill feed rate (0.2 and 0.4 mm/rev). In this case there are a total of 12 combinations to test using tungsten carbide (WC) stepped drills. The drill bit was used to drill 1.5 mm diameter holes in 3 mm thick CFRP laminate. The cutting speed does not count as a variable in this experiment, since the early work by the researcher had shown that the cutting speed was not a significant factor in relation to the tool-life (a cutting speed of 45 m/min was used in this experiment). As seen in Figure 2.10, tool-life varied, and depends on the feed rate and laminate configuration selection. The best tool-life can be achieved with a feed rate as low as 0.2mm/rev, and the results suggest that the maximum operating feed rate allowed for the stepped drill configuration is 0.2 mm/rev.

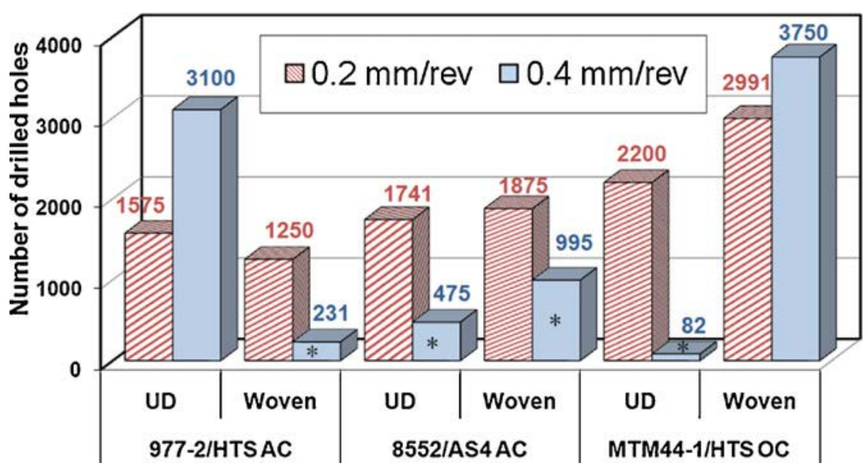


Figure 2.10: Tool-life in terms of number of drilled holes (*tests experienced tool fracture) [35].

Davim and Reis [24] noted that conventional machining methods should be adapted in such a way that they diminish thermal and mechanical damages. They focused on establishing a relationship between cutting parameters and delamination. And, they had the conclusion that the cutting speed is the parameter that has the largest physical as well statistical influence on the delamination factor when drilling CFRP laminate, which indicates that the thermal load likely has more significant influence on delamination than the mechanical load (feed rate) does in drilling CFRP.

Obviously, both cutting speeds and feed rates have impacts on the machinability of CFRP materials, although researchers' opinions differ as to which factor has a larger influence on drilling CFRP material.

2.5 Cooling Conditions

The most widely used cooling condition in drilling CFRP materials is dry drilling. Weinert and Kempmann [6] mentioned that the reason cooling lubricants were not widely used on CFRP is that it can lead to the melting of the matrix material as well as induce chemical reactions. In this case, most of the work of drilling CFRP is under dry drilling.

On the other hand dry machining induces thermal damage due to low thermal conductivity of CFRP materials and high cutting temperatures. Especially when drilling *Al/Ti/CFRP* stack, coolant is required due to the large amount of heat generation. High cutting temperatures and cutting forces can affect the CFRP structure and the shapes of cut surfaces negatively.

Some researchers have been using minimum quantity lubrication (MQL) cooling in drilling CFRP materials. Shyha et al. [35] found that boreholes produced under flood coolant were undersized and hole diameter became smaller as the drilling process proceeded. On the contrary, diameter result of test 10 (which has the same cutting parameter, cutting till except the cooling condition), as shown in Figure 2.10 boreholes produced under mist spray cooling features, was significantly oversized. As seen in Figure 2.11, roundness improved as the tests proceeded except when performed under mist spray cooling. It is probably due to thermal expansion of the drill bit from increased cutting temperature caused by the lack of coolant and lubricant in mist spry cooling. Surface roughness was also significantly lower when using flood cooling. For drilling material containing not only CFRP, but also metal material such as aluminum or titanium, coolant is required. Park et al. [36] also applied MQL externally in their experiments to test tool-wear feature in drilling multi-material stack. Later, they did some work regarding the tool-wear of diamond tool and WC drill [37]. Both experiments were conducted under the MQL cooling condition in order to avoid the excessive heat generated in drilling Ti/ Al stack rather than CFRP stack, and the result showed that tool-wear has been improved under MQL cooling.

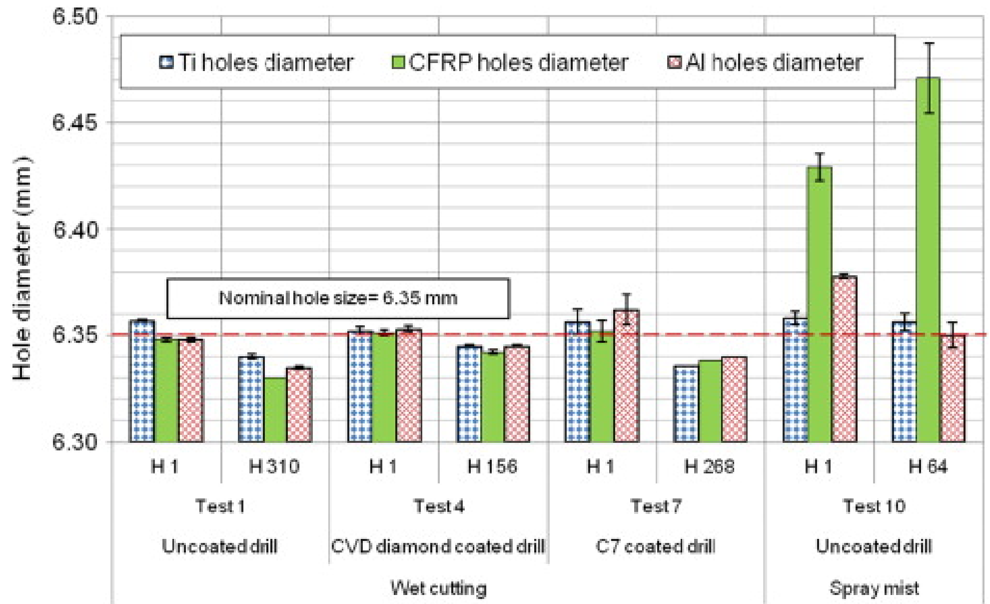


Figure 2.11: Hole diameter results for the first and last holes drilled in all material sections [35].

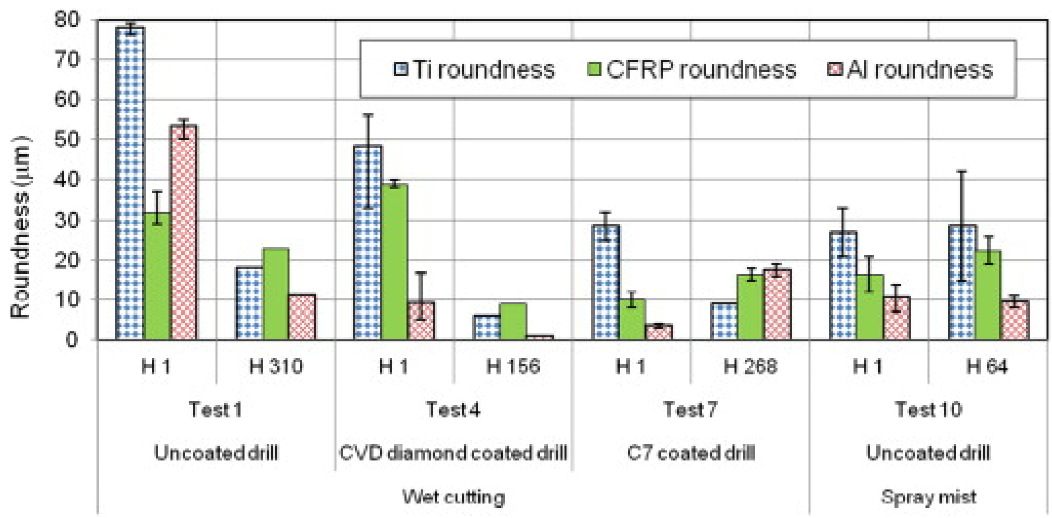


Figure 2.12: Roundness measurement results [35].

No research has so far reported drilling CFRP material under cryogenic conditions. In fact there were very few attempts that have been made for drilling other composite materials under cryogenic cooling. Bhattacharyya [38] is one of the researchers who has worked on drilling composites under cryogenic conditions. He externally applied liquid nitrogen when drilling Kevlar composites. He found that tool performance is further improved by cryogenic cooling. Fuzzy, uncut, and protruding fibers are also almost totally eliminated by the application of cryogenic cooling. The thrust force and the torque are higher under cryogenic conditions than under dry conditions. Ahmed [39] investigated the machinability of a Kevlar fiber reinforced composite material in drilling. Workpiece material was cooled down by the application of liquid nitrogen directly on it, and then allowed to warm up to the desired temperature. He observed that both the thrust force and the torque increased remarkably as the laminate temperature decreased. This can be explained as the stiffness and strength of the fiber and resin both rising under lower temperature. Hole quality in terms of delamination factor has also been found to improve significantly due to the difference of thermal expansion coefficient, which created a compressive stress on the fiber. Therefore, the fiber remained rigid during the cutting process, which led to less delamination. As seen in Figure 2.12, the highest delamination factor was recorded under room temperature, while the lowest delamination factor was recorded when the workpiece was cooled down to -120℃.

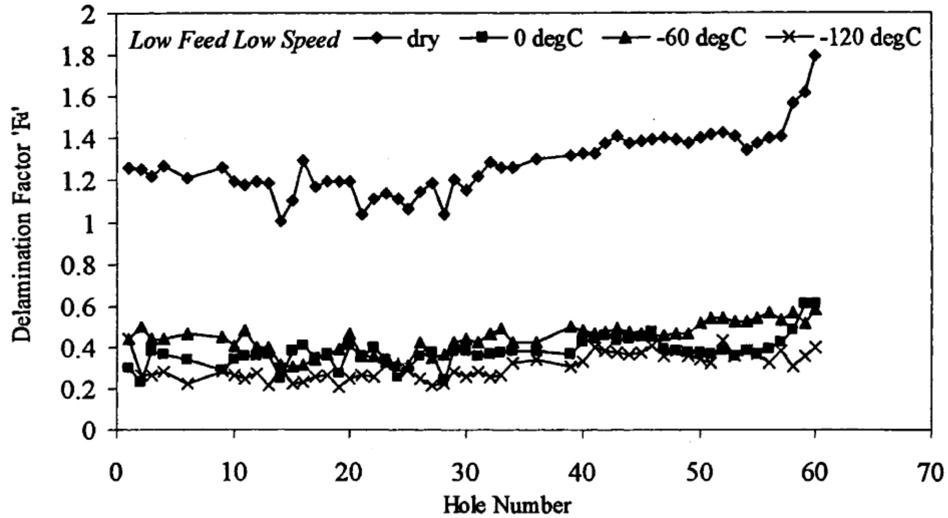


Figure 2.13: Delamination factor against hole number at low feed low speed machining conditions for four different workpiece temperatures [39].

There were also studies related to cooling the drill bit. Kim and Ramulu [40] investigated cryogenically-treated standard twist carbide in drilling graphite fiber reinforced plastics. They reported that hole quality in terms of surface roughness has improved, and delamination has been remarkably reduced with cryogenically treated drill because of their superior abrasion resistance. Carbide drill after cryogenic treatments appeared to be able to keep its sharpness. Therefore, it could cut the fiber effectively instead of tearing or pushing GFRP materials.

Significant recent findings in cryogenic machining and burnishing at the University of Kentucky show a promising opportunity for improved surface integrity in a range of materials leading to improved functional performance [41-43].

2.6 Cutting Temperature Measurements

Cutting temperature influences the result of drilling CFRP material in terms of borehole quality and tool-wear. It is really difficult to measure the cutting temperature during the drilling process. Many approaches have been used in order to get a reliable and accurate value of cutting temperature such as thermocouple and infrared camera [44]. Cutting temperature is hard to capture using infrared, because the tip of drill bit is in the material for the major part of the drilling process. Researchers came up with an idea of putting a mirror under the workpiece. Once the drill bit goes through the workpiece, the temperature would be captured by the reflection, and this temperature should be the highest cutting temperature [45]. Weinert and Kempmann [6] were trying to find how the cutting temperature affects the drilling process on CFRP. They placed a thermocouple on the clearance face of the 8 mm carbide drill bit. During the cutting process they kept the drill bit steady instead of leaving the workpiece rotating, out of technical reasons (thermocouples do not permit rotation). Various combinations of cutting speeds and feeds were used in order to investigate the thermal effect. The temperature range was from 180℃ to 387℃, and it should be higher, as it was not directly measured at the cutting edge.

2.7 Hole Quality and Surface Integrity

Although drilling process is not necessarily the final step of the process for composite parts (sometimes it demands reaming to achieve a better hole quality), a borehole with a fine internal surface and very good surface roughness, with no mechanical and thermal damage, is always the goal of manufacturers. Especially taking productivity into consideration, high rejection and post-drilling process such as boring and reaming would lower the efficiency, not to mention increase the cost significantly.

There are several hole quality and surface integrity issues related to the drilling of CFRP. Weinert [6] found that fiber bending and matrix material melting happened during drilling. The cutting temperature that will influence the machining quality can be related to the heating of the tool, initiated by the rise in the number of bore holes. Because of the extremely low thermal conductivity of carbon fiber reinforced plastic, the thermal load causes the drilling tool to have a severe radial expansion, and therefore the borehole has a continuous diameter increase. Figure 2.7 shows that diameter variation is influenced by heat generation. CFRP only absorbs very little of the generated heat due to its low thermal conductivity. Without coolant applied in the drilling process, a rapid expansion of drill bit will occur as a result of the heat. This tool expansion leads to a borehole expansion. Borehole size increases during the drilling process, and decreases after a cooling phase. It is also observed that the borehole size becomes smaller between each cooling phase, because the drill bit wears severely as it drills more CFRP laminates.

Brinksmeier [4] reported that he found cracks of matrix material and fiber pulled out in the internal surface. He pointed out that thermal load and mechanical load can affect the CFRP structure and the shape of cut surfaces negatively. In order to distinguish between thermal and mechanical effects on the damage of the microstructure, he did two groups of extreme-condition experiments, using the largest cutting speed/ lowest feed and largest feed/lowest cutting speed to achieve the highest cutting temperature and largest thrust force. Figure 2.8 shows subsurface micrographs of borehole cut under those two different drilling conditions. No damage can be detected in the sample with the largest force and the lowest temperature, but near the surface the fibers are bent in the cutting direction. For sample under the largest measured temperature, cracks have been found.

A comprehensive review of surface integrity in material removal processes including drilling of CFRP material was produced by Jawahir et al. [46].

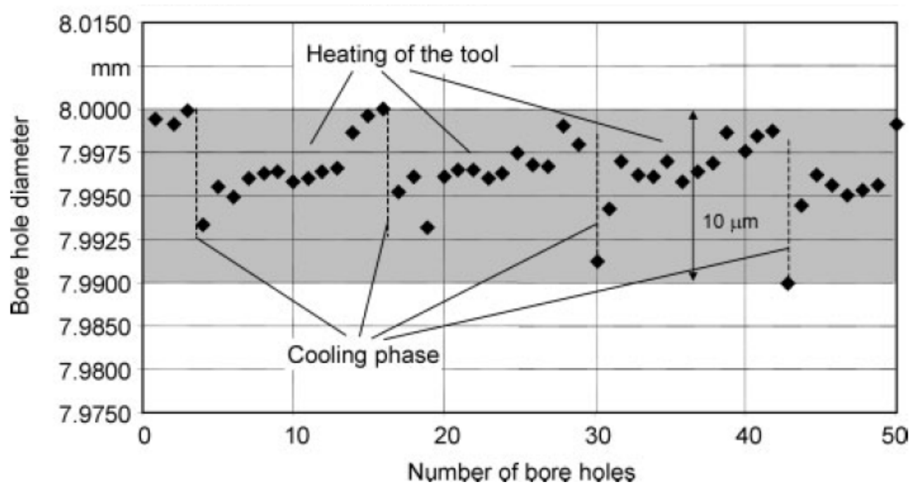


Figure 2.14: Diameter variation as a result of tool heating [6].

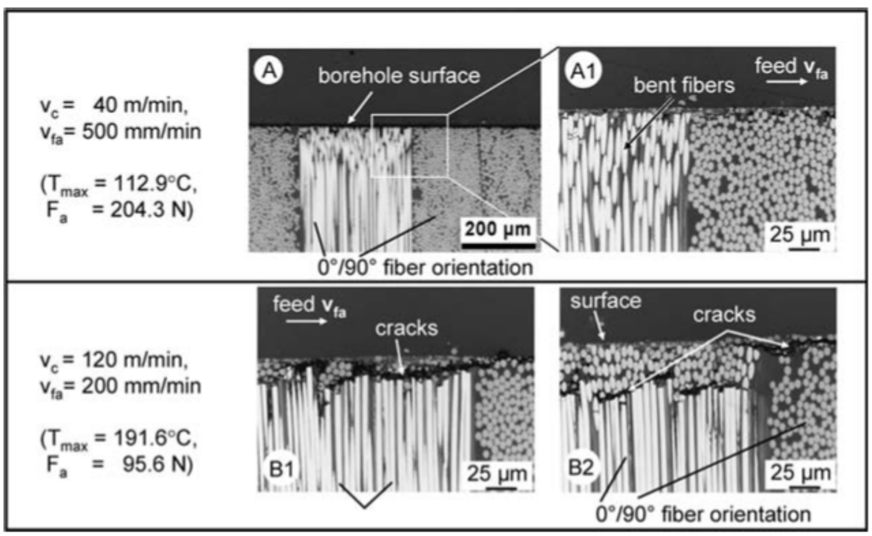


Figure 2.15: Micrographs of CFRP borehole surface layers for two process conditions generated by conventional drilling [4].

2.8 Analytical Models

Delaminaton during drilling in composite laminates can be an outcome of two types of damage mechanisms that are different in their causes and effects: peel-up delamination and push-down delamination [8]. The latter delamination type is more important since exit side delamination often is more severe than entry side delamination. Due to the complication of damage mechanisms, exit delamination can be influence by many factors (cutting tool geometry, cutting parameter, cutting temperature, etc.).

Analysis of delamination mechanisms during drilling using a linear elastic fracture mechanics (LEFM) approach has been developed and different models are presented. Among these, the one most referred to is the Hocheng-Dharan delamination model [9]. They introduced the idea of critical thrust force, which can be estimated using the equation they provided. Critical thrust force is the minimum force above which delamination is initiated .The applied thrust force should not exceed this value, which is a function of the material properties and the uncut thickness to avoid delamination [47]. As shown in Figure 2.9, the cylinder in the middle represents the drill with diameter *D*, F_A is the applied thrust force, X is the displacement, H is the thickness of the structure, h is the uncut depth under tool, and a is the assumed size of an existing crack. As the drill cuts downwards, the uncut laminates under the tool are pushed and deformed elastically by the thrust force. If the resulting strain at the tip of the existing crack goes beyond the critical value, crack propagation occurs. In 1997, Tsao and Chen [47] gave the details of derivation of the equation of critical thrust force. Equation of energy balance, from linear elastic fracture mechanics, can be written as:

$$GdA = F_A X - dU \tag{2.1}$$

G is the crack propagation energy and U is the stored strain energy. To find the correlations between F_A, X, and U, classic plate bending theory for a circular plate with clamped ends and concentrated load is used in this model [48].

The critical thrust force at the onset of crack propagation can be calculated as:

$$F_{A_{cr}} = \pi[\frac{8GEh^3}{3(1-v^2)}]^{1/2} \quad (2.2)$$

where, v is Poisson's ratio, E is Young's modulus, and G_{IC} is the critical crack propagation energy in mode *I*. The value of G_{IC} is assumed as constant because G_{IC} was proven by Saghizadeh and Dharan [49] to be only a mild function of strain-rate. In Equation (2.2), *G* is replaced by G_{IC} since value is easily measured.

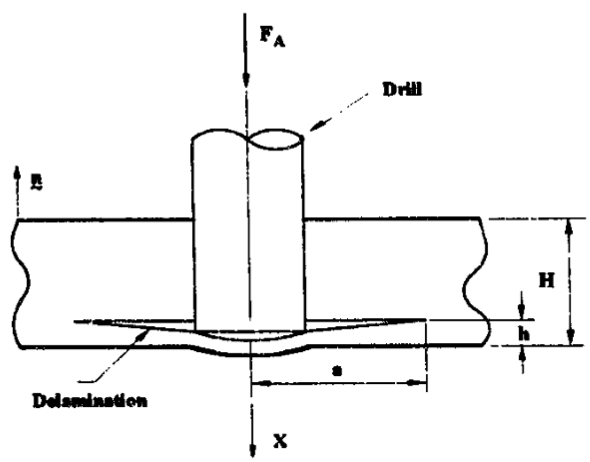


Figure 2.16: Circular plate model for delamination analysis [47].

Later work of Won [50] presented a derivation of drilling force relationships. Following the work of Shaw and Oxford [51], the thrust force and cutting force during drilling may be described by the empirical relations.

