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ANALYSIS OF SURFACE INTEGRITY IN MACHINING OF CFRP UNDER DIFFERENT COOLING CONDITIONS

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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

Arjun Nagaraj

Lexington, Kentucky

Director: Dr. I.S. Jawahir, Professor of Mechanical Engineering

Lexington, Kentucky

2019

ABSTRACT OF THESIS

ANALYSIS OF SURFACE INTEGRITY IN MACHINING OF CFRP UNDER DIFFERENT COOLING CONDITIONS

Carbon Fiber Reinforced Polymers (CFRP) are a class of advanced materials widely used in versatile applications including aerospace and automotive industries due to their exceptional physical and mechanical properties. Owing to the heterogenous nature of the composites, it is often a challenging task to machine them unlike metals. Drilling in particular, the most commonly used process for component assembly is critical especially in the aerospace sector which demands parts of highest quality and surface integrity.

Conventionally, all composites are machined under dry conditions. While there are drawbacks related to dry drilling, for example, poor surface roughness, there is a need to develop processes which yield good quality parts. This thesis investigates the machining performance when drilling CFRP under cryogenic, MQL and hybrid (CryoMQL) modes and comparing with dry drilling in terms of the machining forces, delamination, diameter error and surface integrity assessment including surface roughness, hardness and sub-surface damage analysis. Additionally, the effect of varying the feed rate on the machining performance is examined. From the study, it is concluded that drilling using coolant/ lubricant outperforms dry drilling by producing better quality parts. Also, varying the feed rate proved to be advantageous over drilling at constant feed.

KEYWORDS: CFRP composite, hybrid (CryoMQL) drilling, variable feed rate, hole quality, surface integrity

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8/5/2019

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To my family

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CHAPTER 1

INTRODUCTION

1.1 Background

Carbon Fiber Reinforced Polymers (CFRPs) are a class of composite materials consisting of a reinforcement (carbon fiber) bonded by a matrix which is generally a polymer resin like epoxy. CFRP has a wide variety of applications in the field of aerospace, construction, transportation, and medical applications owing to its superior properties like high strength-to-weight ratio, great modulus-to-weight ratio, good damage tolerance, excellent fatigue and corrosion resistance (Dandekar and Shin, 2012). For instance, Gilpin. (2009) claims that 50% of the Boeing 787 Dreamliner commercial aircraft is composite by weight. One of the biggest advantages of CFRP is that with the selection of an appropriate combination of the matrix and reinforcement, any required property can be obtained for use in versatile applications (Dandekar and Shin, 2012).

Any product or component made of CFRP often requires secondary machining processes with drilling being the most frequently carried out process amongst them. However, due to the inhomogeneous nature of the composites, it is often challenging to machine CFRPs; unlike metals or alloys. Interactions between the matrix and reinforcement during machining are different from metals due to the distinguished mechanical and thermal properties exhibited by the two phases of materials (Bagci and Işık, 2006).

One of the challenges faced by the composite manufacturing industries is tool wear when machining CFRP. Due to the abrasive nature and thermal resistance offered by the material, the cutting tools experience a relatively more hazardous environment and undergo thermal associated wear processes (Sreejith et al., 2000). The result of tool wear on drilling of CFRPs affects the quality of drilled holes.

Apart from tool wear, the anisotropic and non-homogenous properties of CFRP results in various defects when drilling, such as fiber breakage, fiber pull-out, matrix cracking, fiber-matrix debonding, thermal degradation, spalling and delamination (Arul et al. 2006). Among the defects, delamination, which is the separation of layers in the composite is the most critical defect that occurs when drilling composites and it results in decreasing the bearing strength of the material (Tagliaferri et al. 1990). It is estimated that about 60% of the parts produced in the composite manufacturing industry are rejected due to poor-quality holes produced (Capello et al. 2008).

The quality of the drilled holes depend on factors like cutting parameters, tool geometry, tool types and cutting conditions (Abrão et al., 2007). By proper selection of the above factors, a higher magnitude of borehole quality can be obtained.

In drilling the composites, apart from considering the above parameters that influence the thrust force and torque effects, the thermal effect also needs to be considered. Due to the low thermal conductivity of the material, the cutting zone and the tool will be subjected to high temperatures that would affect the tool-life and the quality of the hole. Chatterjee (2009), explained that the temperature is high enough to cause resin degradation while significantly reducing the strength of the material.

Conventionally, drilling of composites is carried out in dry conditions or without any coolant as reported by many researchers. However, few researchers have shown positive results with the use of liquid coolant (Shyha et al., 2011). Furthermore, Xia et al. (2016), studied the effects of cryogenic cooling on the drilling of CFRP and demonstrated better drilling performance with respect to tool wear, surface roughness and diameter error.

Considering the large scale application of CFRP in the world today, there is a need to develop and implement sophisticated machining process to satisfy the required product quality and performance. This study aims at investigating various drilling processes which can improve the product performance and meet the defined quality aspects.

1.2 Thesis organization

- Chapter 2 presents a literature review on the drilling of CFRP that provides a comprehensive study of the past research in the area.
- Chapter 3 presents a brief description of the material used, the experimental setup, and procedures followed during the drilling process.
- Chapter 4 presents a discussion on the measurements of thrust force and torque under various cutting and cooling conditions along with a comprehensive evaluation of delamination and surface integrity of the drilled workpiece.
- Chapter 5 discusses the summary and conclusions of this research work with a brief discussion of future work that can be conducted in the drilling of CFRP material.

CHAPTER 2

LITERATURE REVIEW

Machining of CFRP is a challenging task and there are numerous studies available about machining, in particular, the drilling of CFRP. To understand the basics of machining of CFRP, an overview of the drilling process is presented. Successively, factors affecting the part quality of drilled holes like cutting parameters, tool geometry, cutting conditions, etc., will be discussed.

2.1 Machining of CFRP

As already stated, drilling is the most commonly carried out machining process on CFRPs in industries. Due to the heterogeneous nature of the composite, fibers take up a large portion of the load while machining, causing a series of fractures in the material (Bhattacharyya and Horrigan, 1998). Unlike shearing, which is the cause of chip formation in metals, bending failure regulates the chip formation in CFRP (Pwu and Hocheng, 1998), making the machining process quite challenging. This is further augmented by the anisotropic and non-homogeneous nature of the material which creates problems in the form of defects and tool wear. The machinability of CFRP depends on various factors including material properties, tool material and its geometry, cutting parameter selection, the effects due to thrust force and torque, etc.

2.1.1 Material properties and their effects

Apart from parameters like cutting conditions, material properties play a role in the machining performance of CFRPs. The properties of the material depend on the volume and orientation of the fiber (Setunge).

In addition, fibers can be unidirectional i.e. arranged in a single direction, or oriented perpendicular to each other, called bidirectional or randomly oriented fibers.

The load taking capability of a composite depends on the fiber orientation which decides the type of load it can withstand as shown in Figure 2.1. For instance, ply orientation of 0° responds to axial loads, plies of 90° orientation are more reactive to side loads and those at ±45° react to shear loads (Altin Karataş and Gökkaya, 2018).