Assuming that *u*, which is the specific cutting energy for a drilling operation, remains constant, and is proportional to $(fd)^{-a}$

$$u = \frac{8T}{fd^2} \propto (fd)^{-a} \quad (2.3)$$

The thrust force and torque are equal to:

$$\frac{T}{d^2\, H_B} = K_1 \frac{f^{1-a}}{d^{1+a}} [\frac{1-\frac{c}{d}}{\left(1+\frac{c}{d}\right)^a} + K_2 \left(\frac{c}{d}\right)^{1-a}] + K_3 \left(\frac{c}{d^2}\right) \quad (2.4)$$

$$\frac{T}{d^3\, H_B} = K_4 \frac{f^{1-a}}{d^{1+a}} [\frac{1-\frac{c}{d}}{(1+\frac{c}{d})^a} + K_5 (\frac{c}{d})^{2-a}] \quad (2.5)$$

where, F is the thrust force, T is the torque, a and Ki are constants to be determined, d is the drill diameter, f is the feed, c is the length of chisel edge, H_B is the hardness of the material, and u is a specific cutting energy

Since c/d is constant for one specific drill bit, the equations can be simplified as:

$$F = K_6\, f d^{1-a} + K_7 d^2 \quad (2.6)$$

$$T = K_8\, f^{1-a} d^{1-a} \quad (2.7)$$

where the value of a and Ki could be determined by experimental data. By using $\log(u)$ as a function of $\log(fd)$, a could be determined since slope of the funciton equals to – a. Figure 2.10 demonstrates such a relationship.

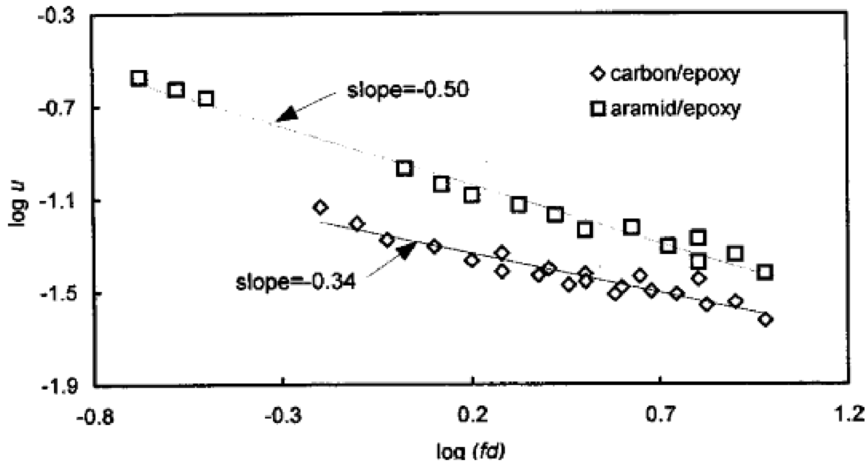


Figure 2.17: Plot of the function [49].

To control a drilling machine with force feedback, one should try establishing relationships between the drilling forces and cutting parameters such as feed, drill diameter, and material properties. These relationships with the predicted critical thrust force for a specific material type can be incorporated into the CNC program for damage-free drilling in a time-optimal manner. In this case, an attempt was made to derive such equations based on the experimental results

Finding the critical value by using Equation (2.2), the researcher then found the feed by using Equation (2.7) under this value. It is notable that equations for critical value of thrust force can be various due to the different geometry of drill bit. The point here is to determine the critical value and then find the proper feed rate. Fernandes and Cook reported such an approach [47]. The novelty of their work is that they also consider the tool-wear as a factor in their analytical model. The results of their model are closer to the experimental data compared with the previous model made by other researchers. The modified equation is shown below:

$$F_{(f,d,wear)} = \text{Tool-wear coefficient} * \quad (K_1 f d^{1-a} + K_2 d^2) \tag{2.8}$$

Gururaja and Ramulu [48] reviewed several previous analytical models, and proposed a modified exit-ply delamination model. A comparison of the existing models with experimental data indicates that the proposed modified exit-ply delamination model yields better correlation. The modified equation is shown as follows, and would be explained further in latter chapters:

$$(P_c)_{modified} = \sqrt{\frac{\pi G_{Ic}}{\xi((C_3/3)-K)}} \tag{2.9}$$

2.9 Critical Analysis

As discussed in the previous sections, significant work has been done in drilling of CFRP materials. Table 2.1 summarizes the major findings of drilling CFRP, and in order to better serve this research， it also includes research areas that have not been done in the previous studies. Generally speaking, although many aspects of drilling CFRP material have been studied, none of them has considered the effect of cryogenic cooling on the drilling process. Therefore, it is necessary to study and find how would the cooling effect of liquid nitrogen impact the cutting performance in drilling of CFRP material in terms of parameters such as thrust force and torque, delamination, hole quality, surface integrity, etc.

2.10 Summary

As shown above, most problems related to drilling CFRP are caused by the high thrust force during the drilling and induce damages such as delamination. Also, due to the low thermal conductivity of CFRP material, cutting temperature in the drilling of CFRP laminates is usually extremely high compared with cutting temperature in metal cutting. This would lead to a degradation of matrix material, increase in tool-wear rate, and thus cause elevation of surface roughness, subsurface damage, diameter error increase, etc.

Table 2.1: General evaluation of drilling of CFRP materials

Reference	Major findings and brief explanation	Work not done
Franke, 2011; Faraz et al., 2009	Thrust force and torque increase with the increase of cutting edge radius. Delamination increases with the increase of cutting edge radius.	Influence of cutting parameter and cooling conditions on cutting edge radius has not been studied.
Weinert and Kempmann, 2004; Brinksmeier et al., 2011	Large cutting temperatures and forces can affect the CFRP structure and shape of cut surfaces negatively. Subsurface damage was observed.	All test were dry drilling, no coolant was used during the drilling process.
Shyha et al., 2011	Effect of cutting parameter on diameter error, roundness.	All tests were dry cutting.
Shyha et al., 2011; Park et al., 2011	Effect of cooling conditions on tool-wear performance and thrust force and torque results.	Lack of experiments under cryogenic cooling.
Hocheng and, Tsao, 2003; 2006	Linear elastic fracture mechanics (LEFM) approach has been developed to predict critical thrust force.	All tests were dry cutting, no cutting fluid or other coolant was applied during the cutting process.

The key to success of drilling CFRP materials is to keep the sharpness of the drill bit, maintain a low level of thrust force, and achieve a low cutting temperature. Applying coolant would to some degree reduce the cutting temperature, and thus reduce the defects related to thermal damage, as well as lower the tool-wear rate. But, since materials tend to have higher modulus under coolant, thrust and torque might elevate.

Meanwhile, to the best of our knowledge, no single study regarding drilling CFRP material under cryogenic cooling has been conducted yet. The purpose of this project is to investigate influence of cryogenic cooling in drilling of CFRP laminates. The assumption is that not only can borehole quality and borehole surface integrity be enhanced by applying cryogenic cooling during the drilling process, but tool-wear resistance of the drill bit also could benefit from lower cutting temperatures. Different aspects of the drilling performance, such as the force result, the borehole quality, borehole surface integrity and the tool-wear, have been studied under different cutting parameters and cooling conditions.

CHAPTER 3: EXPERIMENTAL SETUP AND PROCEDURE

In this chapter, the details of experimental setup and procedure to carry out the investigations are discussed, including the setup of drilling used to conduct the experiments, and the configuration of PC-based data acquisition system to measure the cutting force and torque. The cooling techniques and equipment applied to carry out the experiments are introduced, and the instruments and methods used to measure roundness, diameter deviation, and surface roughness are also discussed in this chapter. Finally, the method of evaluating delamination, and the method of observing subsurface damage, as well as the method of studying burr generation of drilled hole using optical technique, are also presented. A schematic diagram shown in Figure 3.1 summarizes the measurements taken as well as instruments used in this study.

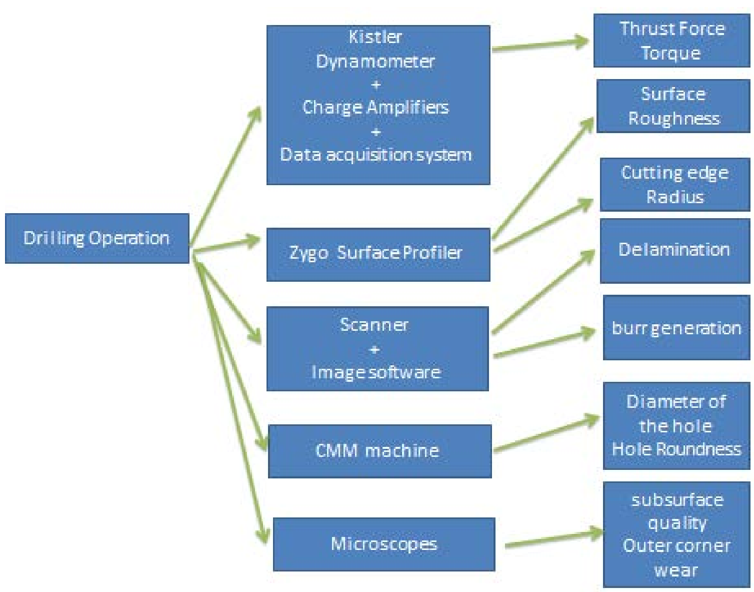


Figure 3.1: Schematic diagram of measurements and instruments selection.

3.1 Experimental Setup and Cutting Conditions

HAAS VF-0 CNC Vertical Milling Center with 20 HP vector spindle drive and maximum spindle speed 7500 RPM was used for all drilling experiments conducted in this research. Photographs of experimental setup, including the machine tool as well as drilling setup, are shown in Figure 3.2. The design matrix of drilling tests performed under dry drilling and cryogenic drilling is shown in Table 3.1. Cutting parameters were selected based on the previous work by other researchers [26].

Table 3.1: Experiment matrix for drilling under different cooling methods

No.	Cooling Method	Cutting Speed, *V* [m/min]	Feed Rate, *f* [mm/rev]	No. of Holes drilled
1	Dry	40	0.05	50
2	Cryogenic	40	0.05	50
3	Dry	40	0.025	50
4	Cryogenic	40	0.025	50
5	Dry	60	0.05	50
6	Cryogenic	60	0.05	50
7	Dry	60	0.025	50
8	Cryogenic	60	0.025	50

Figure 3.2: (a) Experimental setup of the drilling device; (b) HAAS VF-0 CNC vertical milling center.

3.2 Cutting Tool and Workpiece Materials

Sandvik CoroDrill 860 drill bit was used in this study. A fresh drill was used for each test run. This uncoated carbide drill is a conventional twist drill with two flutes and a diameter of 9.92 mm. The point angle of this drill is 130^{o}. It also features a two coolant supply hole to allow coolant to come through. Figure 3.3 shows the pictorial view of the drill bit used in the experiment.

Figure 3.3: Sandvik CoroDrill 860 drill bit.

The carbon fiber reinforced plastics material used in this research was a balanced quasi-isotropic layup utilizing in a 2x2 twill pattern woven CFRP laminates material. The lay-up of the woven laminates were oriented as standard $0^{o}/+45^{o}/90^{o}/-45^{o}$ directions. The fibre volume fraction of the CFRP material is about 0.6. For technical reasons, in order to supply the cryogenic cooling internally through the coolant hole, it was necessary to perform the drilling test with an upside down setup with rotating composite specimen and a fixed drill bit. The so-called inverted drilling setup is shown in Figure 3.2. The dimensions of carbon fiber reinforcement plastics block specimen were approximately 20 mm x 20 mm x 18 mm (shown in Figure 3.4), and it was placed in a specially designed workpiece holder during the drilling process. The workpiece rotated while drill bit in the bottom of the milling center was kept steady during the drilling process. The dynamometer was placed on the bed of the machine in order to record thrust force and torque. On top of the dynamometer was a specially designed tool holder.

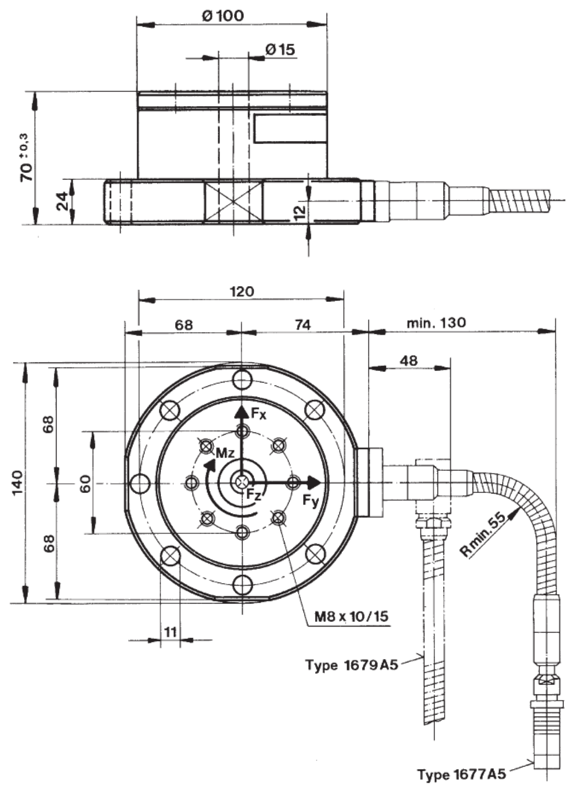
Figure 3.4: Workpiece material.

3.3 Dynamometer and Data Acquisition System

Kistler Type 9272 4-component dynamometer, 1679a5 high insulation connecting cable and two Type 5011A charge amplifiers were used in the experiment. The thrust force and torque generated are recorded during drilling of CFRP materials under various combinations of cutting parameters and cooling conditions by the dynamometer which was connected to a NI USB-6366 X series data acquisition system paired with Lab View Signal Express 2011 software. The thrust force and torque data obtained were transferred into an Excel spread sheet.

Pictorial view and dimensions of dynamometer are shown in Figure 3.5. The calibration of dynamometer was done before performing the drilling test. A specially designed tool holder was built on top of the dynamometer for the experimental setup to keep the drill steady during the drilling process. The thrust force was calibrated by applying different load by putting certain weight block on the dynamometer. For the calibration of torque, a torque wrench was used to apply different torques. The dynamometer was calibrated under ambient conditions. Humidity and temperature recorded at the time of calibration were 45% and 24.3℃ respectively.

NI USB-6366 X series is a PC-based data acquisition system. The software used in this research is Lab View Signal Express 2011, which is very user-friendly, and allows users to easily process the acquired data after recording. Pictorial view of data acquisition system with Kistler 5011A charge amplifiers is shown in Figure 3.6. NI USB-6366 was put in the sliver box and was connected to a laptop. Blue boxes in the bottom right corner are charge amplifiers and each of them was recording one channel of signal. Two of them were used in the experiment since in this research only the thrust force and the torque were recorded.



(a)

(a)

(b)

(c)

Figure 3.5: (a) Dimensions of dynamometer Type 9772; (b) pictorial view of dynamometer; (c) specially designed tool holder.

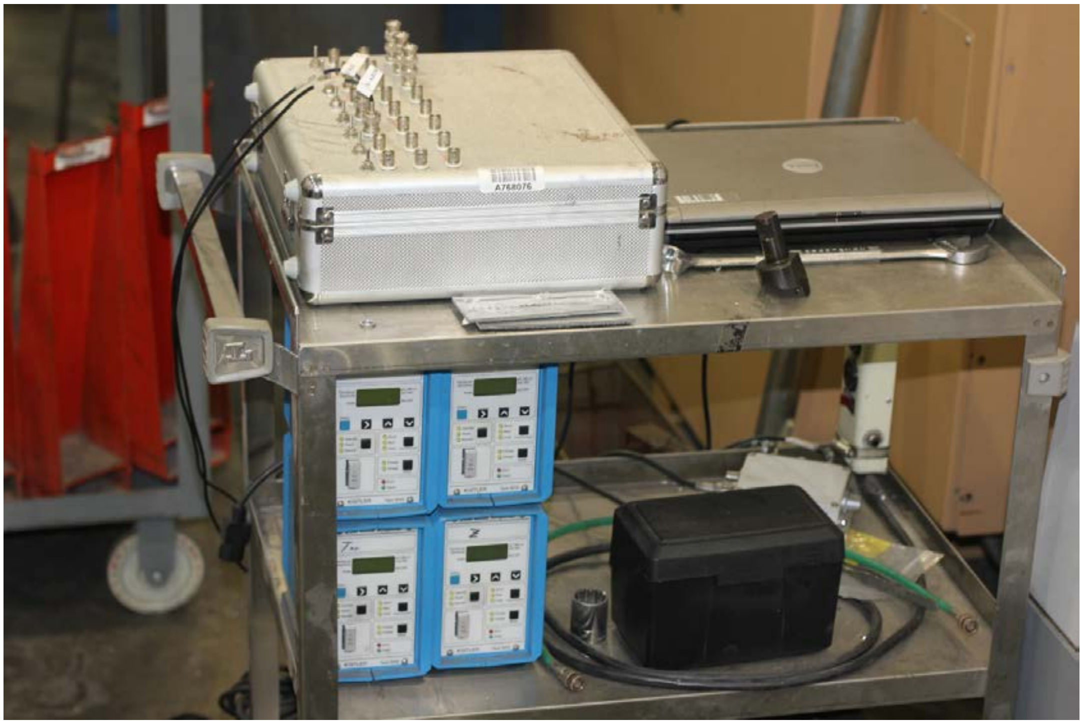


Figure 3.6: Data acquisition system and charge amplifiers.

3.4 Cooling Technique for Cryogenic Drilling of the CFRP Laminates

Liquid nitrogen was used as coolant in this research in order to reach the cryogenic temperature during the drilling. Internal pressure building tank of 250 liters capacity filled with liquefied nitrogen gas was chosen to supply the cooling liquid nitrogen and to keep the cryogenic supply constant for every drilling test. Valves were built on the liquid nitrogen tank, and also on the hose connecting the cylinder and the tool holder mentioned early. Both valves were opened up to the maximum turn to allow the liquid nitrogen go through the tool holder and the coolant supply holes and thus apply cryogenic cooling internally during drilling. Liquid nitrogen tank with hose is shown in Figure 3.7.

Figure 3.7: Liquid nitrogen tank and hose.

3.5 Borehole Surface Integrity Inspection and Borehole Quality Assessment

The drilling process is usually the final process of a production cycle. To avoid rejection because of the poor tolerance, the surface finish of borehole has to be considered as the priority of drilling CFRP material.

In order to evaluate the hole quality and surface integrity with various cutting parameters and under different cooling conditions, several instruments were used and many hole quality and surface integrity criteria were studied in this study. These criteria include: delamination, burr generation, surface roughness, diameter deviation of the borehole, and roundness.

Since no significant delamination and burr generation were found on the entry side of the borehole in any cutting parameters or cooling conditions, this study only focuses on exit delamination and exit burr generation. Following Khashaba's [12] methods, machined samples were first scanned by Epson 3230 scanner, which has a maximum 1600 DPI. The drilled specimens are to be placed directly on the glass plate of the scanner in such a manner that damaged areas and borehole could be recorded. This technique is calibrated by measuring several dimensions on a standard steel ruler. Then the pictures obtained were evaluated by image software CorelDraw (free trial full function version). The software has multiple functions, which could measure the diameter of the damaged area and the diameter of the borehole. By calculating the delamination factors, the hole quality from delamination point of view can be evaluated. Similar to delamination evaluation, several comparisons were made between boreholes obtained with different cutting parameters and under different cooling conditions by visually inspecting images recorded by the scanner.

Diameter error and roundness were measured by TESA Micro-Hite 3D measuring system. This coordinate measuring machine uses a probe (5 mm diameter) to measure the points on a part (in this study, the points are on the internal surface of the borehole). Each point on the internal surface is unique to the machine's coordinate system. The picture of measuring diameter error and roundness is shown in Figure 3.8. Machined sample was put on top of a pair of parallel set in order to keep the height constant, and it was also clamped in a vise to be kept steady during the measuring process. Points were taken at different depths for one sample and were taken multiple times in different areas in the same depth. Then, the CMM combines the measured points to evaluate the diameter error and the roundness.

Surface roughness measurement was done by using Zygo NewView™ 7300 white light interferometer (shown in Figure 3.9) combined with Windows-based software Metro Pro to achieve the characterizing and qualifying of surface roughness, critical dimensions, and other topographical features including the cutting edge radius of drill bit. Subsurface quality was investigated by analyzing micrographs in cross-sectional areas using Nikon EPIPHOT 300 inverted Metallurgical Microscope shown with objective lenses ranging from 2.5X to 50X.

Cutting edge radius progression and outer corner wear were also measured using Zygo profilometer and Microscopes, respectively, and these results will be discussed in the next chapter.

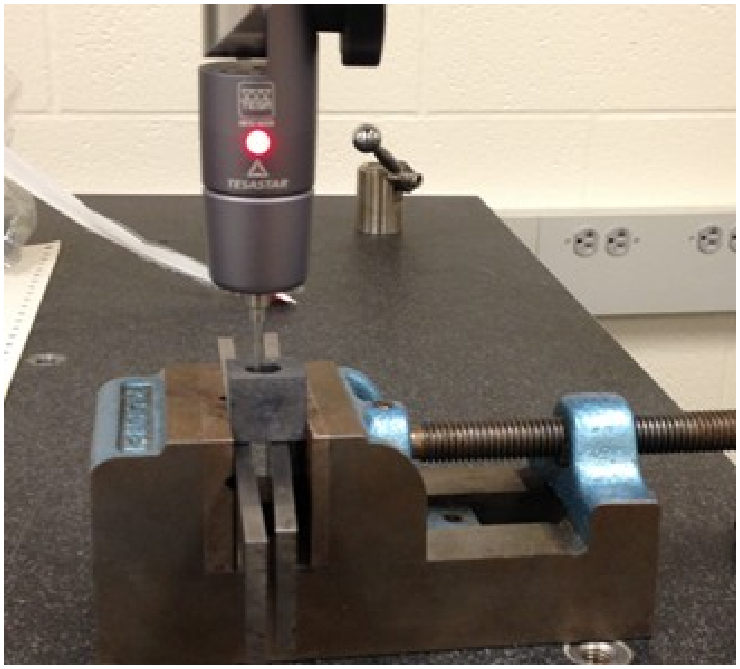


Figure 3.8: TESA Micro-Hite 3D CMM.

Figure 3.9: Zygo NewView™ 7300 White Light Interferometer.

CHAPTER 4: RESULTS AND DISCUSSION ON TOOL-WEAR, THRUST FORCE AND TORQUE

The purpose of the present research work is to study the drilling performance in cryogenic drilling of CFRP materials, using uncoated carbide drill bits. The machinability evaluation variables are thrust force, torque, delamination factor, subsurface damage, surface roughness, diameter error, roundness, cutting edge radius, and outer corner wear.

This chapter presents the results of an experimental investigation of the effects of machining conditions on the force data from drilling of CFRP materials. The force results investigated in this chapter include thrust force and torque. In addition, the effects of cryogenic cooling on outer corner wear were also studied. The influence of cryogenic cooling on cutting edge radius of the tools is one of the most important topics investigated in this chapter, since the cutting edge radius has been shown to significantly influence force results, and also to have a strong influence on surface integrity of the machined CFRP material. A correlation between the thrust force and the cutting edge radius has also been established. Finally, experimental results discussed in the early part of this chapter serve as a basis for the development of an analytical model for drilling CFRP composites, which is presented at the end of this chapter.

The results show that cryogenic drilling leads to significant improvement of wear performance in drilling CFRP materials in terms of: (a) lower cutting edge wear rate, and

(b) reduced outer corner wear. These changes should notably enhance the quality and surface integrity of machined CFRP borehole. Delamination, surface roughness and all other surface integrity and hole quality parameters of these machined samples will be presented and discussed in Chapter 4. It is also notable that thrust force and torque are much larger in cryogenic drilling than under dry condition.

4.1 Effects of Cryogenic Cooling on Tool-wear

The influence of cutting edge radius on borehole quality in drilling CFRP materials, especially delamination and burr generation, has been reported in the literature by many researchers. A smaller cutting edge was found to: (a) induce lower thrust force, and (b) contribute to cutting the carbon fiber effectively instead of pushing or tearing. Meanwhile, the effect of outer corner wear on burr generation is also frequently reported in the literature. The application of liquid nitrogen during machining metallic materials was found to improve the tool-wear performance. Therefore, the focus of this section is to investigate the influences of cryogenic cooling on tool-wear performance in drilling CFRP materials.

4.1.1 Cutting edge radius

The cutting edge radius for fresh drill bit is about 18 μm. The actual values were measured by Zygo New View 5300 measurement system before machining to make sure the edge used was within the range. Figure 4.1 schematically describes the cutting edge rounding. Cutting edge radius value in this study is an average of 10 values recorded along the main cutting edge of the drill bit to ensure the accuracy. Measuring points were selected discretely as shown in Figure 4.2. Typical oblique plots measured by Zygo for some cutting edge radius results are also shown in Figure 4.3. The 3D plots of the cutting edge of drill bits after 50 drillings at f = 0.025 mm/rev and V = 40 m/min under dry and cryogenic cooling methods provide a direct comparison of the differences in edge radius.

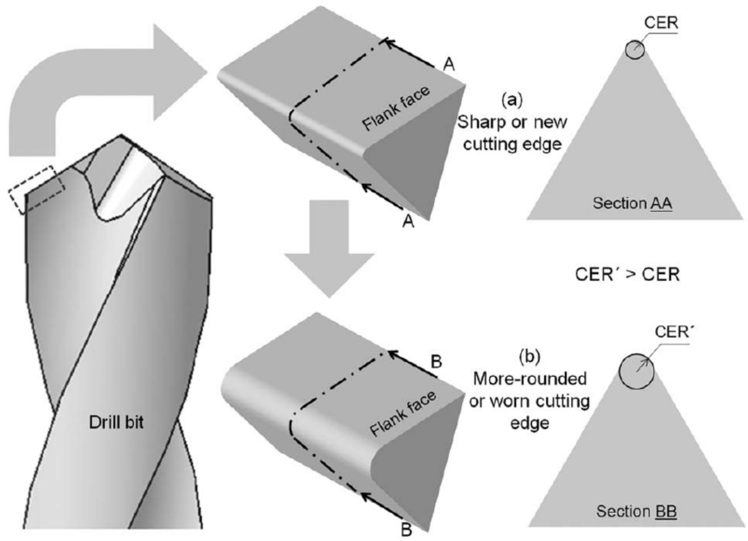


Figure 4.1: Cutting edge rounding: (a) Sharp cutting edge (b) Blunt smoothly worn, rounded cutting edge [8].

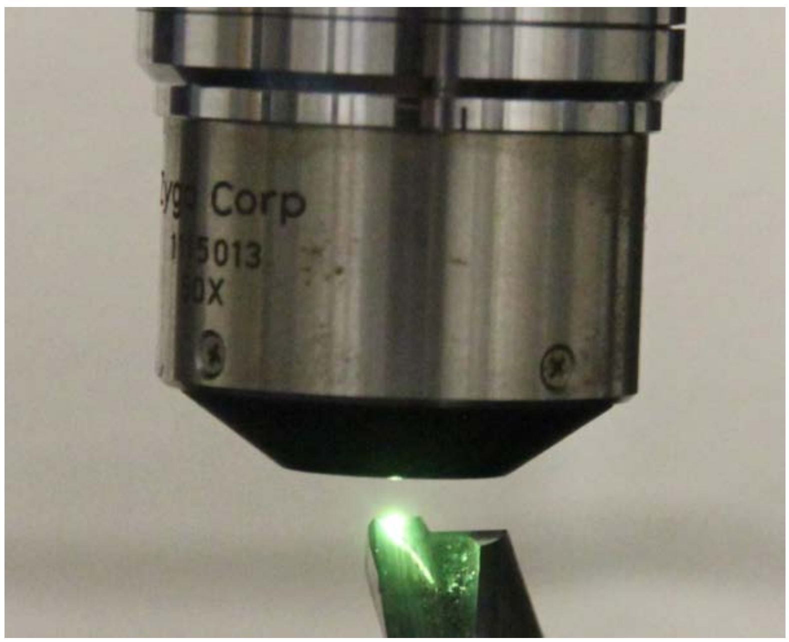
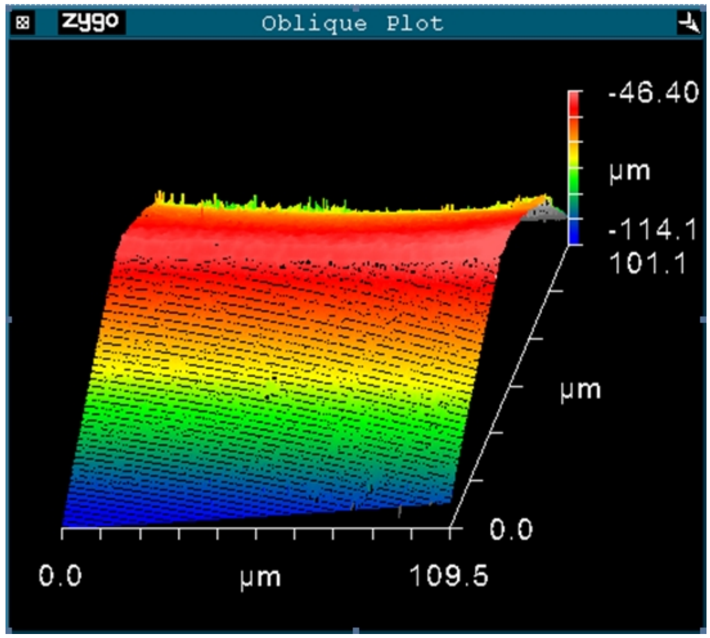
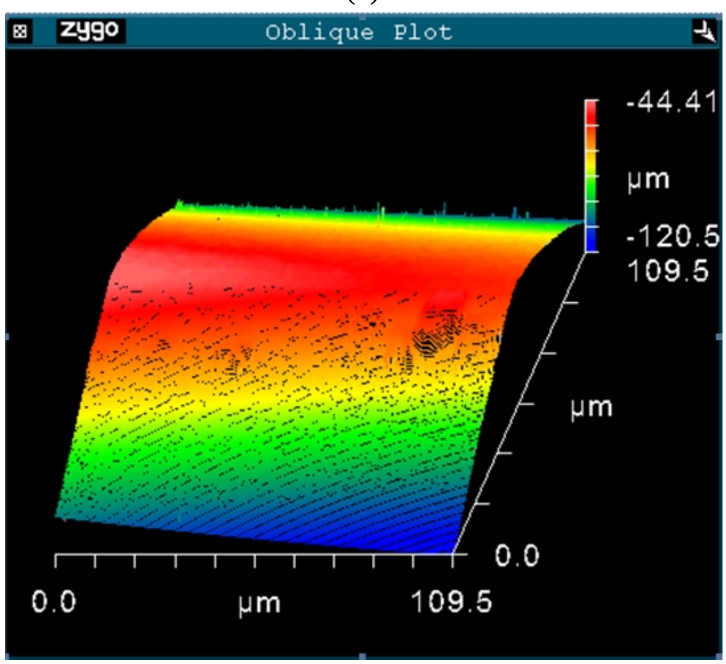


Figure 4.2: Measuring cutting edge radius using Zygo New View 5300 White Light Interferometer.



(a)



(b)

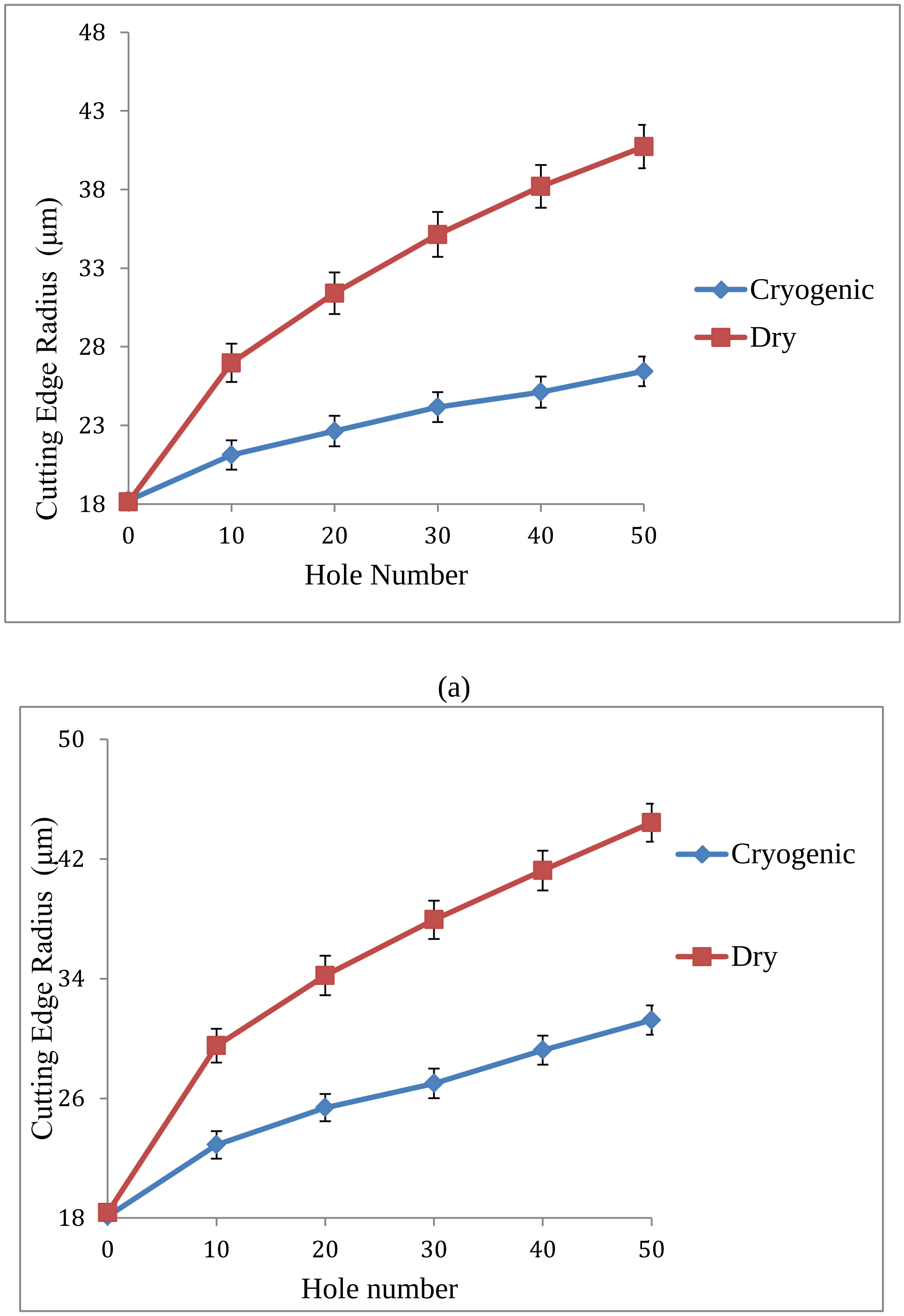
Figure 4.3: Typical oblique plots of edge radius measurement of drill bits at f = 0.025 mm/rev and V = 40 m/min after 50 drillings: (a) under cryogenic cooling method, cutting edge radius = 26.1 µm; (b) under dry cooling method, cutting edge radius = 39.4 µm.

During the drilling experiments, cutting edge radius was measured after every 10 drill holes on each drill bit, and the results of cutting edge radius progression for all tools and cutting parameters are plotted in Figure 4.4 and Figure 4.5. The application of liquid nitrogen cooling led to about 40% decrease in cutting edge wear for both 0.025 and 0.05 mm/rev feed rate. The reason for this reduction in cutting edge radius observed may be due to the significant reduction in the cutting temperature by cryogenic cooling. The low temperature helped reduce abrasion wear (which is the more dominant wear mode in machining CFRP materials) by retaining the tool hardness, and also adhesion and diffusion types of wear that are highly sensitive to temperature [59].

The cutting edge radius slightly increased with the increasing feed rate, which may be due to the fact that small values for feed rate were chosen in this study to avoid severe delamination, and thus the margin of parameter selection is not very large (0.025 mm/rev). It is noted that the progression in cutting edge wear is not uniform: At the start of drilling, the new cutting edges of fresh drills, having smaller cutting edge radius, induce cutting forces to relatively small area of contact. Consequently, the extremely high contact pressure resulting in the tool–workpiece system behaving as a heavily loaded system giving rise to a high wear rate. After the initial wear or cutting edge rounding, the increase in contact area between the tool and the workpiece causes lower contact stresses. As the tool–workpiece system becomes a lightly loaded system, the wear rate is reduced and becomes nearly constant with the increase in the drilling time (or distance) [57, 58].

It is also noticed that the cutting edge radius rises with increasing cutting speed. After drilling 50 holes, the cutting edge radius increased 4.5% and 1%, under dry and cryogenic drilling conditions respectively, when the cutting speed was increased from 40 m/min to 60 m/min at the feed rate of 0.05 mm/rev. The increase is due to the fact that higher cutting speed generates more heat, and thus leading to increased wear rate in the drill bit.

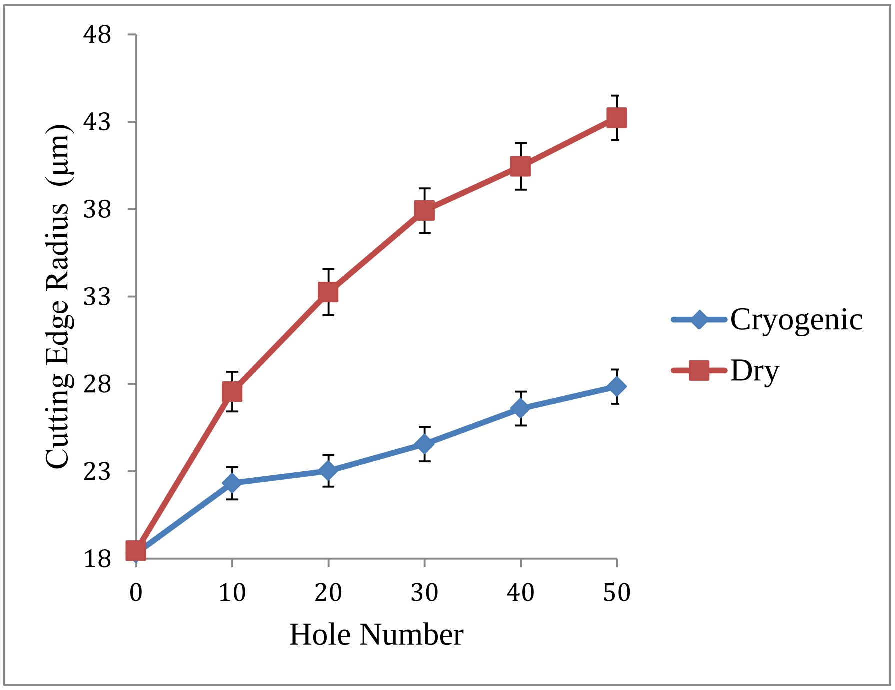
Generally speaking, from the basic findings of some of the researchers, it can be confirmed that the wear is largely smooth and uniform [8]. In this study, it is observed that the cutting edge wear in drilling of CFRP materials is uniform under both dry and cryogenic cooling conditions, but it is notable that there was more deviation in the results of cutting edge wear in dry drilling than in cryogenic drilling.



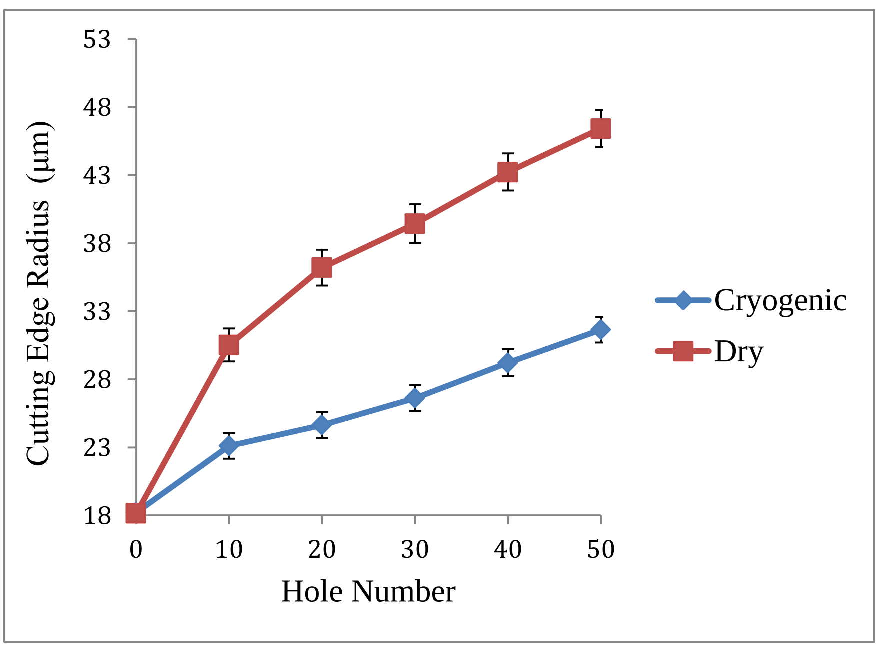
(a)

(b)

Figure 4.4: Cutting edge rounding progression at: (a) f = 0.025 mm/rev and V = 40 m/min; (b) f = 0.05 mm/rev and V = 40 m/min.



(a)



(b)

Figure 4.5: Cutting edge rounding progression at: (a) f = 0.025 mm/rev and V = 60 m/min; (b) f = 0.05 mm/rev and V = 60 m/min.

4.1.2 Outer corner wear

In order to study the effect of cryogenic cooling on outer corner wear performance of uncoated drills, the result of outer corner flank wear was examined using microscopes. By definition, outer corner wear is the wear land on the corner of the flank face of the drill bit. Method of measuring outer corner wear is shown in Figure 4.6. Measuring outer corner wear should take the following steps:

- Choose a fixed reference point
- Before the drilling process, measure the width of margin
- After drilling, measure the distance between the reference points and the wear land. The value of outer corner wear should be the value of margin width minus the distance between reference points and wear land.

During the experiments, the outer corner wear was measured on an optical microscope after every 10 drill holes. Before the drilling test, the image of the fresh drill was taken and is shown in Figure 4.7. Typical images captured by microscopes for outer corner wear of drill bit under dry and cryogenic coolings are shown in Figure 4.8. As shown, cryogenic drilling significantly improves the wear performance in drilling CFRP materials in terms of having lower outer corner wear compared with dry drilling. It shows that outer corner wear rates are 114.7 μm and 219.8 μm after 20 drill holes, and 196.1 μm and 449.1 μm after 50 drill holes under cryogenic and dry conditions, respectively at f =

0.05 mm/rev and V = 60 m/min. The progression of outer corner flank wear from drill tests carried out on an uncoated twist drill under dry and cryogenic cooling conditions is shown in Figures 4.9 and 4.10. The results share the same pattern as the result of cutting edge radius: the outer corner wear rate is higher at the beginning stage and becomes lower after about 10 to 20 drill holes because the tool-workpiece system is more loaded when the drill is fresh. The influence of cryogenic cooling on outer corner wear rate was significant. There were 145% and 165% increases, respectively in outer corner wear at different feed rates when the cooling condition switches from cryogenic to dry. The reason for improvement of the outer corner wear rate under cryogenic condition may also be attributed to the greater hardness of the drill bit at a lower temperature. According to previous studies by many other researchers, the drills were deemed to have failed when the wear land reached 66% of the total margin width [19], and none of the tests in this study exceeded this value.