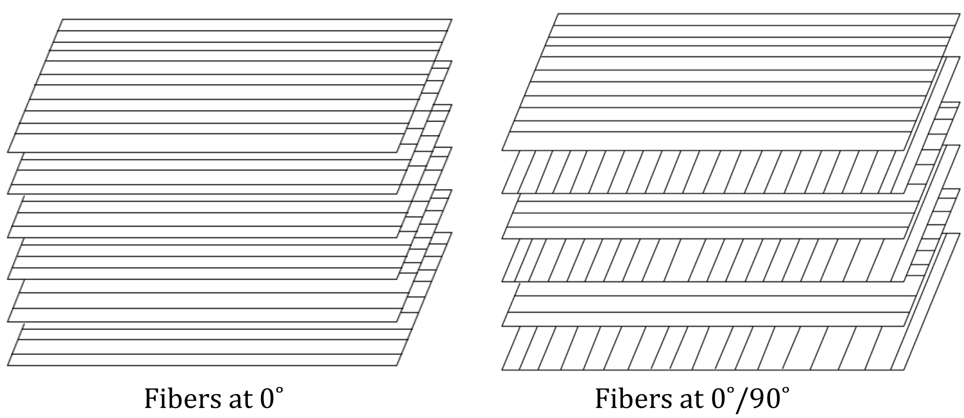


Figure 2.1 Ply orientation in composites

2.1.2 Tool material and its geometry

While metals are good conductors of heat, composites are thermal insulators. In addition, the abrasive nature poses a challenge for the cutting tool to maintain its performance. As a result, the tool used for machining should have high resistance to abrasion along with good hardness.

Figure 2.2 shows the results of a survey pertaining to the tools used in drilling polymeric composites. Traditionally, tool materials that are used for machining CFRPs include High-Speed Steel (HSS), cemented carbides, coated carbides and ceramics (Santhanakrishnan et al., 1989). Additionally, the usage of other tool materials like PCD, CBN, and diamond-like coated tools have been reported to produce good quality parts (Panchagnula and Palaniyandi, 2018).

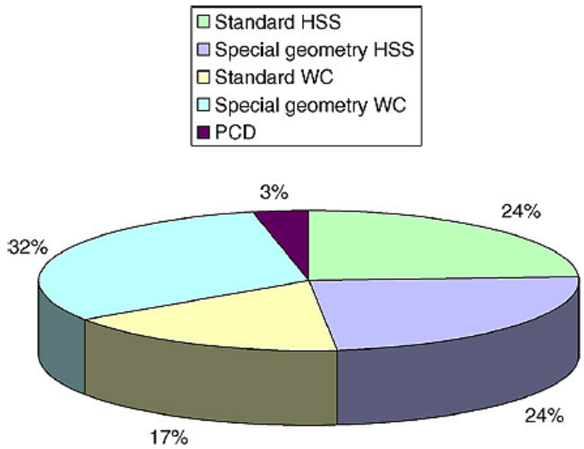


Figure 2.2 Tool materials used in drilling polymeric composites (Abrão et al., 2007)

As seen from the figure, both HSS and WC tools are used to the same extent. However, the use of HSS tools is not a feasible option for composite industries. This is mainly because of their poor heat resistance and high wear rate. While an HSS drill can machine hundreds of holes in carbon steel before wearing out, it may last for a minimum of ten holes in CFRPs owing to the abrasive nature of the composite, which further increases with the fiber volume fraction (Capello et al., 2008). Even though coated HSS performs better initially, it deteriorates the quality of parts eventually. Arul et al. (2006), justified this anomaly on the basis of heat accumulation that spalls off the coating causing the tool to degrade. Hence, they concluded that coated HSS drills don't cause any big improvements in drilling composites.

Contrary to HSS tools, carbide tools possess higher hardness and better wear resistance. Apart from these advantages, carbide tools are cost-effective for industries as well. Moreover, carbide tools can be coated with materials like tungsten to increase its surface hardness, thereby protecting the carbide matrix and even lubricity can be increased for better chip removal (Black, 2004). Davim and Reis (2003), showed in their research that carbide drills exhibit better performance than HSS drills both in terms of delamination and tool wear progression. As far as the selection of machining parameters is concerned, Abrao et al., (2007) reported that carbide tools are preferred for higher cutting speeds and feeds than HSS tools as shown in Figure 2.3. Usually when drilling polymeric composites, cutting speeds from 20 to 60 m/min are employed with feed rate values lower than 0.3 mm/rev, as seen in the figure. The cutting speed is kept below 60 m/min since higher values lead to higher cutting temperature and in turn, causes softening of the matrix. The use of feed rate below 0.3 mm/rev may be associated with the increase in delamination damage with the increasing value of the feed.

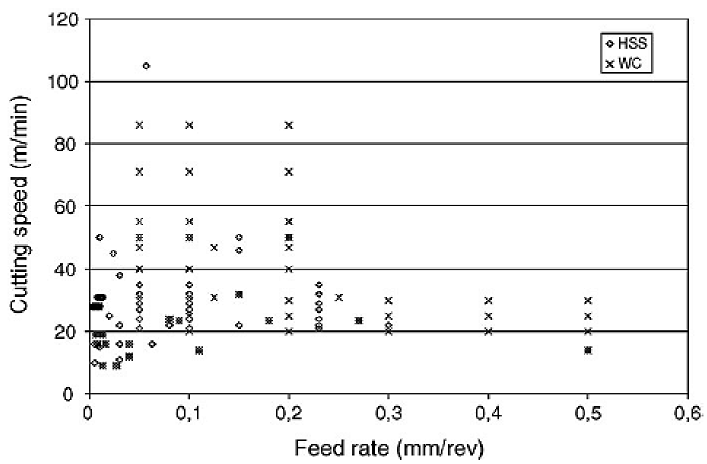


Figure 2.3 Cutting parameters typically followed when drilling composites using HSS and WC drills (Abrão et al., 2007)

PCD tools are another class of materials having a combination of high abrasion resistance, thermal conductivity, hardness, and impact toughness (Karpat et al., 2014). In a study of drilling composite materials involving HSS, carbide and PCD drills, Ramulu et al., (1999) claimed that the PCD drill produces the highest quality holes with least wear. Even though PCD tools deliver better quality parts, it is rarely used because of its cost. Gilpin (2009) stated that the unit cost of a PCD tool is about 6-10 times that of a carbide tool. However, where wear resistance is of primary importance, PCD is always the best choice.

Apart from the tool material, tool geometry also plays an important role in the machining quality of CFRP parts. Durão et al. (2010), claimed that for delamination, the indentation effect caused by quasi-stationary drill chisel edge is the main mechanism which can be minimized by proper selection of tool geometry along with the cutting parameters. In their work, five WC drills of 6 mm diameter have been used; i) 85° twist drill, ii) 120° twist drill, iii) Brad, iv) Dagger and v) step drill. The 120° twist drill along with the step drill is reported to give better results when it comes to delamination among the other tools. In a similar study conducted by Davim and Reis (2003), using 5 mm diameter, 118° - helical flute HSS, a four flute cemented carbide, and a helical flute carbide drills, the helical flute carbide drill provided better performance than the other two drills in terms of delamination. Also, chisel edge geometry affects thrust force induced in the material – shorter the chisel edge length, lower is its contribution to the thrust force (Melentiev et al.,2016).

Compared to twist drills, use of candle-stick drills has proven to show better results. Tsao and Hocheng(2005), reported that candlestick drills provide better results in terms of delamination compared to twist and saw drills. Other special geometry drills like dagger drills, core drills, and step drills have shown to provide better quality holes by Hocheng and Tsao (2006) and Durão et al. (2005). This is justified because of their ability to operate at higher threshold feed rate at the onset of delamination and the thrust force exerted by the drill will be distributed toward the periphery than at hole center (Hocheng and Tsao, 2006). In another study conducted by Shyha et al. (2009), it was reported that the tool-life can be increased with the use of stepped drills.

The thrust force can be reduced either by drilling at low feed or by altering the tool geometry. The disadvantage of adopting low feed drilling is that it reduces the production rate. Therefore, an alternate choice of altering the tool geometry would be a feasible option to minimize the thrust force developed. Among various parameters concerning the tool geometry, chisel edge and point angle have been determined to play a major role in the development of thrust force during drilling of composites (Velayudham and Krishnamurthy, 2007). For instance, Jain and Yang (1993) claimed that the chisel edge contributes up to 40-60 % to the thrust force. Other researchers like Langella et al. (2005) and Won and Dharan (2002) reported that the contribution of chisel edge was even more at higher feed rates.

As far as the point angle of the drill is concerned, a significant amount of research has been done to validate that effect. Although Senthilkumar et al. (2013) claimed that larger point angle drill lead to better chip evacuation and less tool wear, other researchers validated that lesser the point angle, better is the part quality. For instance, Heisel and Pfeifroth(2012), in their work proved that elevated point angle drills increase the thrust force. Furthermore, it is evident from their work that point angles higher than 180° gives the best quality holes at the entrance side but impairs exit hole quality. Another study conducted by Gaitonde et al. (2008), showed that a combination of low feed rate along with point angle minimize delamination defects when drilling CFRP.

2.1.3 Thrust force and torque

The quality of the part produced relies on the thrust force and torque generated during the drilling operation. Since delamination depends on thrust force, it is of utmost importance to minimize the generated thrust force. Tsao and Hocheng (2005), showed that there is a critical thrust force below which there is no delamination.

Figure 2.4 shows the trend of thrust force relative to time. Due to the pushing action involved during the process, it is seen that the thrust force usually remains positive. A gradual increase in the thrust force can be seen as the tool engages the workpiece followed by a constant trend as it descends down the workpiece. The thrust force then rapidly decreases, sometimes causing a negative force as the drill exits the workpiece (Capello et al., 2008).

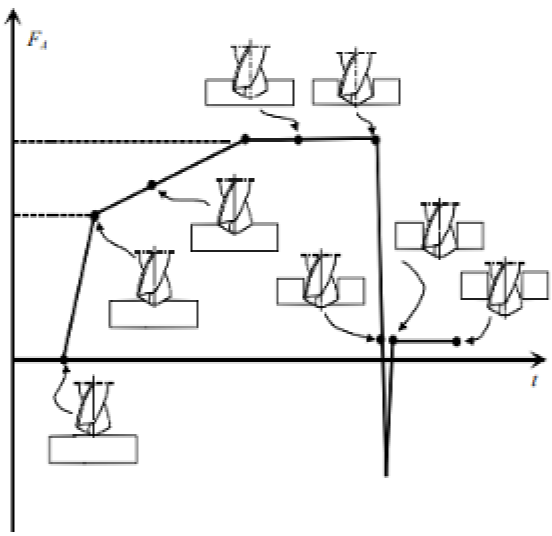


Figure 2.4 General trend of the thrust force as a function of drilling time (Capello et al., 2008)

It was reported by Bhattacharyya and Horrigan(1998), that thrust force is directly dependent on feed rate and tool geometry. It was found that the thrust force increases with increasing feed rate whereas the cutting speed barely affected it (Abrao et al., 2008). However, no significant effect of cutting speed on the thrust force in dry drilling is observed due to the absence of work hardening, unlike metals. Apart from the feed rate, the chisel edge plays a significant role in the development of thrust force in CFRPs. This is explained by Tsao and Hocheng (2003) where the chisel edge pushes the material ahead rather than cutting thereby increasing the thrust force. This effect was investigated by Won and Dharan (2002), and they developed a technique of pre-drilling a pilot hole in the composite with a diameter equal to the length of the chisel edge to reduce the thrust force developed. This is shown in Figure 2.5. It is seen that the thrust force can be reduced by 25-50% with the use of a pilot hole.

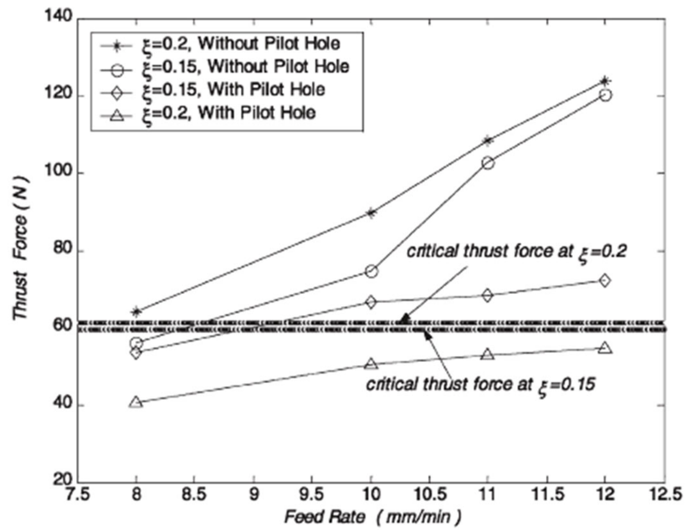


Figure 2.5 Effects of the pilot hole on thrust forces (drill diameter, 10 mm; ξ = 0.15 and 0.2) (Tsao and Hocheng, 2003)

In addition to the chisel edge, the point angle of the drill contributes to the thrust force as well. A study conducted by Singh et al. (2008), showed that a 90° drill induces less damage compared to 104° and 118° drills. In a similar study conducted by Shyha et al. (2009), it is seen that a 118° drill produced lower values of thrust force compared to the 140° drills. Even while using special drill bits, the thrust force is found to be lower. This is supported by Hocheng and Tsao (2006) in their study where core drill, candlestick drill, saw drill, and step drill outperform the twist drill. As seen in Figure 2.6, induced thrust force is the highest for twist drill and lowest for the candlestick drill and step drill.

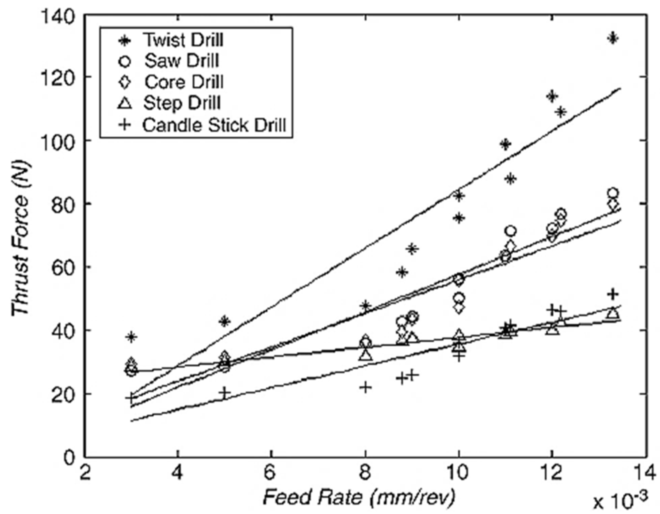


Figure 2.6 Correlation between thrust force and feed rate for special drills.
(Hocheng and Tsao, 2006)

Torque developed during the drilling process is mainly due to the horizontal forces generated during cutting. Unlike thrust force where drill type and feed rate are the main contributing factors, cutting speed and feed rate significantly affects the torque developed (Shyha et al., 2009).

Figure 2.7 shows the trend of torque relative to time. Initially, the torque increases linearly until it reaches T_i because of the cutting process. This increases further till T_{max} mainly due to friction between the tool and the part. The torque then gradually decreases when the drill cuts through the lower surface of the part and reaches T_m after which it remains constant (Capello et al., 2008).

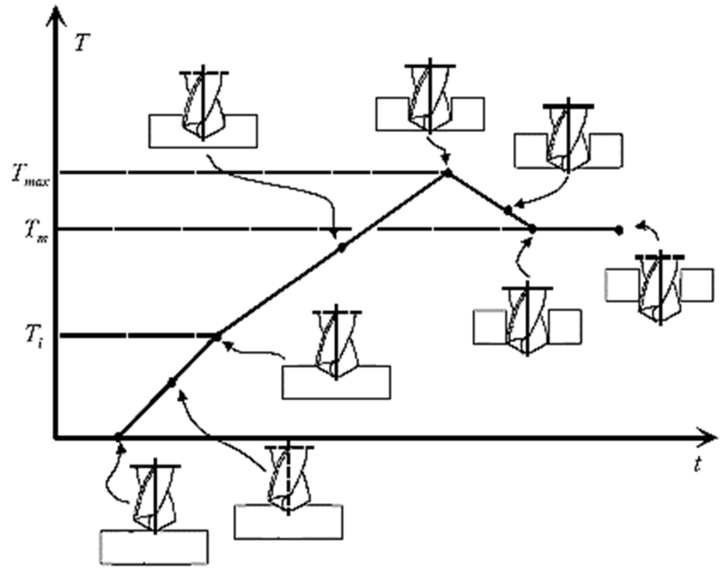


Figure 2.7 General trend of torque as a function of drilling time (Capello et al., 2008)

Torque generally depends on cutting speed, tool geometry and tool wear of the drill. A study conducted by Lin and Chen (1996), showed that with increase in cutting speed, the torque increases. However, the magnitude of increase is less compared to the thrust force. They further conveyed that twist drill produces more torque compared to a multifaceted drill at higher cutting speeds.