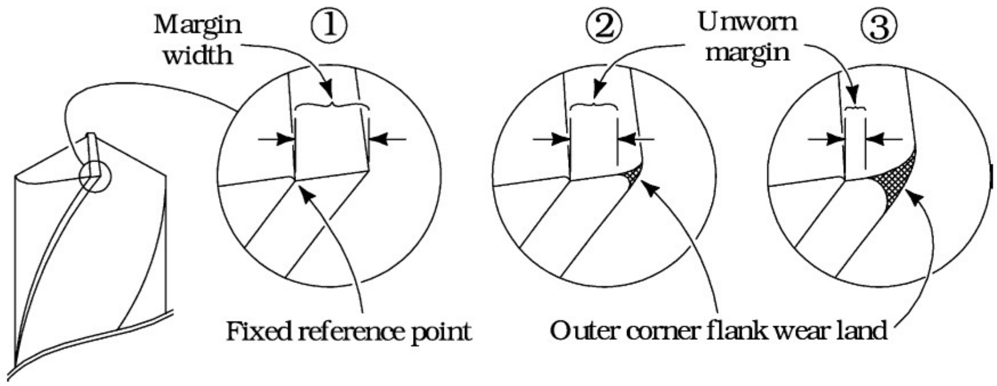


Figure 4.6: Method of measuring outer corner wear [30].

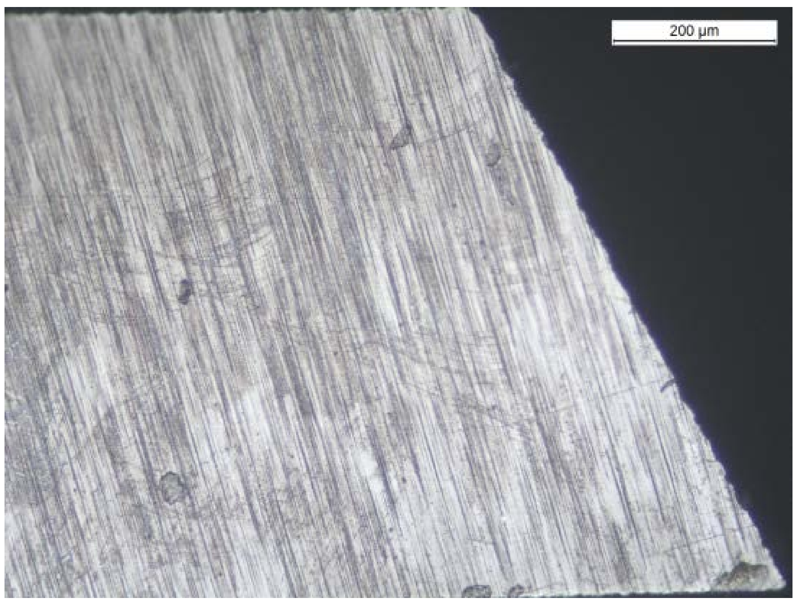


Figure 4.7: Cutting edge rounding progression at f = 0.05 mm/rev and V = 60 m/min.

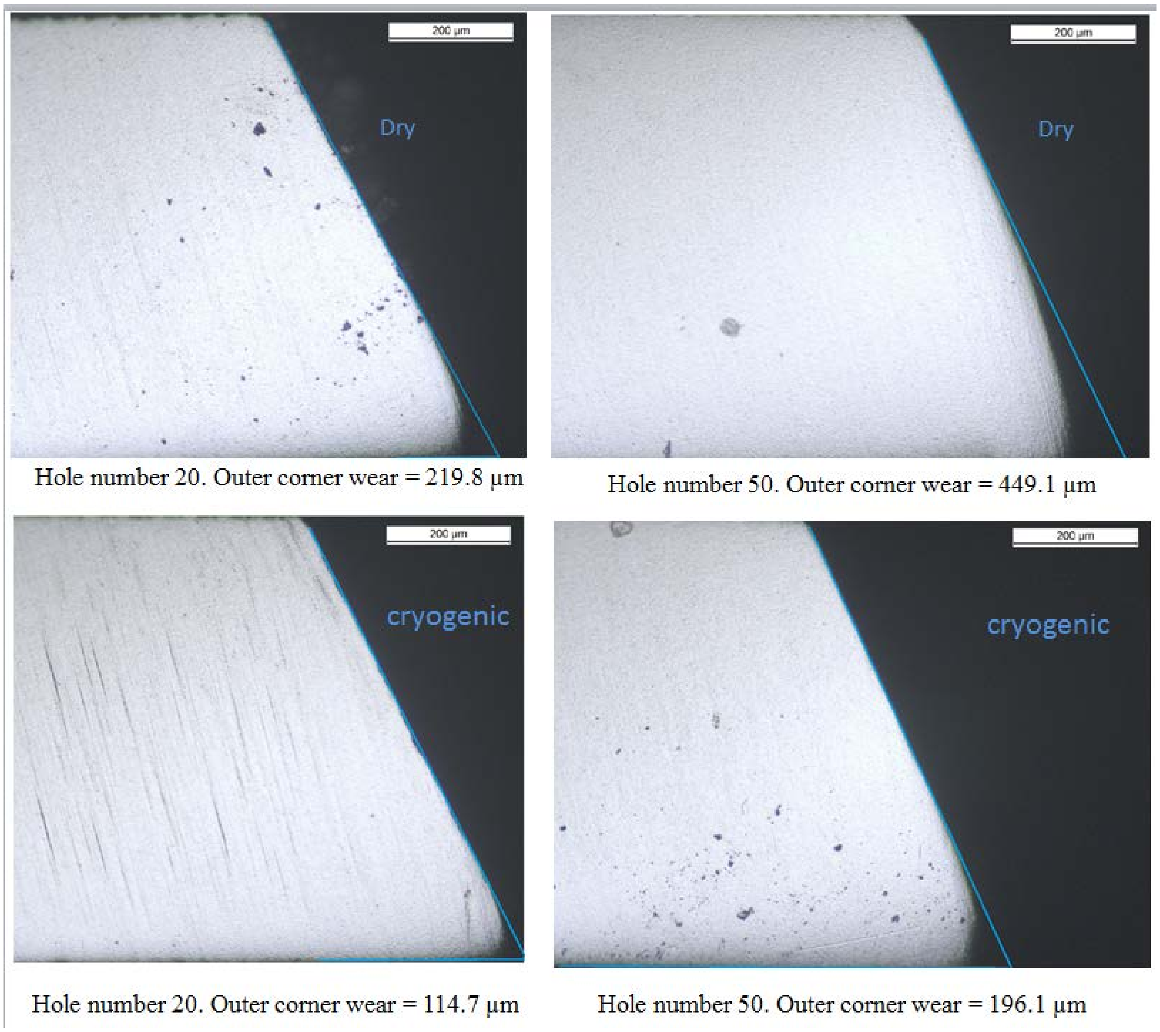


Figure 4.8: Cutting edge rounding progression at f = 0.05 mm/rev and V = 60 m/min.

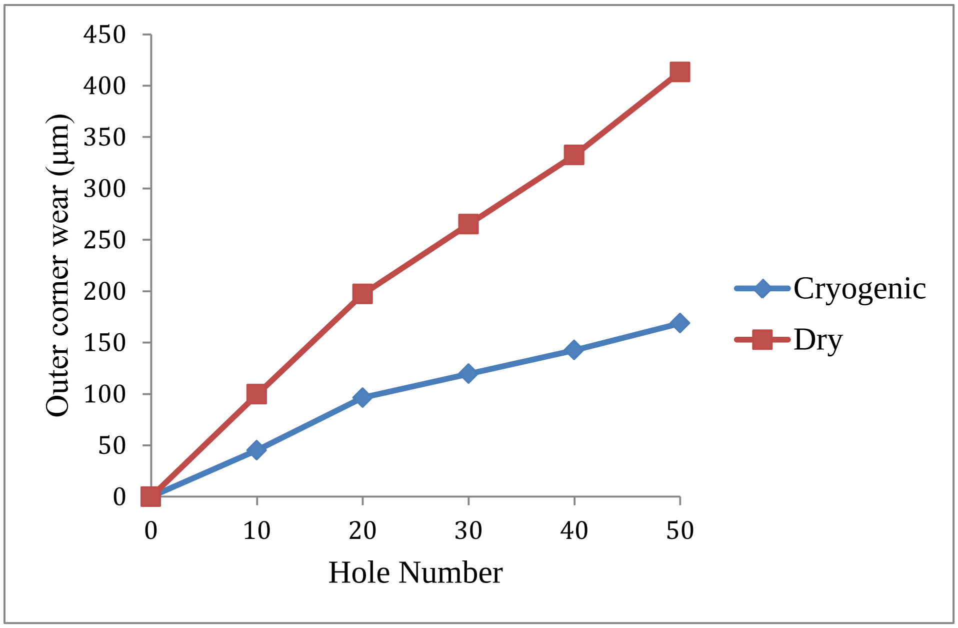


Figure 4.9: Outer corner wear progression at *f* = 0.025 mm/rev and *V* = 60 m/min.

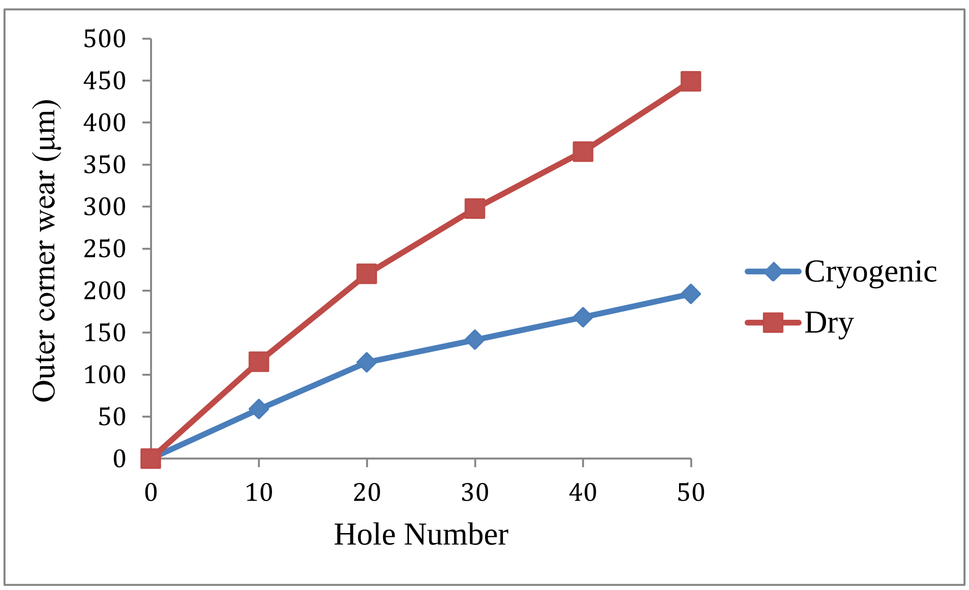


Figure 4.10: Outer corner wear progression at *f* = 0.05 mm/rev and *V* = 60 m/min.

4.2 Effects of Cryogenic Cooling on Thrust Force and Torque

This section of the chapter presents results pertaining to the effects of cryogenic cooling of CFRP materials on drilling thrust force and torque. The thrust force and torque components measured by the dynamometer are shown in Figures 4.11 and 4.14. As one of the most important hole quality criteria in drilling CFRP materials, delamination is proved to be related to maximum thrust force by many researchers. In this study, all the force data are maximum thrust force and torque.

4.2.1 Thrust force

The application of liquid nitrogen had a large influence on the thrust force. As shown in Figure 4.11, compared with data obtained under dry machining, the average maximum thrust force for cryogenic drilling was increased by 91%, 69%, 112% and 77% respectively. The increase is due to the effective cooling from the liquid nitrogen applied via drill bit coolant holes, which enhances the mechanical properties of the materials. The cryogenic temperature characteristic of several carbon fiber reinforced composite materials was investigated and summarized in detail in relation to its mechanical and thermal aspects by Reed and Golda [54, 55], who reported that Young's modulus and tensile strength of carbon fiber reinforced composites increase as the temperature decreases. Kim and Donaldson [56] also studied mechanical properties of carbon fiber reinforced epoxy polymer composite. They claimed that thermo-mechanical properties, such as transverse modulus, shear modulus, transverse shear modulus and transvers strength were increased when the temperature was reduced.

Another reason for elevation of thrust force in cryogenic drilling may be because of the experimental setup in this study. Liquid nitrogen was delivered internally via drill bit coolant hole. After cooling the tool and workpiece, the liquid nitrogen converts to gas, but with no outlet. Therefore there was a lot of pressure built up inside the specimen and push the specimen to the dynamometer, which may increase the result of thrust force.

The influence of feed rate on thrust forces, both under dry and cryogenic conditions, was significant. There were 60% and 53% increases respectively in the thrust force under dry and cryogenic conditions, when the feed rate was increased from 0.025 mm/rev to 0.05 mm/rev at the cutting speed of 40 m/min. When the cutting speed was increased to 60 m/min, there were 64% and 46% increases, respectively in the thrust force under dry and cryogenic conditions when the feed rate was increased from 0.025 mm/rev to 0.05 mm/rev.

In metal cutting, increasing cutting speed usually affects the forces in two ways: (a) generating more heat leading to a higher temperature and reducing the forces; and (b) increased strain-rate leading to stronger work hardening and thus increasing the forces. In the drilling of CFRP materials, the only cutting mechanism is fracture, there were no plastic deformations involved during the drilling process, and thus increasing cutting speed does not lead to work hardening effect on CFRP materials. As it is seen in Figure 4.11, thrust force only slightly decreased with the increase of cutting speed under both dry and cryogenic cooling. This may be due to the fact that the thrust force is less sensitive to cutting speeds than feed rates, which has been confirmed by several researchers [13, 53]. It also needs to be pointed out that the cutting speeds selected in this study were 40 and 60 m/min. This margin of cutting speed may not create a huge difference in heat generation, thus there was limited elevation of cutting temperature after increasing cutting speed.

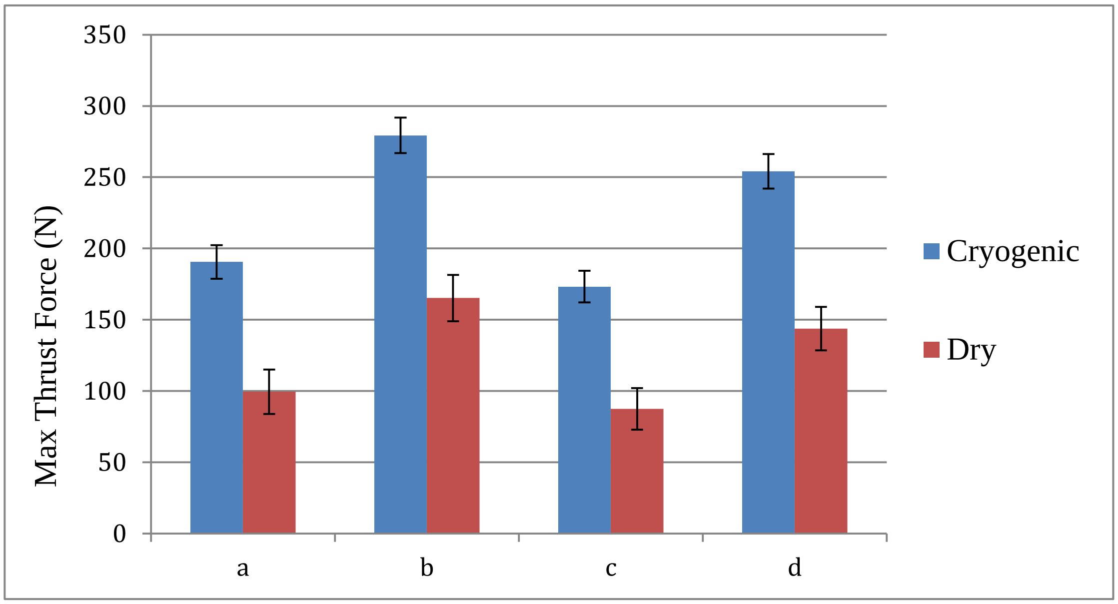


Figure 4.11: Average maximum thrust force at: (a) f = 0.025 mm/rev, V = 40 m/min; (b) f = 0.05 mm/rev, V = 40 m/min; (c) f = 0.025 mm/rev, V = 60 m/min; and (d) f = 0.05 mm/rev, V = 60 m/min;

The effect of cutting edge radius on thrust force has also been studied in this research. Figure 4.12 shows plots for the maximum drilling thrust values. Maximum thrust force results of every drilling case under both dry and cryogenic conditions were demonstrated in the plot. Thrust force increased with the increase in drilling hole number due to the fact that fresh drill became blunt during the drilling process. The drilling thrust force progression in both dry and cryogenic drilling was observed to share a nearly similar trend to the progression of cutting edge radius, which indicates that thrust force might be correlated to cutting edge radius. Figure 4.13 confirms the previous assumption, as it shows the increasing (correlation) drilling thrust force, with the cutting edge radius progression. Cutting edge radius values were measured after every ten drill holes and correlated with the maximum thrust force results of corresponding drill hole number. Thrust correlation curves for both dry and cryogenic cooling conditions, as seen from Figure 4.13, show a relatively clear pattern that maximum thrust increases with the increase of cutting edge radius. As discussed in the previous section, cutting edge radius grows more slowly in cryogenic drilling than in dry drilling. In other words, according to the correlation seen from Figure 4.13, the increasing rate of thrust force in cryogenic drilling should be lower than in dry drilling. Figure 4.12 shows that the slope/rate of maximum thrust progression in cryogenic drilling is slightly lower than in dry drilling.

In summary, even though results of thrust force in cryogenic drilling were higher than in dry drilling, the increasing rate of thrust force in cryogenic drilling is lower than in dry drilling due to the fact that cutting tool could maintain its sharpness during the drilling under cryogenic cooling.

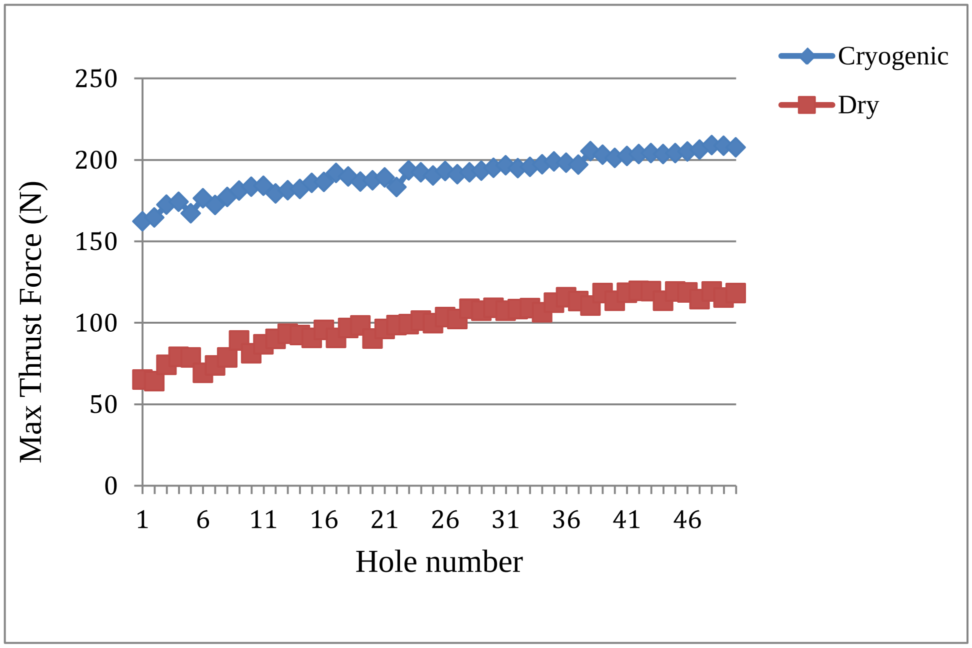


Figure 4.12: Thrust force progression at *f* = 0.025 mm/rev, *V* = 60 m/min.

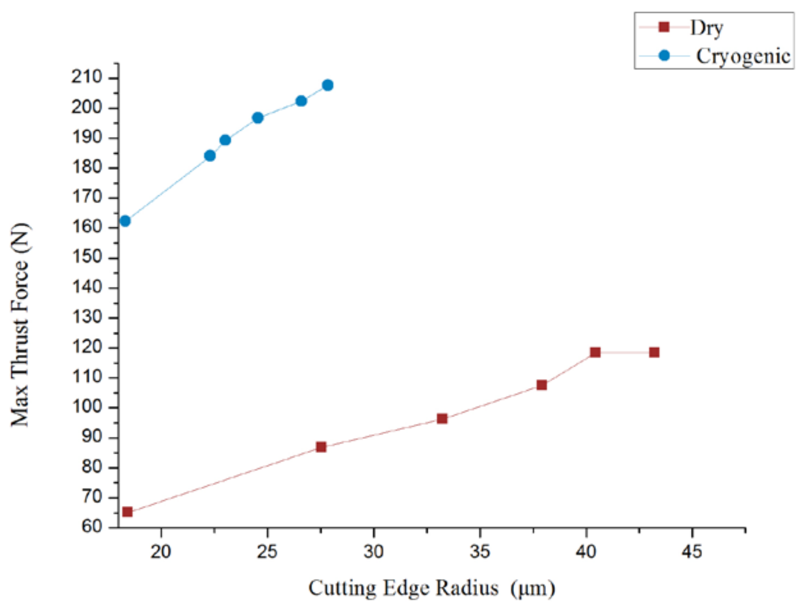


Figure 4.13: Correlation between thrust force cutting and edge radius at *f* = 0.025 mm/rev, *V* = 60 m/min.

4.2.2 Torque

The mean values of maximum drilling torque results from tests with different cutting parameters are plotted in Figure 4.14. Each data point also includes an error bar that shows its degree of variability.

As shown in Figure 4.14, it is clear that the mean value of maximum torque increases when the cooling condition switches from dry condition to cryogenic cooling. This increase can be explained in a manner similar to that of drilling thrust mentioned in the previous section: the elevation is due to the fact that the mechanical properties of the CFRP material was enhanced at lower temperature cooling, and thus the torque was higher under cryogenic cooling.

The effect of cutting parameters on the drilling torque can also be evaluated from the plots in Figure 4.14. The figure shows for both cooling conditions and feed rates, the effect of increasing speed form 40 m/min to 60 m/min is to decrease the average value of maximum drilling torque. It also shows the influence of increasing feed rate for different cooling conditions and cutting speeds in the increase in torque. This increase in torque with increase in feed rate and cutting speed is due to the higher friction. As discussed in the previous section, tool-wear increases with increase in feed rate and cutting speed, thus blunter tools might be another reason that torque results are higher at a higher cutting speed and feed rate.

The effect of cutting edge radius on torque has also been studied in this research. Figure 4.15 shows plots for the maximum torque values under both dry and cryogenic conditions. Torque increased with the increase in drill hole number, and in other words, torque is also related to the sharpness of the cutting tool. Meanwhile, the trend of torque progression in both dry and cryogenic drilling is similar to what was observed in cutting edge progression. Figure 4.16 correlates torque to cutting edge radius. As seen from Figure 4.16, maximum torque increases with the increasing cutting edge radius.

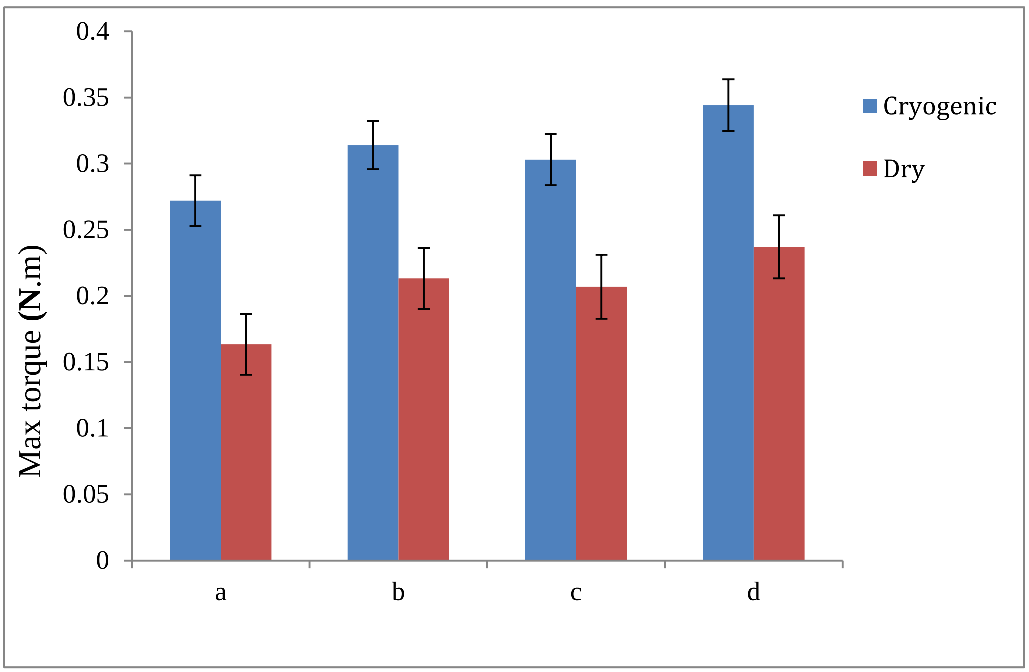


Figure 4.14: Average maximum torque at: (a) f = 0.025 mm/rev, V = 40 m/min; (b) f = 0.05 mm/rev, V = 40 m/min; (c) f = 0.025 mm/rev, V = 60 m/min; and (d) f = 0.05 mm/rev, V = 60 m/min;

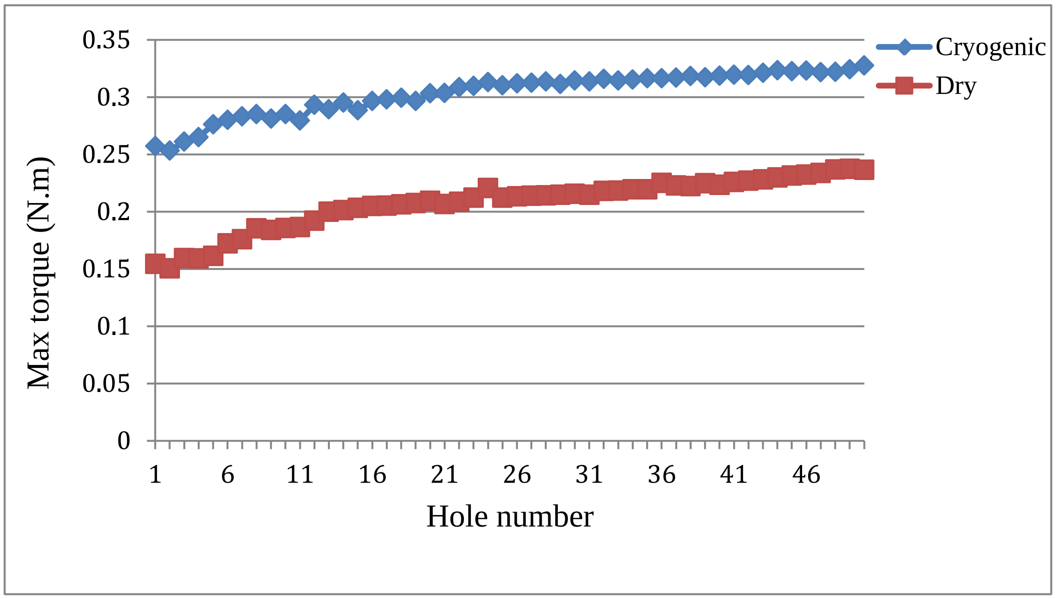


Figure 4.15: Torque progression at *f* = 0.025 mm/rev, *V* = 60 m/min.

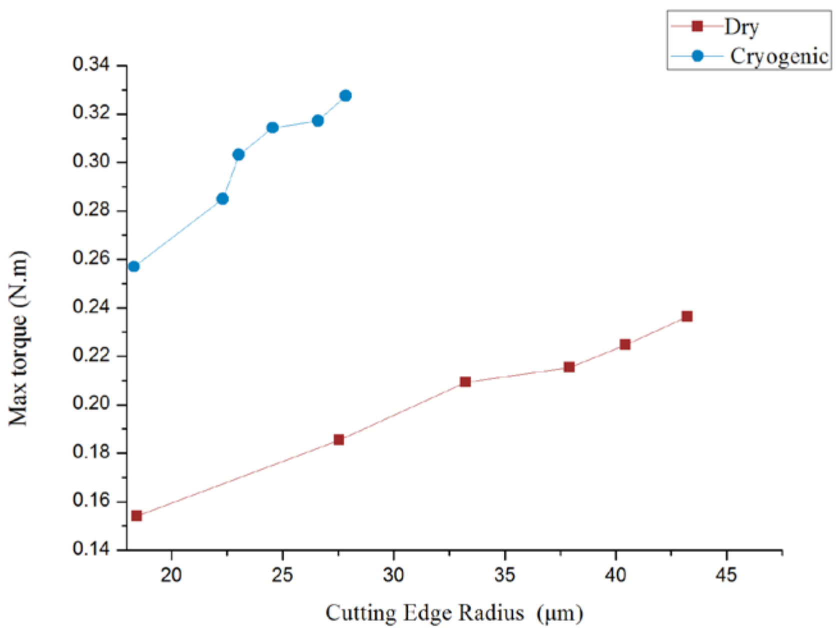


Figure 4.16: Correlation between torque cutting and edge radius at *f* = 0.025 mm/rev, *V* = 60 m/min.

4.3 Analytical Model for Critical Thrust Force

Many researchers studied thrust force in drilling of CFRP composite, especially critical the thrust force, and it was shown that this thrust force is related to hole quality and delamination in drilling CFRP materials. Therefore, being able to accurately predict critical thrust force could be used to optimize the cutting parameter (in this specific case the cutting parameter is feed rate) in order to avoid defects and to improve productivity.

Hocheng-Dharan delamination model [45] has been used in this study. They introduce the idea of critical thrust force, which can be estimated using the equation they provided.

As shown in Figure 4.17, the cylinder in the middle represents the drill with diameter D, F_A is the applied thrust force, X is the displacement, H is the thickness of the structure, h is the uncut depth under tool, and a is the assumed size of an existing crack. As the drill cuts downwards, the uncut laminates under the tool are pushed and deformed elastically by the thrust force. If the resulting strain at the tip of the existing crack goes beyond the critical value, crack propagation occurs [45].

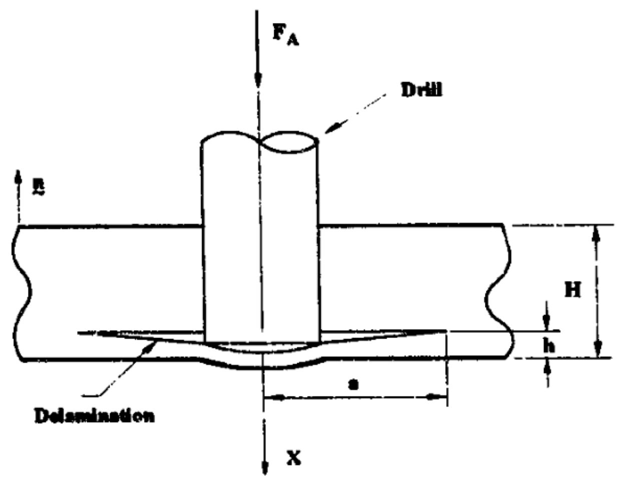


Figure 4.17: Circular plate model for delamination analysis (twist drill) [45].

In 1997, Tsao [43] gave the detail of a derivation of the equation of critical thrust force. Equation of energy balance, from linear elastic fracture mechanics, can be written as:

$$G\mathrm{d}A = F_A\,\mathrm{X}\text{-}\mathrm{d}U \qquad (4.1)$$

where d*A* is the increase area of the crack, which equals to:

$$\mathrm{d}A = \pi(a + \mathrm{d}a)(a + \mathrm{d}a) - \pi \mathrm{a}^2 = 2\pi a \mathrm{d}a \qquad (4.2)$$

Substituting Eq. (4.2) into Eq. (4.1):

$$2\,\pi \mathrm{Gada} = F_A \mathrm{dX} - dU \qquad (4.3)$$

where *G* is the crack propagation energy and *U* is the stored strain energy.

To find the correlations linking F_A, U and X together, classic plate bending theory for a circular plate with clamped ends and concentrated load is used in this model [44]. For a circular plate with clamped ends and a concentrated load, the stored strain energy is [45]:

$$U = \frac{8\pi M X^2}{a^2} \tag{4.4}$$

where M is the stiffness per unit width of the fiber reinforced materials given by

$$M = \frac{Eh^3}{12(1-v^2)} \tag{4.5}$$

The displacement X is expressed as:

$$X = \frac{F_A a^2}{16\pi M} \tag{4.6}$$

Substituting Eq. (4.4)-(4.6) into Eq. (4.3), the critical thrust force at the onset of crack propagation can be calculated:

$$F_{A_{cr}} = \pi[\frac{8GEh^3}{3(1-v^2)}]^{1/2} \tag{4.7}$$

where v is Poisson's ratio, E is Young's modulus, and G_{IC} is the critical crack propagation energy in mode I.

The value of G_{IC} is assumed as constant because G_{IC} was proven by Saghizadeh and Dharan [55] to be only a mild function of strain-rate. In Eq. (4.7), G is replaced by G_{IC} since the value is easily measured.

The critical thrust force at the onset of crack propagation can be calculated as:

$$F_{A_{cr}} = \pi[\frac{8G_{IC}Eh^3}{3(1-v^2)}]^{1/2} \quad (4.8)$$

Composite laminates were made of woven 2 x 2 twill woven pattern pregregs and the lay-up of laminates was oriented as standard $0^o/+45^o/90^o/-45^o$ directions. The fiber volume fraction was 0.6, the thickness for a single ply is 0.42 mm, the Young's modulus was 17 GP_a, Poisson's ratio was 0.3, and the strain energy release rate was 90 J/m^2.

Drill bits selected for this study were standard twist drill. Based on the available information and Eq. (4.8), the critical thrust force for the CFRP composite in this study is $F_{A_{cr}} =$ 57.2 N. Drilling tests were carried out to test the analytical model. The entire test were performed at cutting speed of 40 m/min and feed rate range of 0.002, 0.004, 0.006, 0.008, 0.001, 0.012, 0.014, 0.016, 0.018, and 0.02 mm/rev under dry drilling. Delamination was observed after drilling at cutting speed of 40 m/min and feed rate of 0.016 mm/rev and the maximum thrust force was record as F = 56.73 N. This result suggested that the model is reasonable.

4.4 Summary

An experimental investigation has been conducted to study the effect of the different machining parameters, including cooling method (dry, cryogenic), cutting speed and feed rate, on the thrust force, torque and tool-wear performance in drilling of CFRP composite. Major observations can be summarized as the following points:

- Remarkable tool-wear resistance was achieved during cryogenic drilling in terms of having lower cutting edge radius and outer corner wear compared with dry drilling. Significant reduction of cutting temperature by supplying liquid nitrogen through coolant hole of the drill bit onto the tool-workpiece interface is the main reason for this superior tool-wear performance. Compared with dry drilling, cryogenic drilling produced 53% - 63% less cutting edge radius depending on the cutting parameters: dry drilling induced more than twice outer corner wear compared with cryogenic drilling. Both cutting speed and feed rate were confirmed to influence cutting edge radius and outer corner wear. Only a marginal elevation of cutting edge radius and outer corner wear has been found with the increase of cutting speed and feed rate.
- Both thrust force and torque were larger in cryogenic drilling than in dry drilling due to the fact that cryogenic cooling increases the strength of the workpiece and makes the material harder to drill. Using the cutting speed of 40 m/min and the feed rate of 0.05 mm/rev, the application of liquid nitrogen increased thrust force and torque by about 70% and 61% respectively. The effect of cutting parameters on thrust force and torque has also been investigated. Thrust force and torque increased with the increasing feed rate, meanwhile both thrust force and torque decreased with the

increasing cutting speed.

- An analytical model has been used to predict critical thrust force. The value is calculated using the mechanical properties provide by the material supplier. The applied thrust force should not exceed this value to avoid delamination. After getting the value of critical thrust force, drilling tests were carried out in order to examine the analytical model. All tests were performed under dry condition since no properties of CFRP composite under cryogenic temperature were available.

CHAPTER 5: HOLE QUALITY AND SURFACE INTEGRITY IN DRILLING OF CFRP MATERIALS

5.1 Introduction

This chapter discusses the investigation of the effects of cooling conditions and cutting parameters on hole quality and surface integrity of the borehole, when they are drilled using uncoated carbide drill bit through CFRP materials. The hole quality and surface integrity criteria investigated in this study include: delamination, burr generation, diameter error, roundness of the borehole, surface roughness, and subsurface damage. It has been reported that delamination and surface roughness depend on cutting edge radius; that burr generation is related to outer corner wear; and that subsurface damage is related to cutting temperature and thrust force. All these factors were found to be influenced by the cryogenic cooling as seen in the previous chapters.

This study demonstrates the success of a novel setup to improve the hole quality and surface integrity of CFRP borehole by cryogenic drilling.

5.2 Delamination

In order to evaluate the extent of the delamination damage, a term called 'delamination factor' was used. The delamination factor, 'F_d', is the ratio of the maximum diameter of the damaged zone to the diameter of the borehole [8], as shown in

Figure 5.1.

$$F_d = \frac{D_{max}}{D_0} \quad (5.1)$$

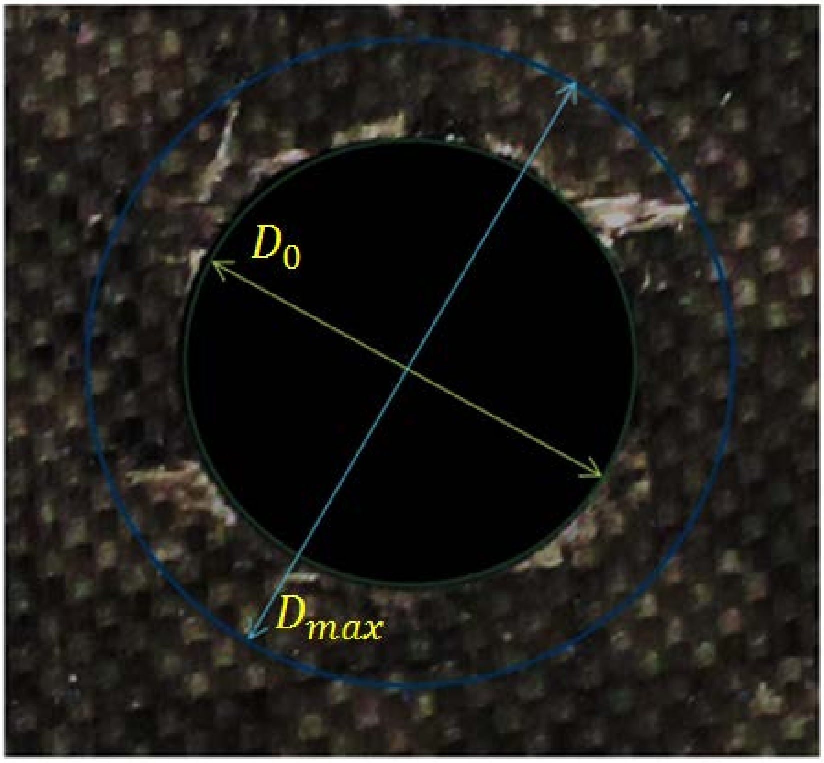


Figure 5.1: Demonstration of D_0 and D_{max}.

To calculate the delamination factor, optical images of boreholes that were drilled through CFRP material were captured by scanner, and D_0 and D_{max} and measured by CorelDRAW image software. Then, the delamination factor, 'F_d', is calculated for each hole using Eq. (5-1). Due to the fact that only limited delamination was observed for the entry side in all the drilling tests, only exit delamination was calculated in this study. It has been reported that the delamination significantly depends on the thrust force. Also, as was discussed in Chapter 4, under the same cutting parameters, compared with dry drilling, cryogenic drilling generates a much larger thrust force. Therefore, more severe delamination occurred in drilling test under cryogenic cooling. In this study, there were 8 tests as shown in Table 3.1, and there were 50 drill holes produced for each test. Figure 5.2 shows the image of first and last boreholes under dry and cryogenic cooling conditions at V = 60 m/min, f = 0.025 mm/rev.

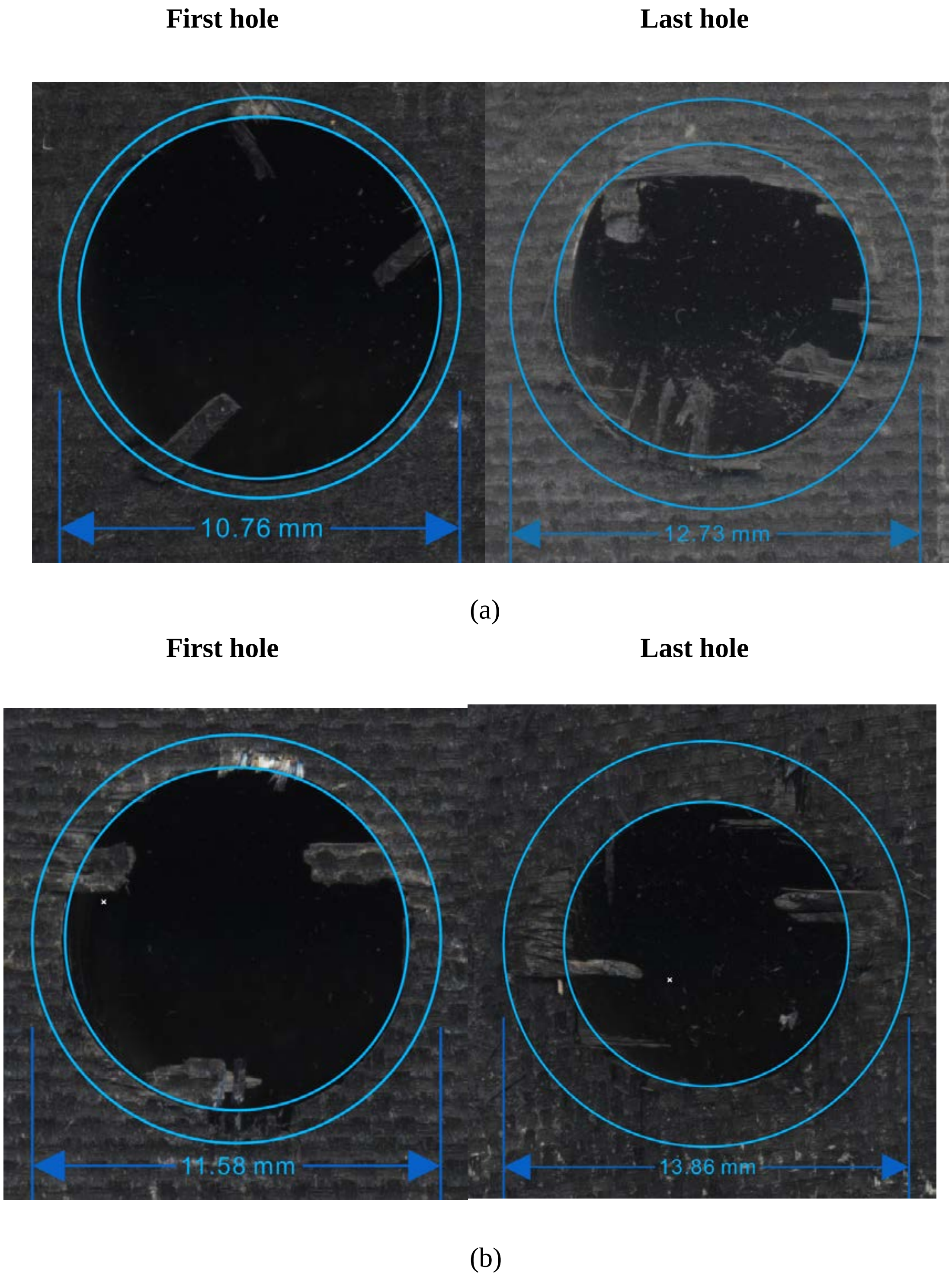


Figure 5.2: Optical images of first and last hole of CFRP materials drilled at V = 60 m/min, f = 0.025 mm/rev, under: (a) dry condition; (b) cryogenic conditions.