There is a mixed opinion on the effect of point angle on torque. A study conducted by Heisel and Pfeifroth (2012) with four different tool geometries showed that the variation in the values of torque with different point angles is marginal. Chen (1997), in his studies suggested that torque decreases with increasing point angle and helix angle. In addition, even with increase in the chisel edge rake angle, the values of torque seemed to decrease. However, in another study conducted by Velayudham and Krishnamurthy (2007) using three different tools showed that the reduction in point angle results in decreased values of torque.

With the increase of wear on the tool, torque value increases. This was proven by Murphy et al. (2002), in their study dealing with the effect of coatings on the performance of tungsten carbide drills in the drilling of CFRP. They found that the maximum torque is initiated when the outermost corner of the drill enters the workpiece and with wear, the tip of the tool induces maximum torque as evident from Figure 2.8.

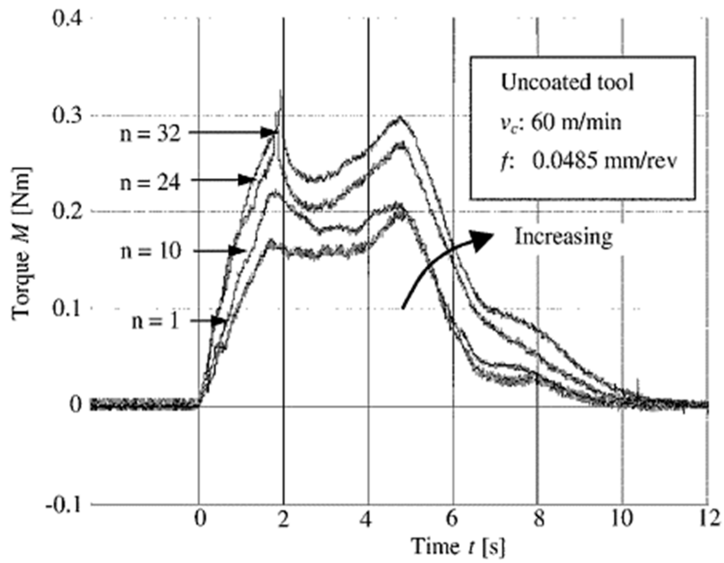


Figure 2.8 Variation in torque when using an uncoated tool to drill carbon-epoxy (Murphy et al., 2002)

Park et al. (2011), studied the mechanism of tool wear and its effect on torque when drilling composites. As per their study, increasing flank wear length increases the thrust forces induced while increasing edge wear length affects the torque developed. . This is because of the increase in area of contact as the cutting edge becomes blunter resulting in higher torque values.

2.1.4 Delamination

As previously mentioned, delamination is one of the most critical process induced defects in composites. It manifests in the form of plies separated from each other due to debonding of the material around the periphery of the drilled hole and along the direction of the fibers. It is classified into "peel-up delamination" which occurs at the hole entrance and "push-down delamination" that occurs at the hole exit.

Initially, when the drill comes in contact with the workpiece, the cutting edge will abrade the material of the composite. When the drill advances further, there will be a tendency of the abraded material to be pulled along the flute causing the material to spiral up before being cut. This results in creation of a pulling force which separates the upper plies of the laminate and is called peel-up delamination (Ho-Cheng and Dharan, 1990). Peel-up delamination is not always encountered. However, push-down delamination is the most common defect found in composites.

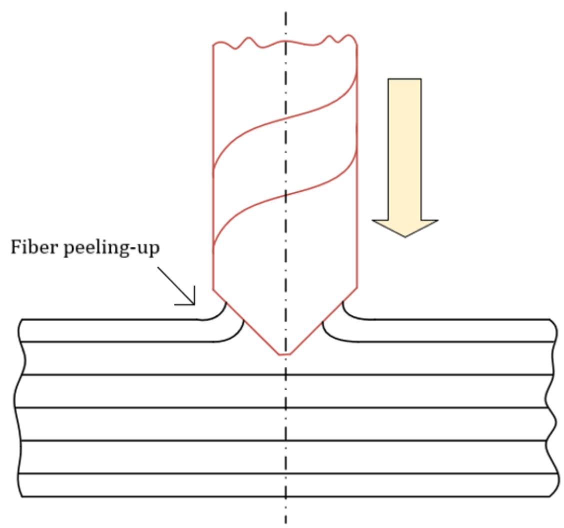


Figure 2.9 Peel-up delamination at the entrance

As shown in Figure 2.10, push-down delamination is developed in two phases viz., the chisel edge action phase and the cutting-edge action phase. The thrust force of the chisel edge reaches a critical value and ends with the chisel edge just penetrating the exit surface of the laminate which marks the beginning of the first phase. This is followed by the development of a small bulge in the vicinity of the drilling axis that spreads along the fiber direction. At a certain point, the surface layer splits open causing the chisel edge to penetrate and onsets the beginning of the second phase. The delamination from the first phase further develops due to the thrust force and torque from the cutting edge. This results in the formation of exit delamination. It is observed that the chisel edge generates over 50% of the thrust force because it cuts the material with a big negative rake angle. Hence, chisel edge plays an important role in the effort of eliminating delamination in composites (Zhang et al., 2001).

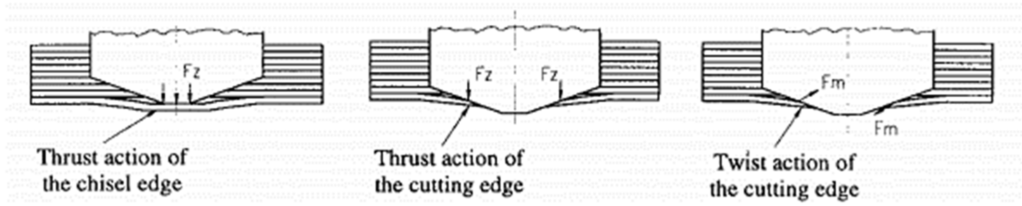


Figure 2.10 Schematic of the formation process of push-down delamination (Zhang et al., 2001)

Delamination is usually measured in terms of delamination factor F_d. It is defined as the ratio of the maximum diameter of the damaged zone D_{max} to the diameter of the hole D, as shown in Figure 2.11.

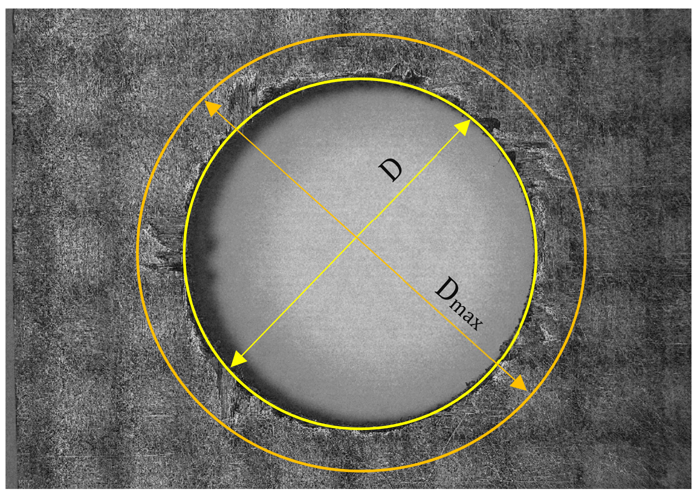


Figure 2.11 Measurement of the delamination factor

The factors affecting delamination are machining parameters and cutting tool geometry. There are numerous studies available regarding the effect of the above-said parameters on delamination.

2.1.4.1 Effect of machining parameters on delamination

Thrust force affects delamination to a great extent and itself depends on the machining parameters, especially the feed rate. There are mixed opinions about the effect of cutting speed on delamination. Davim and Reis (2003) in their study established a relationship between cutting speed, feed and delamination during drilling CFRP validating the increase in delamination with increasing cutting speed and feed. Zhang et al., (2001) in their study provided conclusions; delamination depends directly on the cutting speed and feed rate although cutting speed has a negligible effect and there exists a critical ratio of cutting speed to feed speed beyond which delamination can be minimized. Another study by Rubio et al.,(2008) showed that increasing spindle speed decreases the delamination. However, in another study by Tsao (2008) it was concluded that delamination increases with increasing feed rate and decreasing spindle speed.

2.1.4.2 Effect of tool geometry on delamination

Drill geometries like point angle and chisel edge affect the delamination induced in composites. As mentioned before, increasing the point angle of the drill increases the thrust force and hence delamination. There are numerous studies available where researchers have studied the effect of using different types of drill bits on delamination. One such study by Heisel and Pfeifroth (2012), involving the performance of 155°, 175°, 185° and 185° with the center tip of 178° tools, showed that increasing point angle of the drill results in lower entry delamination but higher exit delamination. In another study by Velayudham and Krishnamurthy (2007) using three drills of 118°, 85° and Brad and spur type carbide drills, it was determined that the special drill bit outperforms the other drill types in terms of delamination. Similar studies are available where different geometry drill bits like saw drills, core drills, step drills, etc., are used to study the performance with respect to delamination. However, most of them conclude that cutting speed and feed rate highly influence the delamination process in composites.

2.1.5 Cooling conditions

Most of the available work related to drilling CFRP is carried out under dry condition i.e., without using any coolant/lubricant. It is because of the notion that moisture affects the mechanical properties of composites (Turner et al., 2015). However due to the abrasive nature of CFRP, dry drilling results in shortened tool-life. Moreover, any machining process involves friction and generation of heat. CFRP, as it is being a low thermal conductor of heat, leads to thermal damage of the material during the machining process. Considering these factors, using cutting fluid improves the machining performance of the composites. Also, it is a well-known fact that the dust from CFRP machining is hazardous to human health which can be reduced by the fluids which trap those particles and prevents it from being scattered in the machining area.

There is a limited research on the effect of using cutting fluids in machining CFRP. It was reported that adopting MQL and cryogenic cooling benefits the performance of the machining process. Iskandar et al.,(2013) compared the performance of dry, MQL and flood cooling during routing of CFRP laminates. According to their study, MQL is found to give better results in terms of tool wear and geometrical accuracy when compared to the other two conditions. In a similar study conducted by Elgnemi et al.,(2017) using two types of cutting fluids and comparing the performance in terms of cutting force and tool wear reduction and surface roughness with dry milling validates that MQL machining provides positive results with respect to the aforementioned parameters.

Cryogenic machining using liquid nitrogen is another technological advancement in the field of machining which has proven to be environmentally friendly and promotes the performance of the parts in addition to improving the process performance. Xia et al.,(2016) did the pioneer work of studying the process performance of cryogenic drilling of CFRP material and comparing it with machining under dry condition. It has been reported that though the cutting forces were larger under LN_2 machining leading to higher delamination, it gave the best results in terms of tool wear, and hole dimensions as shown in Figures 2.12 and 2.13.

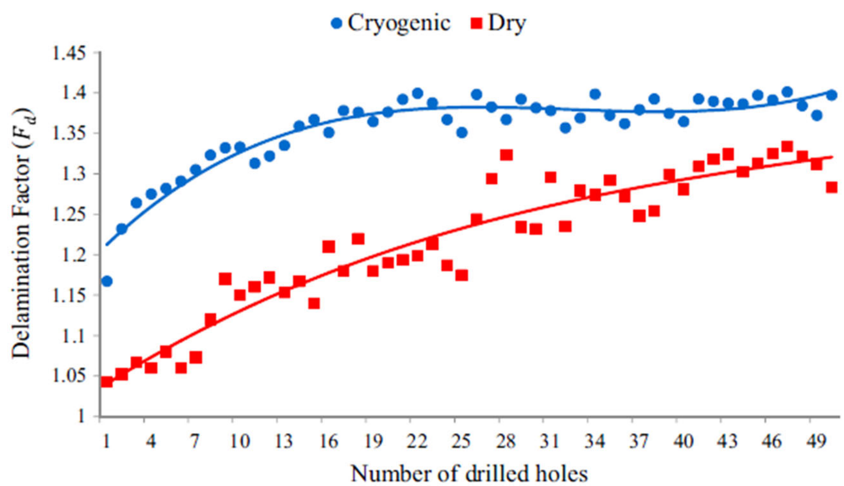


Figure 2.12 Variation of delamination factor as a function of the number of drilled holes (V = 60 m/min; f = 0.025 mm/rev) (Xia et al., 2016)

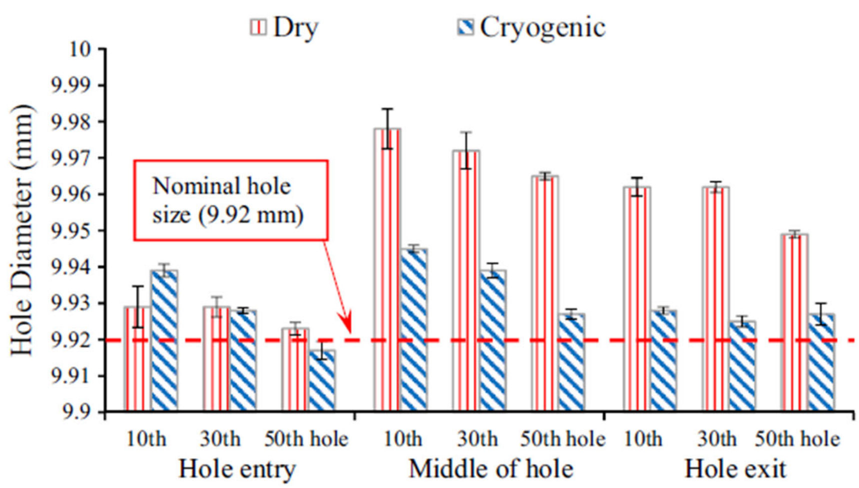


Figure 2.13 Measured diameter from entry, middle and exit of 10th, 30th and 50th holes drilled under dry and cryogenic cooling conditions (V = 60 m/min; f = 0.025 mm/rev) (Xia et al., 2016)

A similar study conducted by Basmaci et al.,(2017) investigated the effect of feed rate and drill diameter on drilling performance under dry and cryogenic (part immersed in LN_2)

environments. They reported that delamination was larger under the cryogenic condition with the larger diameter drill producing higher values as shown in Figure 2.14. But, cryogenic treatment of the workpiece improves tool-life and surface roughness parameter of the drilled part as shown in Figure 2.15.