Figure 5.3 shows the average delamination of 50 drill holes at different feed rates and cutting speeds under both dry and cryogenic cooling conditions. Machined samples under cryogenic cooling suffered more severe delamination than the ones in dry drilling. Generally speaking, delamination is about 11% to 15% higher in cryogenic drilling than in dry drilling. It is also noticeable that the delamination factor increased with increasing feed rate and decreased when the cutting speed increased from 40 m/min to 60 m/min. These findings of delamination factor fairly agree with thrust force results in this study as discussed in Chapter 4, which has also confirmed the previous studies by other researchers that delamination factor highly depends on the thrust force. The highest average delamination factor was found in the samples machined at V = 40 m/min, f = 0.05 mm/rev under cryogenic cooling.

Another noticeable fact is that there was more deviation in the delamination factor of dry drilling due to the fact that although not as big as in cryogenic drilling, the delamination factor increased more in dry drilling as the experiment proceeded. Figures 5.4 – 5.7 show the delamination factor progression for drilling tests at different feed rates, cutting speeds and under different cooling conditions. The rapidly increasing rate of delamination factor in dry drilling can be explained by the thrust force results and cutting edge radius results presented in Chapter 4: the thrust force in dry drilling was not as big as in cryogenic drilling, but grew faster since drill bits have better tool-wear performance under cryogenic cooling; drill bits could not hold their sharpness in dry drilling as much as in cryogenic drilling. When the drilling test proceeded under dry condition, the drill bits pushed material rather than cut it.

Figures 5.8 and 5.9 show the correlations of the exit delamination with the maximum thrust force and the correlations of the exit delamination with cutting edge radius. A direct correlation is observed, which confirms that the delamination is significantly dependent on the induced thrust force during drilling, and increases with the increase of cutting edge radius due to the increased bluntness of the tool.

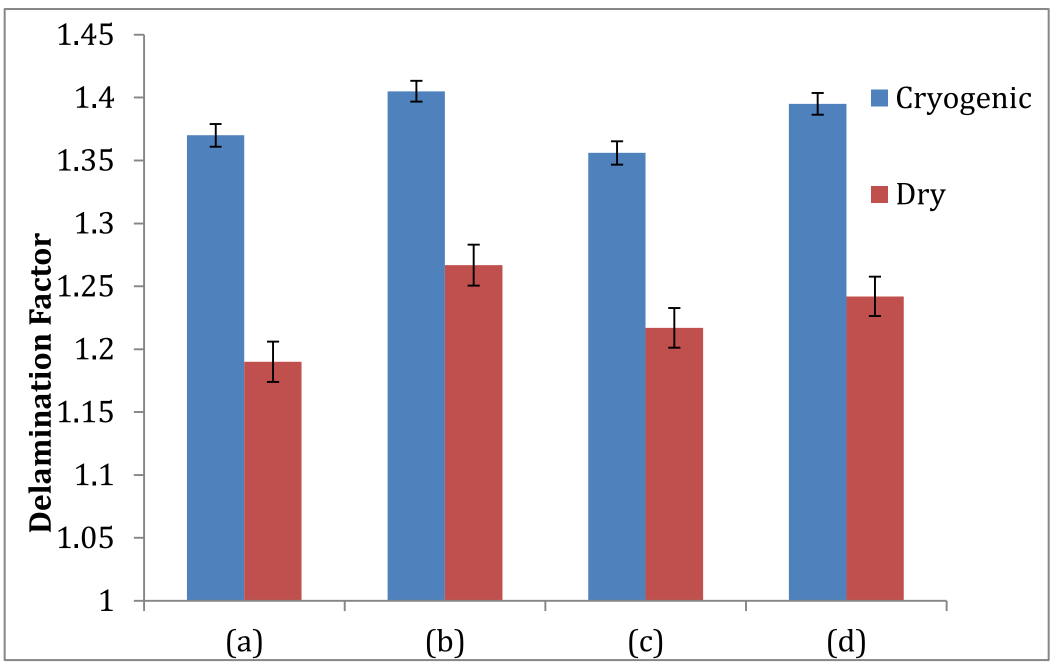


Figure 5.3: Average delamination of boreholes of CFRP materials drilled at different cutting speeds and feed rates: (a) V = 40 m/min, f = 0.025 mm/rev; (b) V = 40 m/min, f = 0.05 mm/rev; (c) V = 60 m/min, f = 0.025 mm/rev; and (d) V = 60 m/min, f = 0.05 mm/rev.

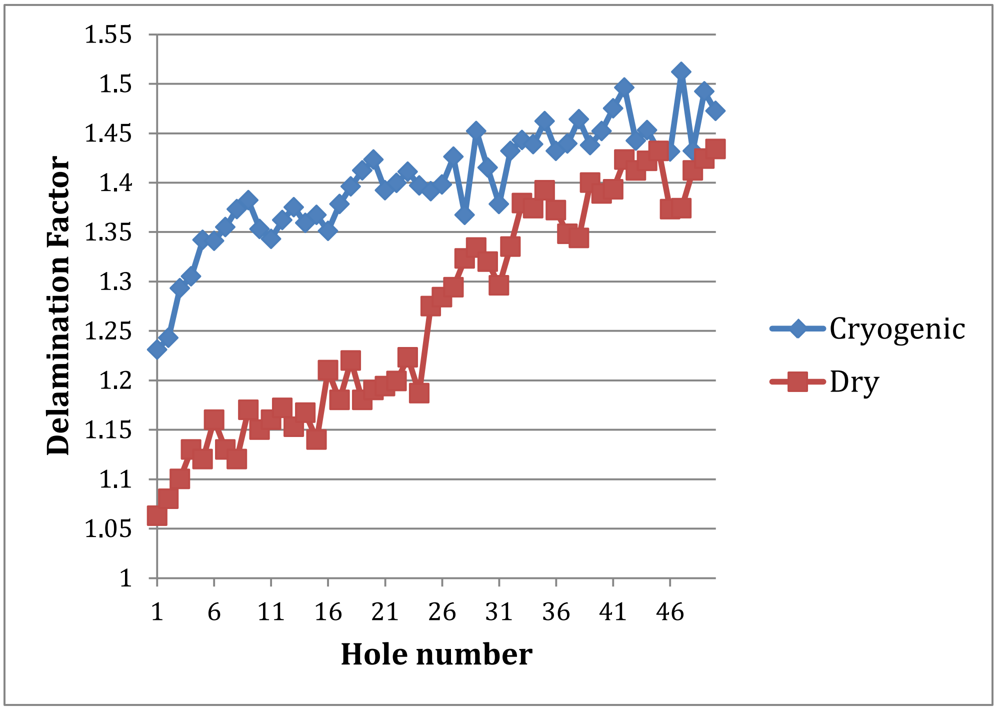


Figure 5.4: Delamination progression at V = 40 m/min, f = 0.05 mm/rev.

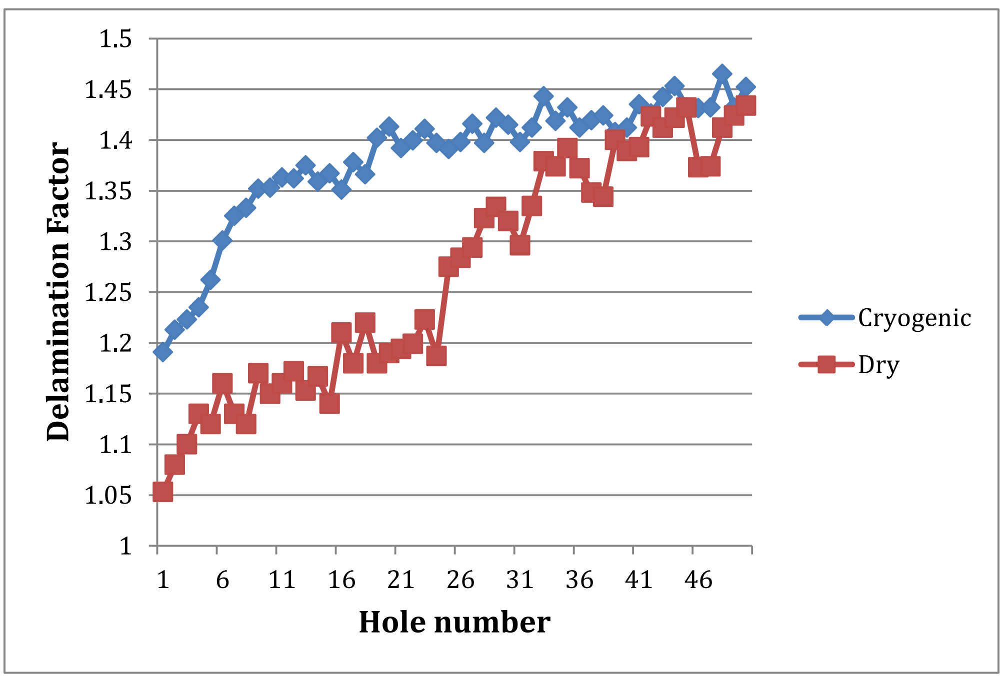


Figure 5.5: Delamination progression at V = 40 m/min, f = 0.25 mm/rev.

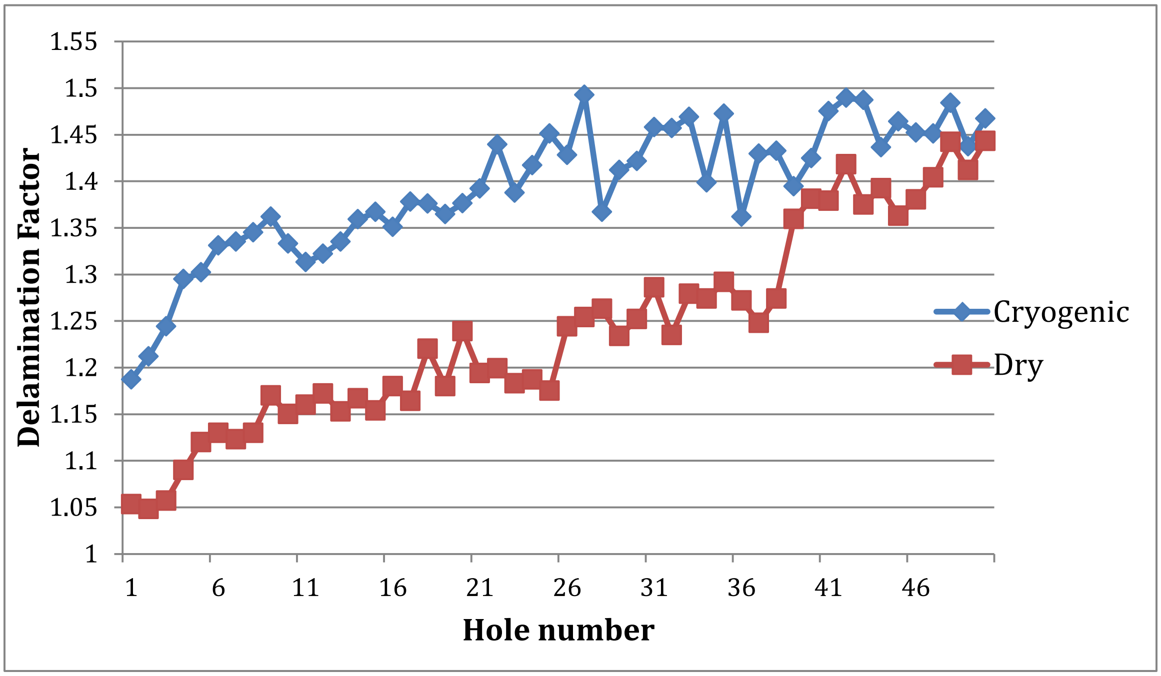


Figure 5.6: Delamination progression at V = 60 m/min, f = 0.05 mm/rev.

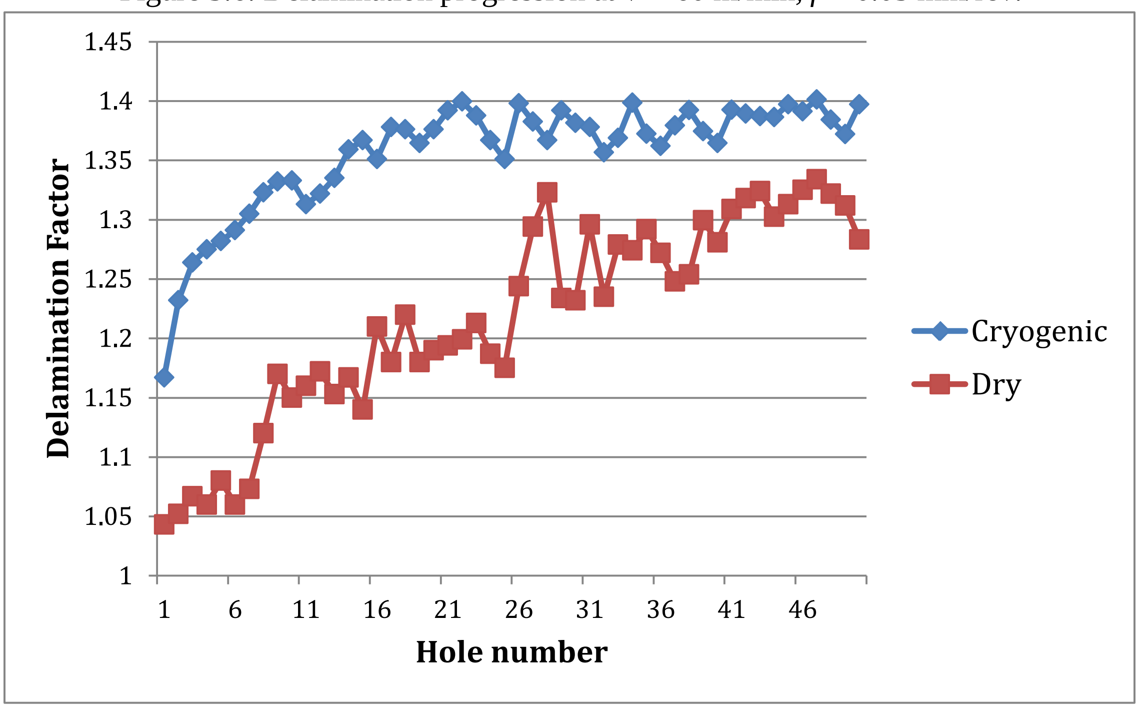


Figure 5.7: Delamination progression at V = 60 m/min, f = 0.025 mm/rev.

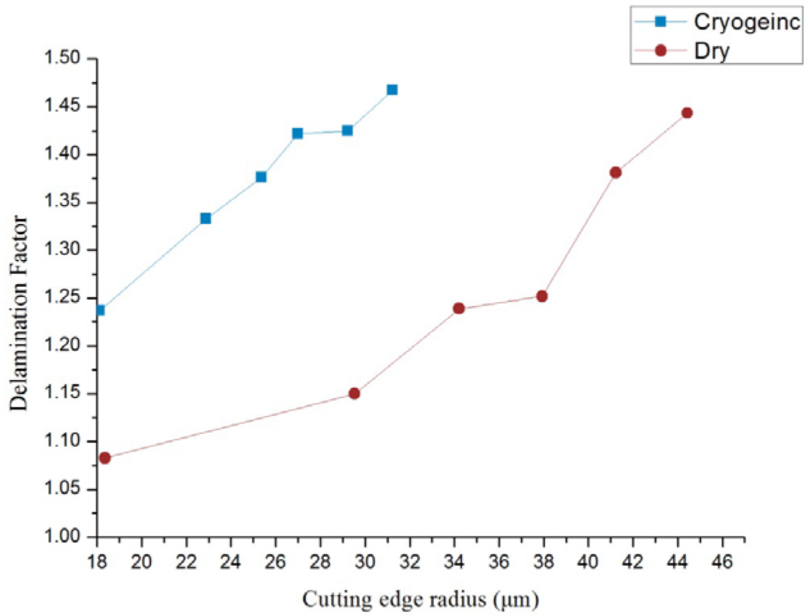


Figure 5.8: Delamination progression with cutting edge radius at V = 60 m/min, f = 0.025 mm/rev.

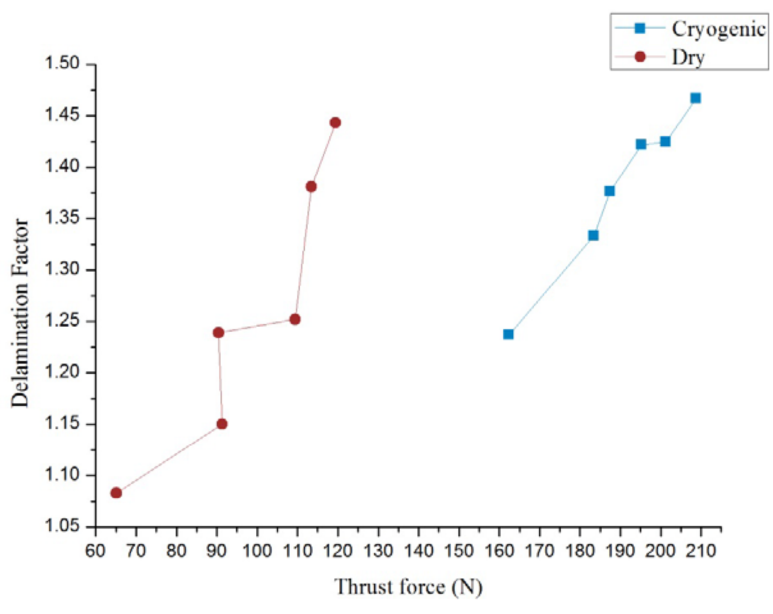


Figure 5.9: Delamination progression with thrust force at V = 60 m/min, f = 0.025 mm/rev.

As discussed in Chapter 2, it has been reported that a back-up support would significantly minimize delamination in drilling of CFRP materials. As shown in Figure 5.10, CFRP cubic was sliced into a 2 mm plate as the back-up material and was adhered to the exit side of workpiece. The adhesion material was only applied to the corners of the exit side surface (avoiding the drilling area) in order to make sure that drilling process would not be influenced by the adhesion. The experimental matrix of this extended work is shown in Table 5.1. Both dry and cryogenic cooling methods were used for the purpose of comparison. Each test performed five drillings and a comparison of last borehole with or without back-up support at different cutting parameters and the associated cooling methods are listed in Figure 5.6.

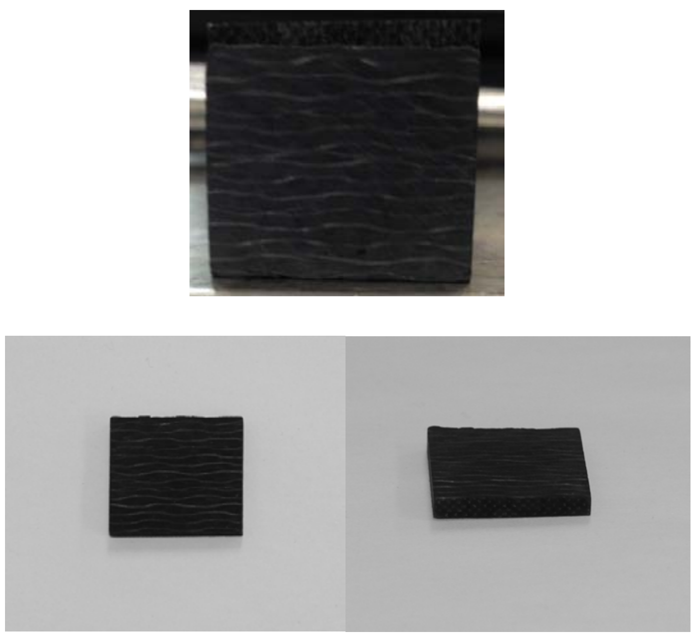


Figure 5.10: Back-up materials and preparation of samples with back-up materials.