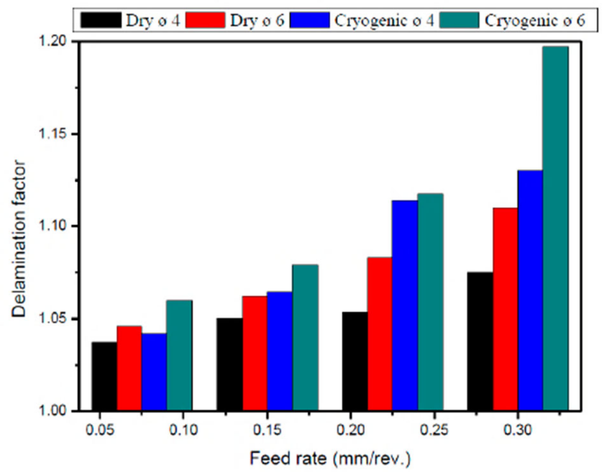


Figure 2.14 The effect of drill diameter, feed rate, dry and cryogenic conditions on delamination (Basmaci et al., 2017)

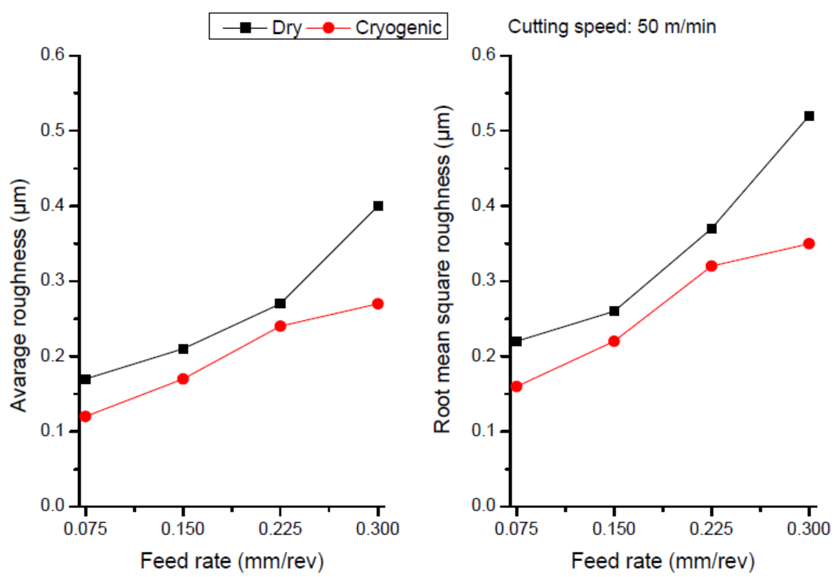


Figure 2.15 Average surface roughness and root mean square roughness under several machining conditions (Basmaci et al., 2017)

Another study by Barnes et al., (2013) compared the effect of drilling CFRP under dry, flood cooling and with a tool cooled to LN_2 temperature. It was concluded that the drilling performance with respect to tool wear and cutting force did not improve with the usage of LN_2 precooled tool or flood cooling. However, they improved the quality of the drilled hole i.e., lower values of delamination than when machined under dry condition. This can be explained by the decrease in interlaminar fracture strength of CFRP with the increase in temperature thereby resulting in lower resistance to delamination under dry condition.

With the available literature, it is well established that cutting fluids improve the process performance along with quality of the machined parts.

2.1.6 Quality and surface integrity assessment

The quality of hole produced is a crucial aspect especially in the field of aerospace. As per the available literature, hole quality in composites is typically measured in terms of delamination, diameter error, roundness and surface roughness.

In the mechanical assembly of parts, hole diameter plays an important role. Temperature developed during the process plays a big role in creating the desired hole size. This was explained by Ashrafi et al. (2016) in their experiments conducted under different feed and cutting speed conditions. As seen in Figure 2.16, they validate that the hole size tends to be larger than the nominal size at lower feed and higher speeds probably due to thermal expansion of the tool and the workpiece.

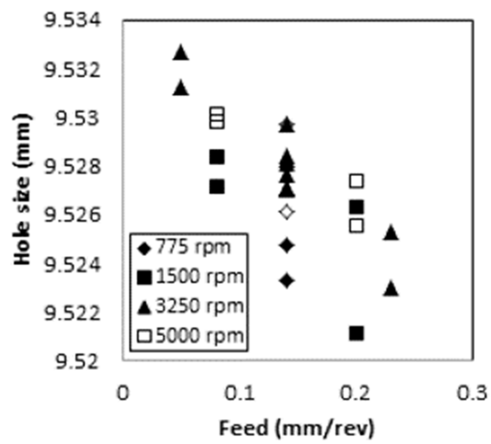


Figure 2.16 Effect of feed on the average hole size (Ø = 9.525 mm) (Ashrafi et al., 2016)

Shyha et al. (2011), in their study concerning MQL and flood cooled drilling justified that spray mist condition gave oversized holes because of the higher temperatures during cutting resulting in thermal expansion of the matrix. Further, the diameter increased from the 1st hole to the last hole because of the tool wear as seen in Figure 2.17.

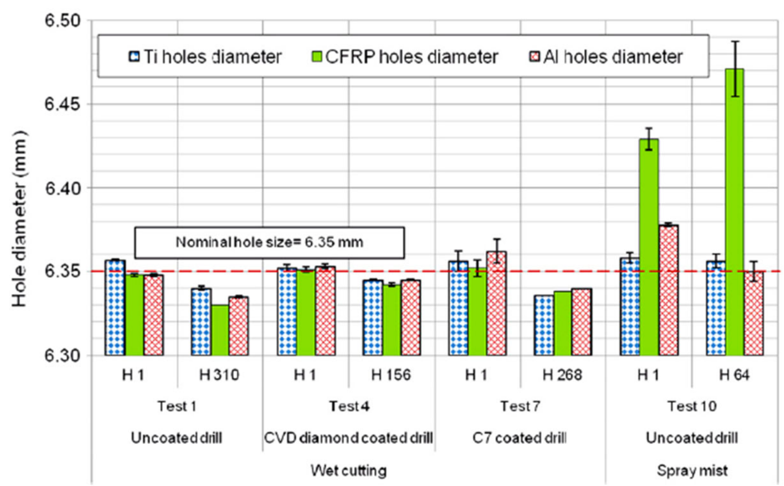


Figure 2.17 Hole diameter results for the first and last holes drilled in all material sections (Shyha et al., 2011)

Similar results were obtained with the roundness of the hole as seen in Figure 2.18. The roundness under flood cooling improved compared to spray mist cooling because of effective lubrication/cooling in the former process.

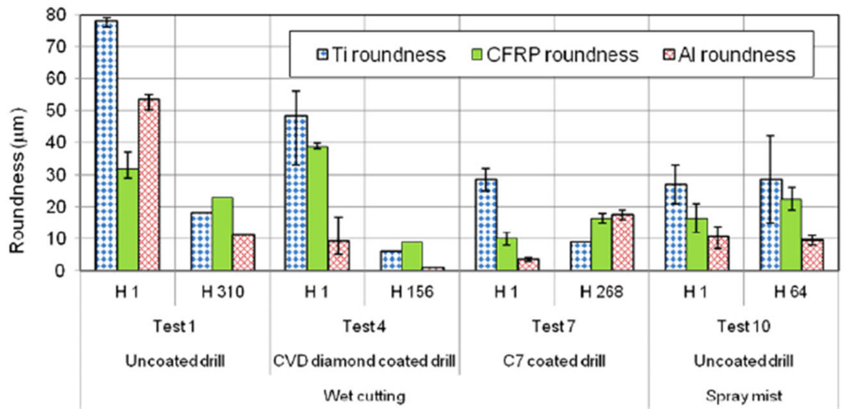


Figure 2.18 Roundness measurement results (Shyha et al., 2011)

When it comes to surface roughness of the holes, feed rate plays a significant role as per Ogawa et al. (1997).

Apart from the aforementioned quality parameters, surface integrity also plays an important role as it exhibits the impact of surface properties and condition upon the product performance, longevity, and reliability (Astakhov, 2010). Composites being a very important material in the aerospace sector needs to be analyzed for subsurface damages after machining. Any subsurface defects in the form of fiber/matrix pullout or fiber/matrix loss or internal cracks can be discovered and analyzed.

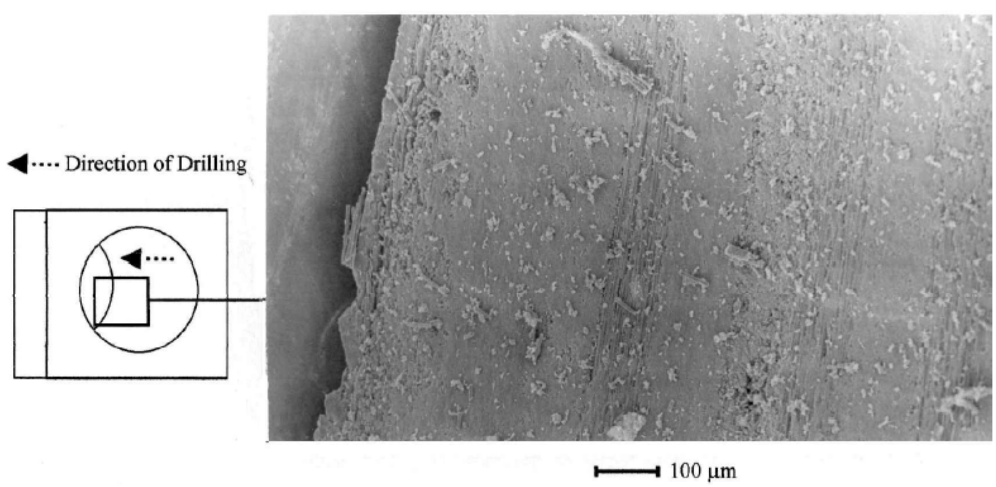


Figure 2.19 Scanning electron micrograph showing exit of an initial hole drilled for an uncoated tool (Murphy et al., 2002)

2.2 Synopsis

A comprehensive review of literature provided a cumulative understanding of the past research carried out in the area of composite machining, in particular drilling. It gave an overview of the material properties, the effect of cutting tool material and its geometry along with the effects of selection of the cutting parameters on the quality of the machined part. Delamination, one of the most critical defects in CFRP machining is of utmost concern during the process. Since cutting parameters like cutting speed and feed rate influence the quality variables like hole diameter error, roundness, surface roughness including the delamination factor, it is of great importance to make an appropriate selection.

Apart from the machining parameters, cutting temperature also plays a role in producing good quality parts. CFRP being a material with low thermal conductivity, the quality of machining can be improved by adopting cooling strategies like MQL or cryogenic machining to reduce the temperature and also to maintain good tool-life to a considerable extent.

2.3 Research gap

The need for producing high quality parts in composites require proper machining process which reduces tool wear by also reducing thermal induced damages. Considering all the content explained before, to the best of the author's knowledge there is a gap in the drilling process of CFRPs that needs to be addressed.

1) Since the usage of coolant/ lubricant has been proved to improve machining process in metals and alloys, not much research has been conducted regarding the application of coolant/ lubricant when drilling CFRP. Thus, comparing the process performance of MQL and cryogenic drilling of CFRP with respect to surface integrity parameters like surface roughness etc., needs to be carried out.

2) Similarly, hybrid (CryoMQL) machining of metals have been shown to provide better process and product performance in metals. However, the application of hybrid cooling in composites has not been explored yet. Hence, the potential benefits of employing hybrid drilling and investigating its performance based on the quality and surface integrity of the produced part is to be examined yet.

This thesis addresses those gaps through systematic investigation of drilling CFRPs under different machining conditions and analyzing the process performance for each condition.

2.4 Proposal

With increasing use of composite materials in the world today, there is a need to develop a novel approach for drilling CFRPs that not only produces better quality products but also makes the process more sustainable. Most of the available literature consider either dry or flood or Minimum Quantity Lubrication (MQL) or cryogenic drilling of CFRPs. That being said, this thesis advances one step ahead with the proposal of hybrid drilling of CFRPs.

The main objective of this research is to investigate and compare the machining performance of drilling CFRP in terms of thrust force, torque, part quality based on delamination, diameter error and roundness, surface integrity assessment including surface roughness, hardness and sub-surface damage analysis under different cutting parameters and cooling conditions involving dry, MQL, cryogenic and hybrid (CryoMQL) techniques.

Also, feed rate plays an important role in the generation of thrust force, torque, and delamination based on literature (Panchagnula and Palaniyandi, 2018); (Tsao and Hocheng, 2004). Hence, to explore the potential benefits of varying the feed rate on machining performance, variable feed rate strategy is investigated.

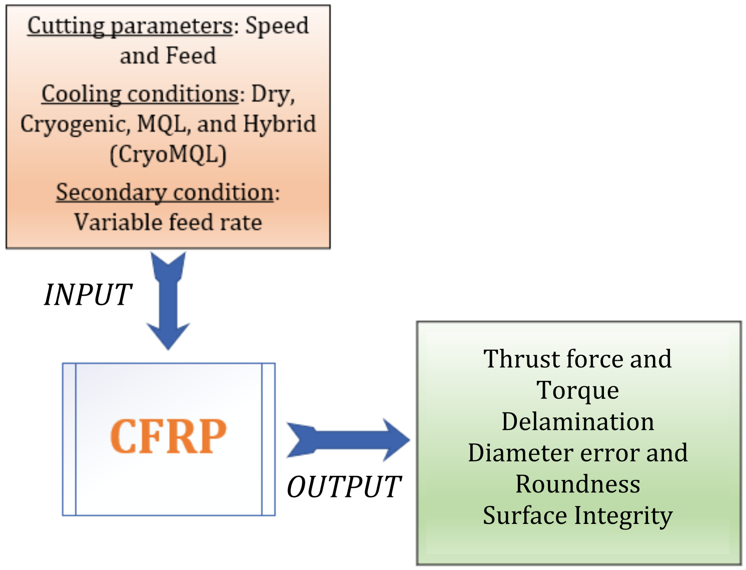


Figure 2.20 Research outline

CHAPTER 3

EXPERIMENTAL WORK AND PROCEDURE

3.1 Introduction

This chapter explains the procedure followed to investigate the performance of drilling CFRP under various aforementioned conditions. This includes the work material used, drill tool material used, machining setup for drilling CFRP laminates and instruments used for measurement of data and other parameters. Finally, a comprehensive review of measurement of all the parameters like thrust force and torque, delamination, diameter error, roundness, surface roughness, hardness and the method of determining the subsurface damage is presented.

3.2 Workpiece and drill tool materials

The workpiece used in this study are CFRP blocks of 21mm x 21mm x 12.5mm with a ply thickness of 0.201 mm. The fiber volume fraction of the material is 0.5448. The material is a 3K plain woven fabric and utilizes Cytec MTM 45-1 epoxy resin with the plies stacked at 0°/90° orientations. Figure 3.1 shows the work material used.

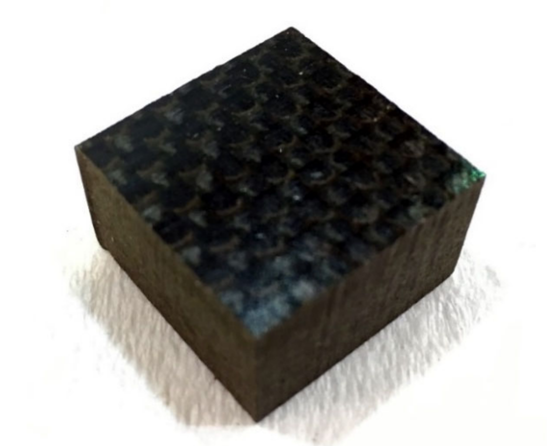


Figure 3.1 Workpiece

HPS Beyond™ high-performance solid carbide Kennametal drills were used in this investigation. They are uncoated twist drills of 10 mm diameter with 135° point angle and 30° helix angle. Along with the 2-flute construction, it also features two through-coolant holes for the flow of coolant through the tool during the drilling process. Figure 3.2 shows the tool used.