Table 5.1: Experiment matrix for drilling under different cooling methods

No.	**Cooling Method**	**Cutting Speed, *V* [m/min]**	**Feed Rate, *f* [mm/rev]**	**No. of Holes drilled**	**With or Without Back-up**
1	Dry	60	0.05	5	With
2	Cryogenic	60	0.05	5	With
3	Dry	60	0.05	5	Without
4	Cryogenic	60	0.05	5	Without

As seen in Figures 5.11 and 5.12, hole quality in terms of delamination factor improved significantly with the application of back-up support under both cryogenic and dry cooling methods. After applying the back-up material, the average value of delamination factor drops 14% and 17 % under cryogenic drilling and dry drilling respectively. The delamination factors was slightly smaller in dry drilling compared with in cryogenic drilling for the scenario that back-up support was not used due to the fact that dry drilling generates a lower thrust force. Meanwhile, delamination factors were almost the same in cryogenic drilling and dry drilling when back-up materials were used. These results prove that the approach of using back-up material would significantly minimize delamination in drilling of CFRP materials under cryogenic and dry cooling methods. Despite the advantage of cryogenic cooling in drilling of CFRP material, severe delamination is the biggest concern due to the high thrust force. The results in this study suggest that using a back-up material will lead to a practical and effective set up for applying cryogenic cooling in drilling of CFRP materials.

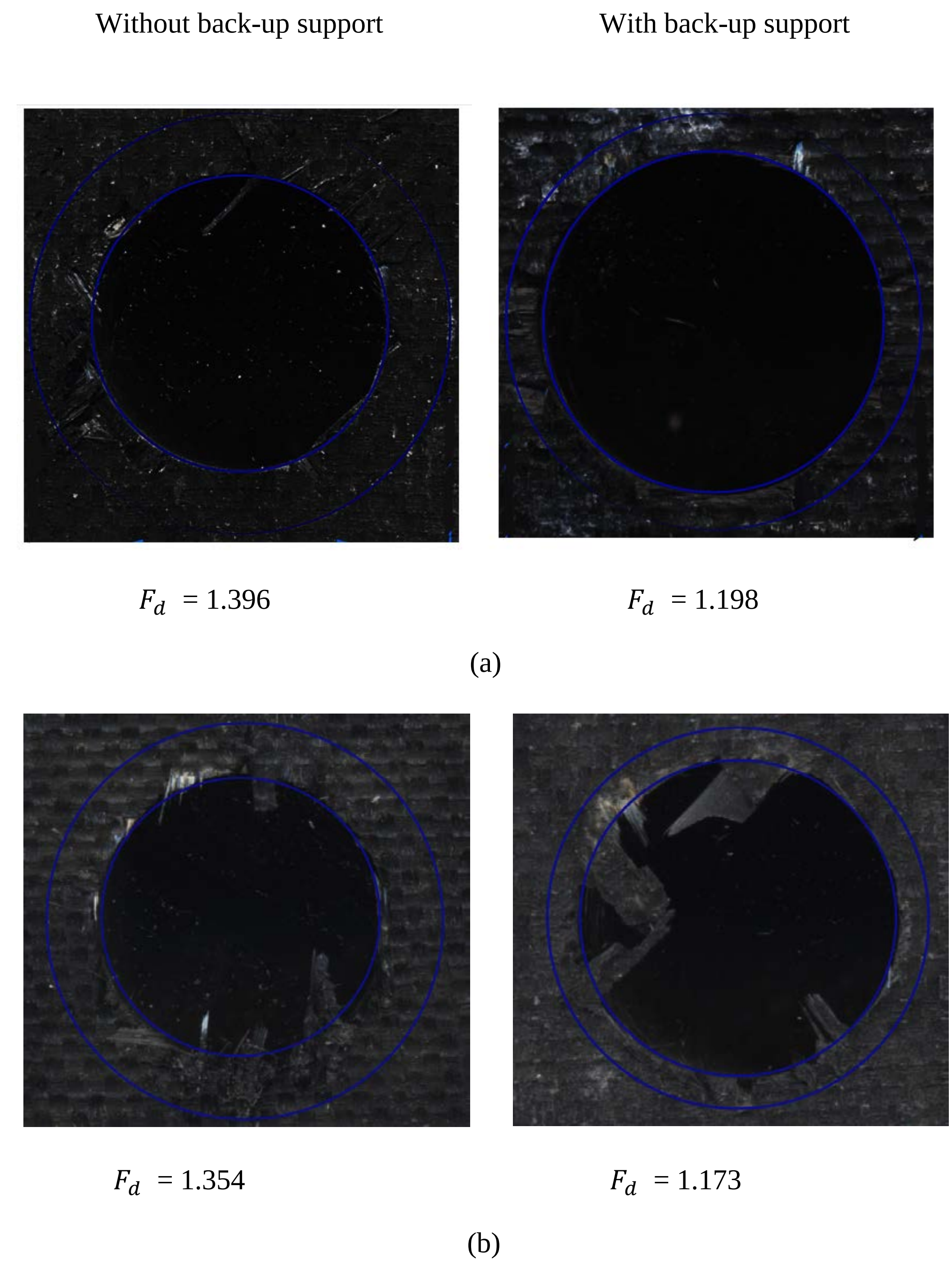


Figure 5.11: Last hole with and without back-up support under: (a) cryogenic cooling condition; (b) dry condition.

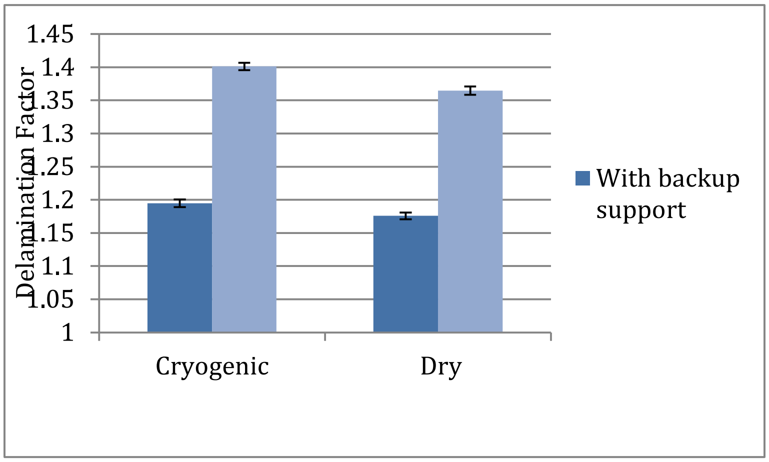


Figure 5.12: Average delamination factor for samples with and without back-up support.

5.3 Burr Generation

The problem of burr generation in drilling of CFRP with different cooling methods is investigated in this study. Figure 5.9 gives comparisons of burr generation of boreholes drilled using cryogenic method and dry method at *f* = 0.05 mm/rev and *V* = 60 m/min. It is noticeable that burr generation became more severe as the drilling process proceeded under both dry and cryogenic drilling. However, the borehole under cryogenic cooling suffered extremely less generation of burr compared with borehole under dry cooling method. As discussed in chapter it has been reported by Teti [3] that the burr is mainly caused by the outer corner wear of the drill. The excessive burr generation in dry drilling agrees with the results of outer corner wear we discussed in Chapter 4. The fuzzy edge of the boreholes is due to the fact that drill bits tend to wear fast under dry cooling method in terms of a rapid increase in outer corner wear. The blunt tool could not cut the fiber effectively, but to push the fiber and tear the workpiece material.

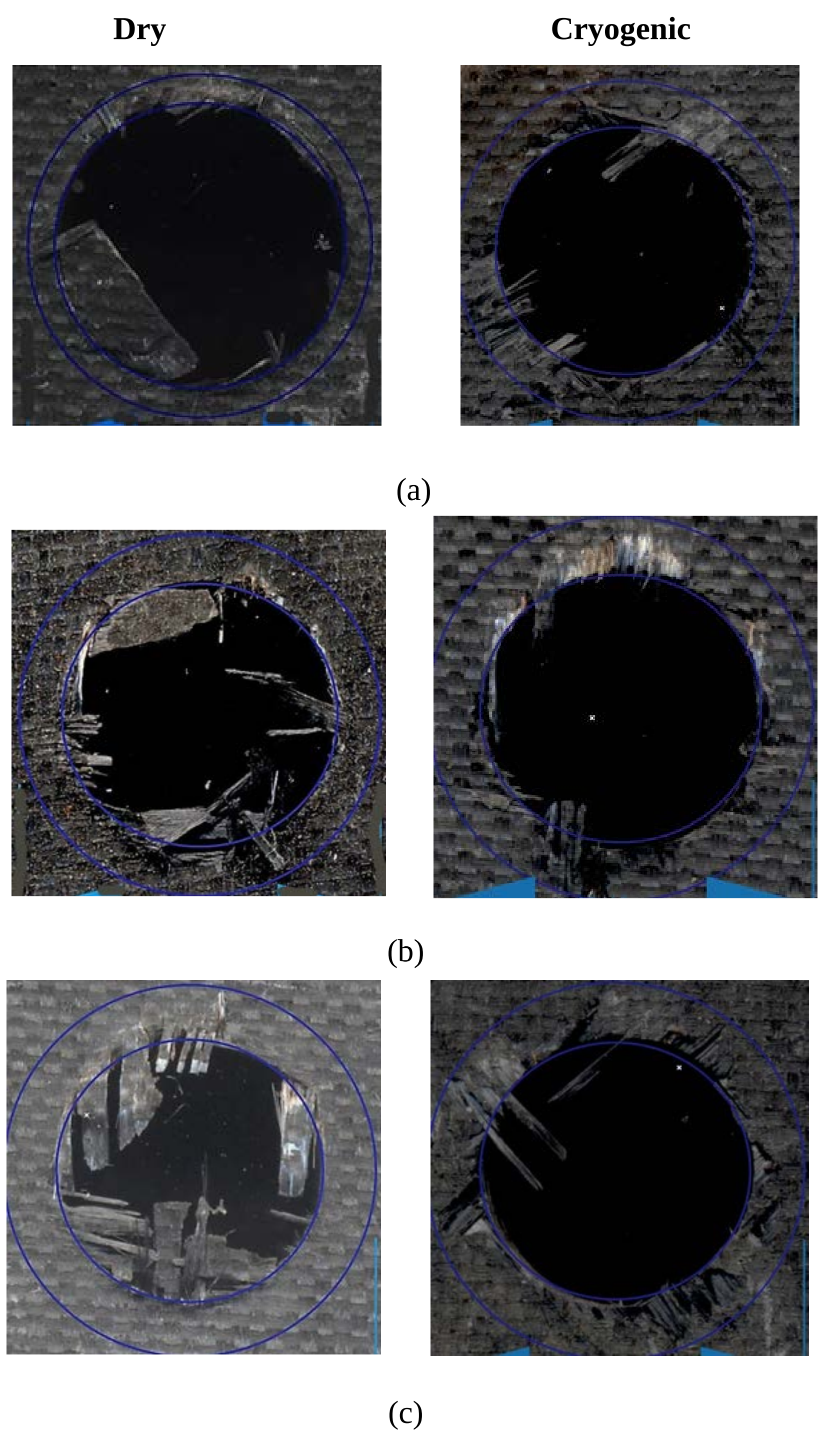
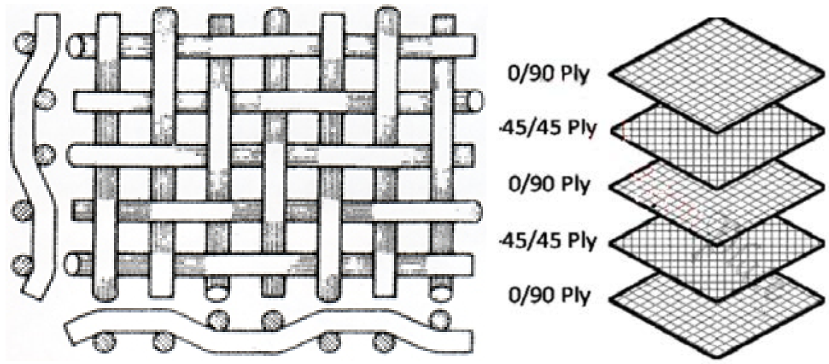


Figure 5.13: Burr generation for: (a) Hole number 30; (b) Hole number 40; and (c) Hole number 50.

5.4 Analysis of Borehole Sub-surface Damage in Drilling of CFRP Materials

An analysis of the cause of damage in drilled CFRP has been made in this study. Micrographs at boreholes were taken selecting the specimens at different cutting speeds, feed rates and cooling methods.

The workpiece material in this study is 2x2 twill quasi-isotropic CFRP laminates. 2x2 twill is a common pattern for woven CFRP laminates as shown in Figure 5.14 (a). And, as we discussed in the previous section, CFRP material is an isotropic material. Although woven CFRP composite is more advanced in terms of isotropy compared with unidirectional CFRP composite, it is still necessary to come up with a better approach to improve the performance of CFRP materials. Figure 5.14 (b) shows the method of preparing quasi-isotropic CFRP laminates. With different fiber orientation in each layer, the isotropy of CFRP materials is significantly improved.



(a) (b)

Figure 5.14: Information of workpiece: (a) 2x2 twill pattern [32];
(b) quasi-isotropic lay-up.

Drilled boreholes were cut in halves and samples were prepared using cold mounting method in case the heat of hot mounting method induces thermal damage to the sample. Typical cross-section area observed is as shown in Figure 5.15. The white part in the picture is carbon fiber; the dark part is matrix material. As mentioned, the material in this study is quasi-isotropic CFRP laminates, and there are three different oriented layers in the picture marked in Figure 5.16 as section A, B, C which refers to the direction of fiber 0, -45°/ 45°, 90°, respectively.

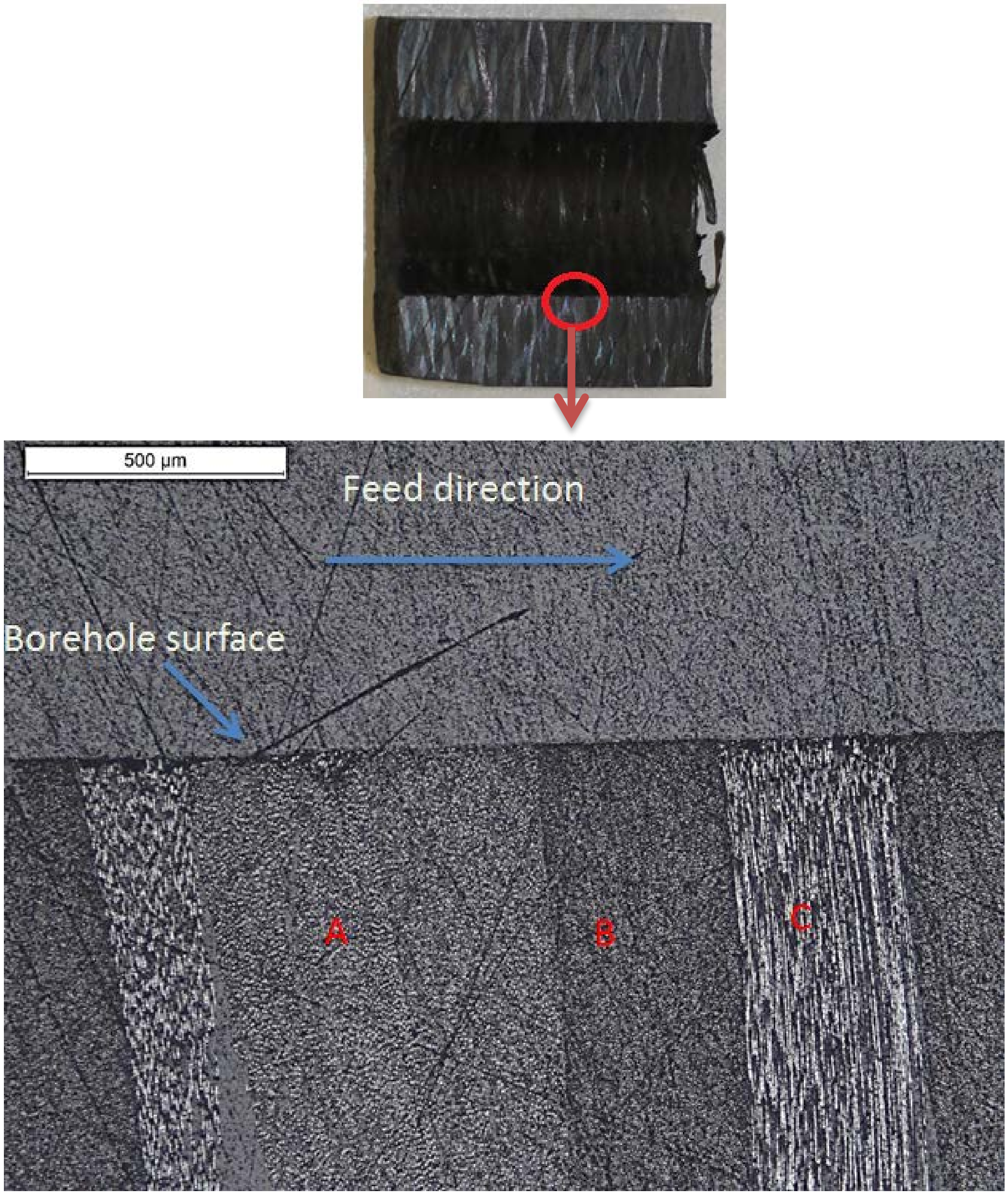
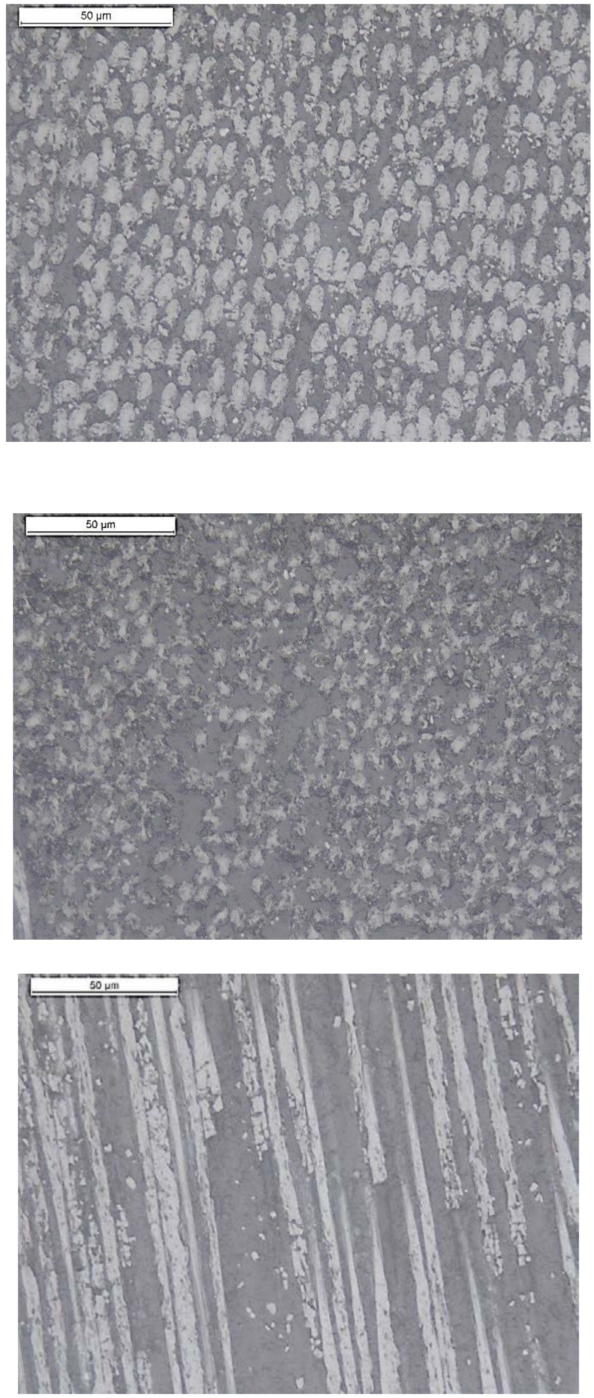


Figure 5.15: Cross-section image of samples.



(a)

(b)

(c)

Figure 5.16: carbon fiber with direction of: (a) 0°; (b) -45°/ 45°; (c) 90°.

A comparison has been made for images at cutting speed of 60 m/min and feed rate of 0.05 mm/rev under cryogenic and dry cooling methods. As shown in Figure 5.17, no surface cracks and other obvious damage could be found in the sample under cryogenic drilling. Both fibers and matrix material were clearly cut by the drill bit. However, in the image of sample cut in dry drilling, the cross-section shows clearly damage of the composite structure. There were cracks down to a depth of more than 100 µm. There was no matrix material melting, but a thermal damage was found.

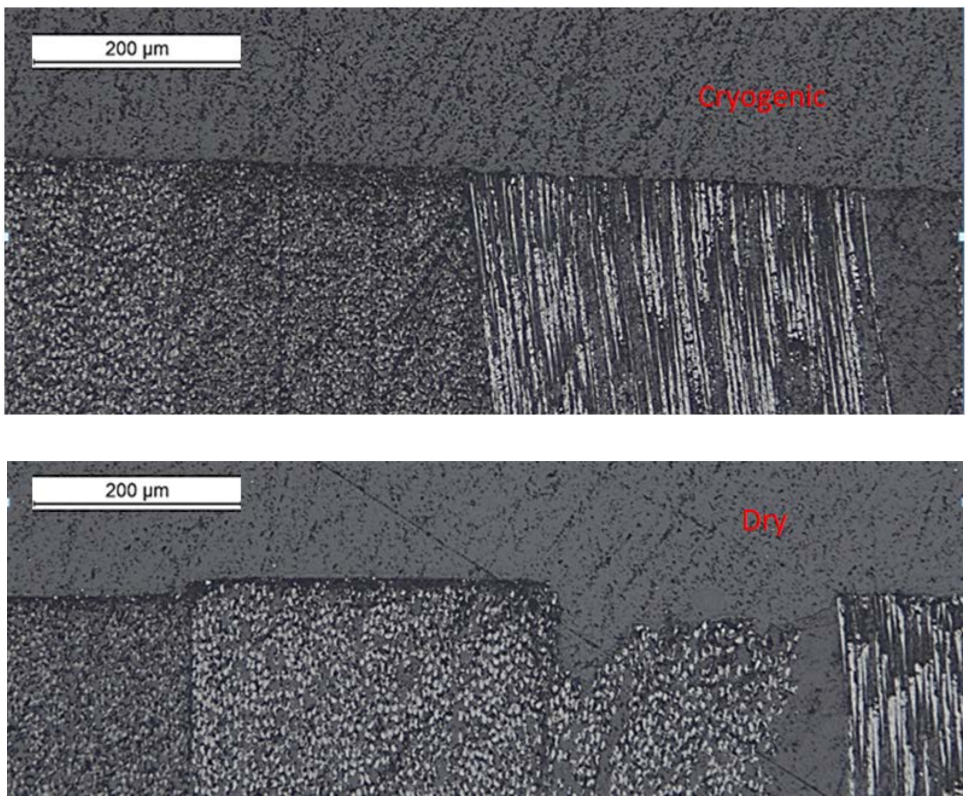


Figure 5.17: Cross-section image of samples machined at *f* = 0.05 mm/rev and *V* = 60 m/min under cryogenic and dry cooling methods.

Both cutting temperature and thrust force can affect the CFRP structure negatively. Figure 5.18 shows the borehole sub-surface for the largest feed rate with the lowest cutting speed (*f* = 0.05 mm/rev and *V* = 40 m/min) under cryogenic cooling, thus the largest thrust forces and the lowest temperature respectively. Under the machining condition mentioned above, borehole surface was smooth and had a sharp edge. No obvious damages can be detected, but near the surface the fibers bending was found in cutting direction.

Fig. 5.14 shows the sub-surface image of borehole No. 10 and No. 50 for the lowest feed rate with the highest cutting speed (*f* = 0.025 mm/rev and *V* = 60 m/min) under dry drilling, therefore the lowest thrust force and the highest cutting temperature. Not only was the crack observed, but it is seen to be continually growing as the drilling process proceeded. The depth of crack for borehole No. 10 and No. 50 are 134 µm and 174 µm respectively. The increase of crack depth may be due to the fact that drill bits became dull during the drilling, and could not cut effectively.

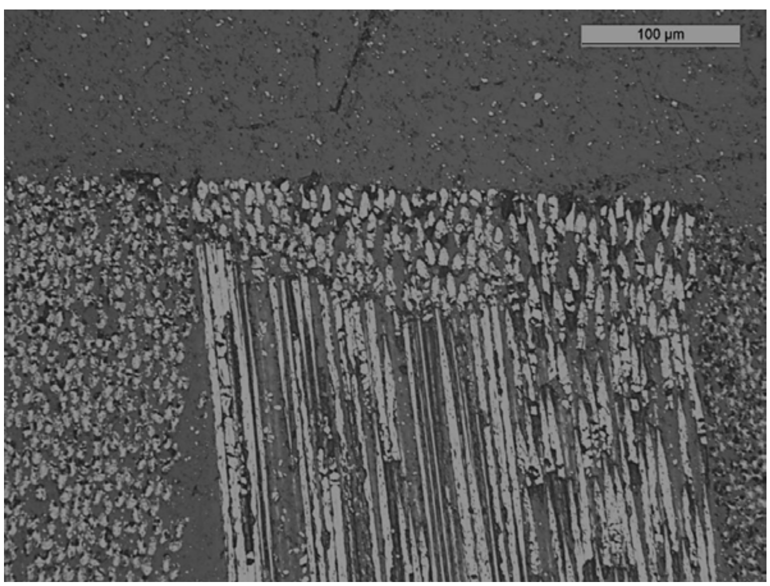
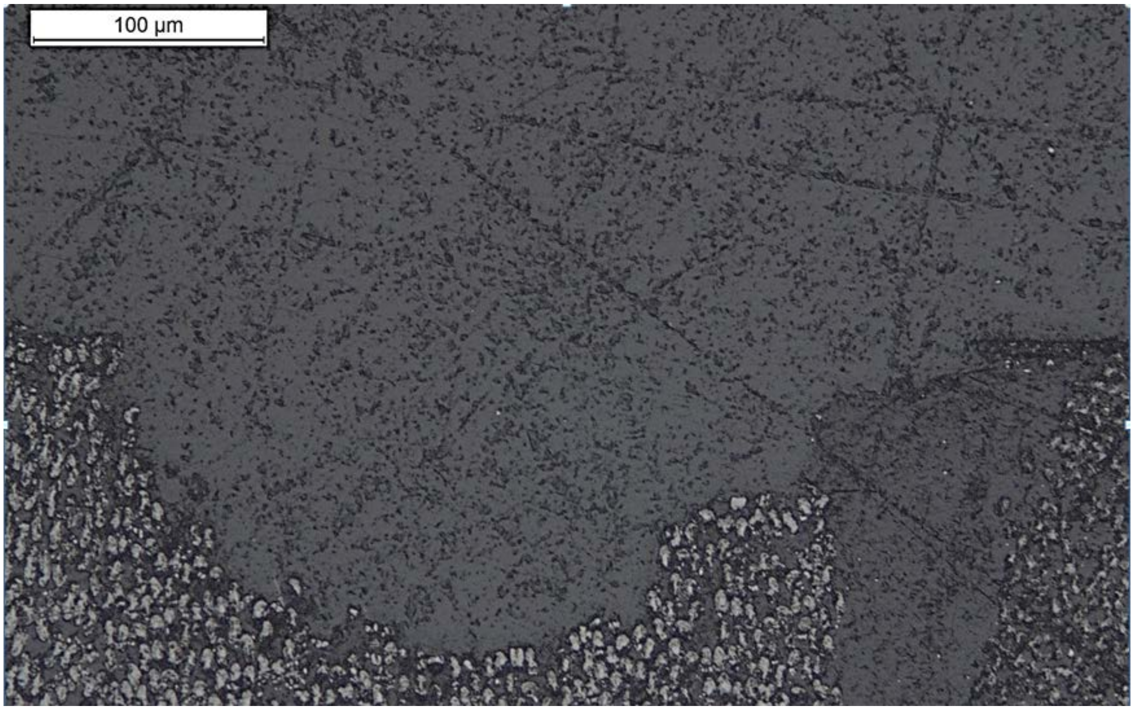
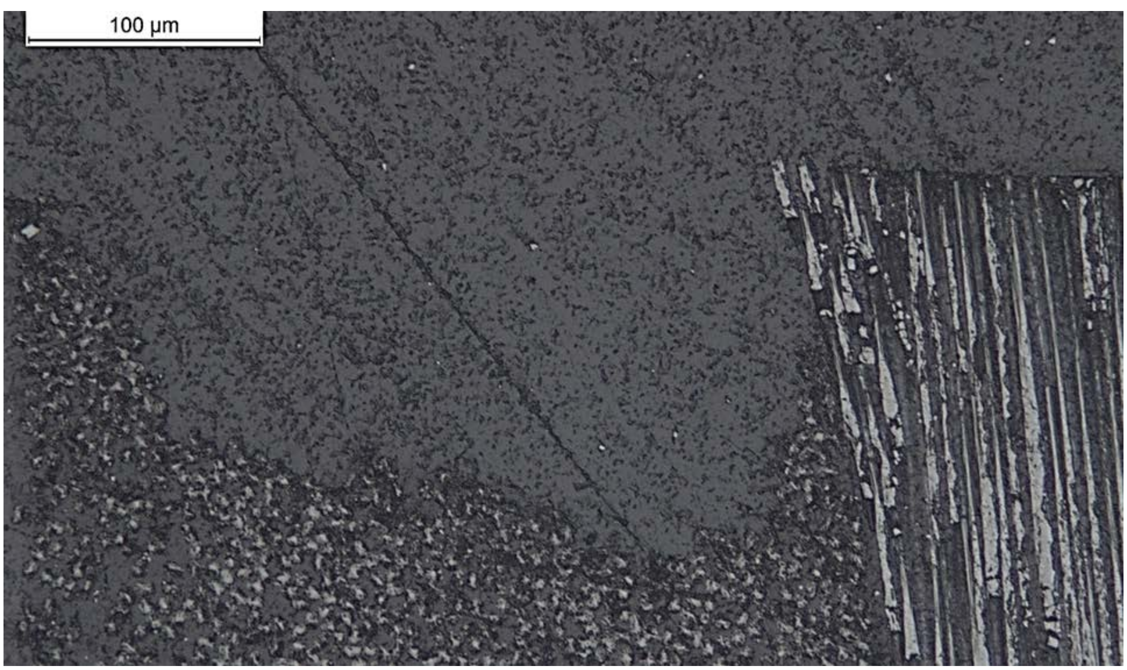


Figure 5.18: Cross-section image of hole at *f* = 0.05 mm/rev and *V* = 40 m/min under cryogenic cooling.



(a)



(b)

Figure 5.19: Cross-section image of hole at f = 0.05 mm/rev and V = 40 m/min under cryogenic cooling: (a) Hole No 10; (b) Hole No 50.

5.5 Surface Roughness

Figure 5.16 shows the surface roughness (R_a) at different cutting parameters under dry and cryogenic conditions. Surface roughness ranges from 0.53 μm to 0.78 μm under dry condition. The application of liquid nitrogen led to much better surface roughness. The surface roughness is reduced from 0.35 μm to 0.23 μm after cryogenic drilling. A large deviation of surface roughness is shown in dry drilling compared with cryogenic drilling. The surface roughness of CFRP drilled hole could give some indication on the level of damage of the produced hole in terms of fiber pullout, fiber fuzziness and crack. Crack observed in the sub-surface of borehole machined under dry condition could be the reason for poor surface finish in dry drilling. The results also could be correlated to the tool-wear result presented in Chapter 3, since that machining with larger edge radius tools increased the surface roughness as blunt tools induced more pushing and tearing of the fiber and heat generation. Cryogenic cooling maintains the sharpness of the drill bit, which led to a better surface finish. Both cutting speed and feed rate influence surface roughness negatively although an increase in surface roughness is more significant with the increase in feed rate.

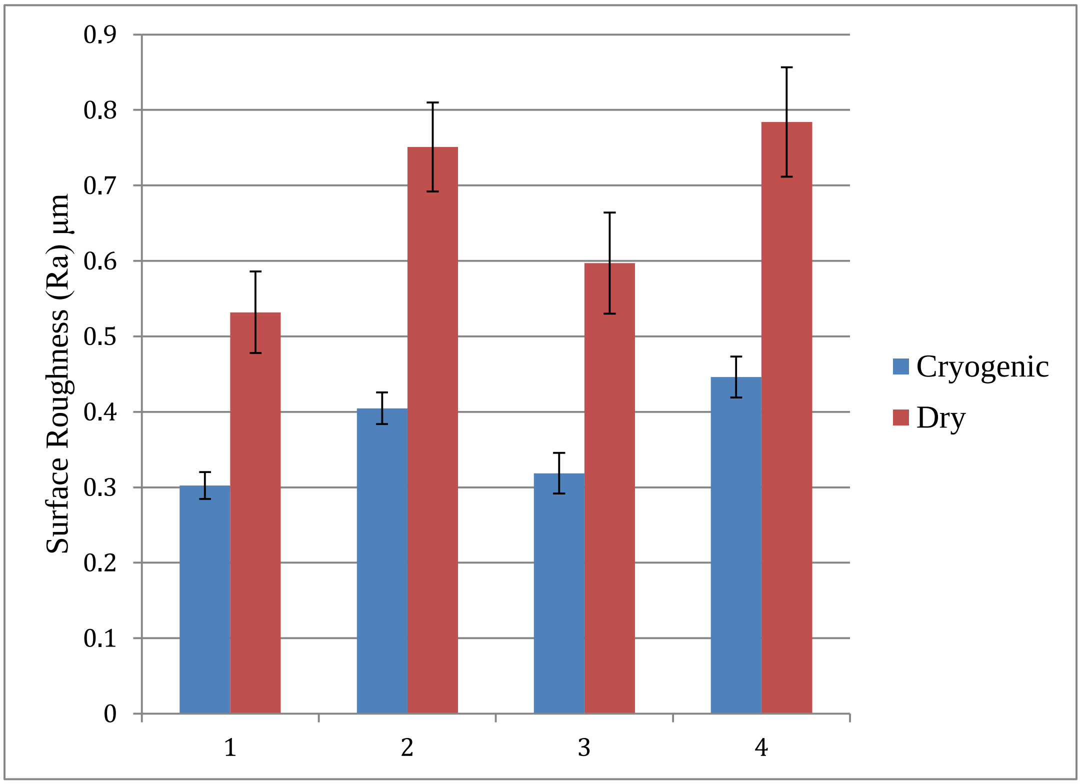


Figure 5.20: Average surface roughness (R_a) for tests at: Figure 4.11: Average maximum thrust force at: (a) f = 0.025 mm/rev, V = 40 m/min; (b) f = 0.05 mm/rev, V = 40 m/min; (c) f = 0.025 mm/rev, V = 60 m/min; and (d) f = 0.05 mm/rev, V = 60 m/min;

5.6 Diameter Error

The drilled hole diameter was measured using a CMM machine. The thickness of the CFRP laminate is around 18 mm. In order to have a better idea of the shape of the borehole, the diameter was measured every 2 mm along the drilling path, and therefore for each borehole there were 8 different measurements, and for each measurement (or each depth) 10 points were taken by the CMM probe in order to get more accurate results.

As shown in Figures 5.17 and 5.18, all holes feature oversize under any machining parameters. Borehole under dry condition tends to be larger since a higher cutting temperature in dry drilling leads to more severe expansion of the drill bit. The diameter of borehole continually increased, and then dropped after the drill went through half of the thickness of the laminate, due to the barreling effect. On the contrary, borehole under cryogenic drilling was closer to the drill diameter and more consistent, since liquid nitrogen carried away a lot of heat, and thus the drill bit did not expend as much as in dry drilling.

It is also noticeable that the diameter decreased with the increase of drill hole number and borehole in cryogenic drilling declined less. This trend agrees with the finding from tool-wear results presented in Chapter 4.

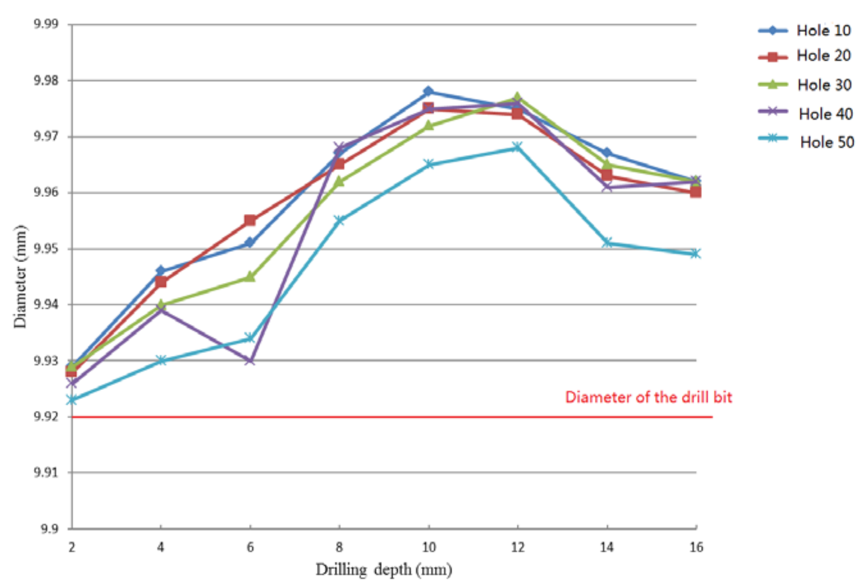


Figure 5.21: Diameter of boreholes at V = 60 m/min, f = 0.05 mm/rev, dry cooling condition.

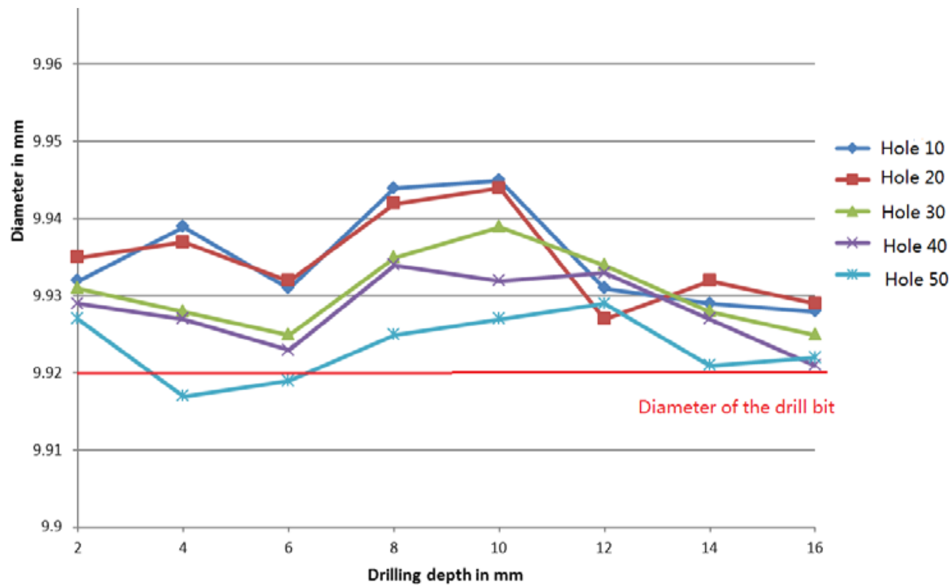


Figure 5.22: Diameter of boreholes at $V = 60$ m/min, $f = 0.05$ mm/rev, cryogenic cooling condition.

5.7 Summary

The influences of drilling, under both dry and cryogenic conditions on several aspects of hole quality and surface integrity, were investigated, including delamination, burr generation, sub-surface damage, diameter error, and surface roughness. Major observations can be summarized as follows:

- Delamination in cryogenic drilling is more severe than in dry drilling due to the higher thrust force. Delamination grows faster in dry drilling because of the rapid increase in cutting edge radius. Back-up material has been proved to be a practical approach to minimize delamination in cryogenic drilling to an acceptable level.
- Excessive burr generation has been found in dry drilling due to the higher outer

corner wear.

- Both thrust force and cutting temperature have influences on sub-surface quality. Borehole under cryogenic cooling features sharp edge, without crack, but with fiber bending; meanwhile, surface deviation, crack, and other thermal damage have been found in borehole drilled under dry condition.
- Surface Roughness (R_a) is significantly improved by cryogenic cooling for the reason that liquid nitrogen not only can keep the sharpness of drill bit, but also helps to carry away the heat generated in the drilling process to avoid thermal damage to the surface.
- Borehole under cryogenic drilling has less diameter error, because the diameter is more consistent at every depth of the borehole. Also, because of the better tool-wear performance, diameter of borehole under cryogenic drilling does not declines as much as under dry condition.

CHAPTER 6: CONCLUSIONS AND FUTURE WORK

6.1 Summary of Present Work

In this thesis work, experimental studies on the influence of various machining conditions (cooling methods and cutting parameters) on the drilling performance of CFRP composite, including tool-wear performance, thrust force and torque, hole quality and surface integrity of the borehole, etc., have been conducted. The benefits of cryogenic cooling for machining metal were reported frequently in the literature, while cryogenic drilling of CFRP laminate was barely investigated, and this is the main focus for this research work.

In addition to the experimental work, an analytical approach for predicting the critical thrust force for drilling operation has been carried out. The following major conclusions can be drawn from this research work:

- Significant reduction of cutting temperature by supplying liquid nitrogen through coolant hole of the drill bit onto the tool-workpiece interface improves tool-wear performance in cryogenic drilling, in terms of having a lower cutting edge radius and outer corner wear compared with dry drilling. Increase of cutting speed and feed rate led to marginal elevation of cutting edge radius and outer corner wear.
- Both thrust force and torque were larger in cryogenic drilling than in dry drilling due

to the fact that cryogenic cooling increases the strength of the workpice and makes the material harder to drill. Thrust force and torque increased with increasing feed rate, meanwhile both thrust force and torque decreased with increasing cutting speed.

- An analytical model has been used to predict critical thrust force. In order to achieve borehole with no delamination, the applied thrust force should not exceed this value.
- Delamination in cryogenic drilling is more severe than in dry drilling due to the higher thrust force. Delamination grows faster in dry drilling because of the rapid increase of cutting edge radius. Back-up material has been proven as a practical approach to minimize delamination in cryogenic drilling to an acceptable level.
- Excessive burr generation has been found in dry drilling due to higher outer corner wear.
- Both thrust force and cutting temperature have an influence on sub-surface quality. Borehole under cryogenic cooling features sharp edge without crack, but with fiber bending. Meanwhile, surface deviation, crack, and other thermal damage have been found in borehole drilled under dry condition.
- The application of liquid nitrogen dramatically improved surface roughness (R_a) since cryogenic cooling is not only able to keep the sharpness of drill bit, but it also carries away the heat generated in the drilling process to avoid thermal damage to the surface.
- Borehole under cryogenic drilling has less diameter error in terms of consistency of

hole diameter in different depth. It is also notable that the diameter of borehole under cryogenic drilling does not decline as much as under dry condition

6.2 Future Work

There has been a substantial increase in the study of drilling of CFRP materials recently, and it is a promising research area from the application point of view. Because there are so many variables involved in drilling of CFRP material, countless research could be conducted. Further research work in machining of CFRP materials could include: the effects of drill bit grade and coatings, cutting temperature measurement, more systematical study of the effect of cutting parameters on the drilling performance, etc.

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