Figure 3.2 Kennametal solid carbide drill bit

3.3 Experimental setup

The drilling tests were performed on a HAAS VF0 CNC vertical milling machine as shown in Figure 3.3. The spindle of the machine is driven by a 20 HP vector spindle drive with a maximum speed of 7500 rpm.

Figure 3.3 HAAS VF0 CNC vertical milling machine

The workpiece was held in a custom-made jig during the machining process. This setup was attached to the machine spindle and the drill bit was held in position by a custom-made tool holder which was clamped to a dynamometer to record the drilling forces. This setup is quite contrary to the conventional drilling wherein the drill bit rotates, and the workpiece is fixed. MQL was applied through the coolant hole of the tool, whereas liquid nitrogen was applied externally for cryogenic machining and in case of CryoMQL mode, MQL was fed through the tool and LN_2 was applied externally. This made sure that MQL reached even the exit side of the hole and did not freeze during the process due to interaction with the LN2. The machining setup is shown in Figure 3.4.

Figure 3.4 Machining setup

3.4 Thrust force and torque measurement

The thrust force and torque generated during the process were recorded by a Kistler type 9272 dynamometer. The dynamometer was connected to two Kistler Type 5004 charge amplifiers via 1679a5 high insulation connecting cables to eliminate the effect of any undesirable external conditions.

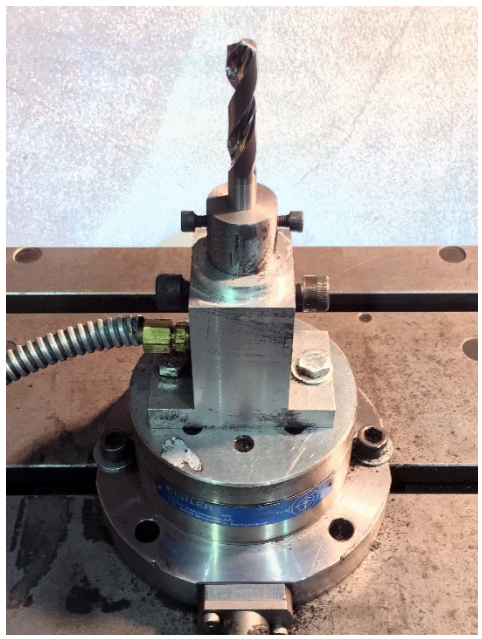


Figure 3.5 Dynamometer with tool holder mounted

The generated forces were recorded and analyzed on a computer using DynoWare software. The dynamometer was calibrated for thrust force by applying different magnitudes of load i.e., weight blocks and torque was calibrated by a torque wrench. Figures 3.5 and 3.6 show the dynamometer setup and charge amplifiers respectively.

Figure 3.6 Kistler charge amplifiers connected to a computer with DynoWare software

3.5 MQL and liquid nitrogen delivery system

Generally, drilling tests are carried under dry, cryogenic, MQL and CryoMQL cooling conditions. Figure 3.7 shows the Unist Coolubricator; a commercially available MQL delivery system used while machining. Coolube 2210, a plant-based oil is used as the fluid and is stored in the fluid reservoir. Air required to produce the mist is delivered separately through a coaxial output until it is combined with the liquid at the nozzle tip. The air surrounding the liquid evenly atomizes the liquid and is delivered to the through-coolant hole of the drill bit via a hose at a flow rate of 0.01 ml/s selected based on trial runs. MQL was delivered through the tool and not externally because external application will not reach the interior of hole during the drilling process.

Figure 3.7 MQL delivery system

Liquid nitrogen used for cryogenic machining is stored in a tank as shown in Figure 3.8. The pressure of the coolant was set based on initial trial runs at 50 psi using valves. A hose with a valve to control the flow of the coolant delivers the coolant through a flexible hose clamped by a magnetic holder during machining as shown in Figure 3.9. Through the tool supply of LN_2 was not used since it produced severe delamination given the nature of the material used.

Figure 3.8 Liquid nitrogen delivery system

Figure 3.9 Cryogenic machining setup

Figure 3.10 shows the setup for hybrid machining. The liquid nitrogen was supplied externally through a nozzle, whereas MQL was fed through the tool to the workpiece.

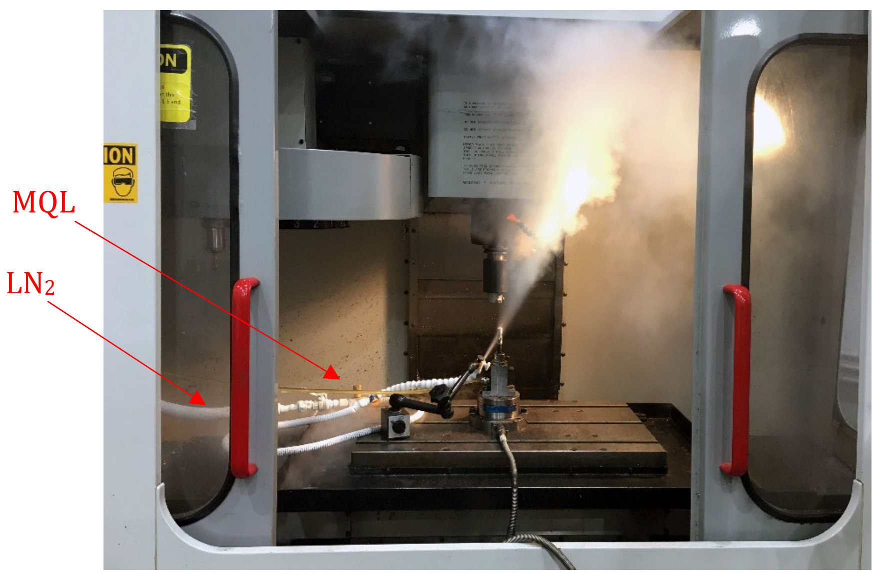


Figure 3.10 Hybrid machining setup

Cutting speed and feed rate were selected based on the literature review and trial runs and are shown in Table 3.1. Machining speed was set constant at 90 m/min, i.e., $V_c = 90$ m/min.

Trial No.	Cooling condition	Feed, *f* (mm/rev)
1 (CF)	Dry	0.2
2 (VF 1 *)		0.2 up to 8 mm 0.05 for 4.5 mm
3 (VF 2 **)		0.05 for 4 mm 0.2 up to 4 mm 0.05 for 4.5 mm
4 (CF)	Cryogenic	0.2
5 (VF 1)		0.2 up to 8 mm 0.05 for 4.5 mm
6 (VF 2)		0.05 for 4 mm 0.2 up to 4 mm 0.05 for 4.5 mm
7 (CF)	MQL	0.2
8 (VF 1)		0.2 up to 8 mm 0.05 for 4.5 mm
9 (VF 2)		0.05 for 4 mm 0.2 up to 4 mm 0.05 for 4.5 mm
10 (CF)	CryoMQL	0.2
11 (VF 1)		0.2 up to 8 mm 0.05 for 4.5 mm
12 (VF 2)		0.05 for 4 mm 0.2 up to 4 mm 0.05 for 4.5 mm

Table 3.1 Machining parameters ($V_c = 90$ m/min)

* VF 1 = Variable feed 1

** VF 2 = Variable feed 2

3.6 Hole quality and surface integrity assessment

As mentioned before, delamination, diameter error, roundness and surface roughness are measured to assess the quality of the drilled hole.

The drilled holes were examined for delamination defects using a Nikon SMZ800 microscope. The microscope is connected to a computer and the images of the damaged region were recorded using Leica application suite. The images obtained were analyzed using Microsoft Visio as shown in Figure 2.13. The delamination factor is then calculated using the equation;

$$F_d = D_{max} / D \quad (3.1)$$

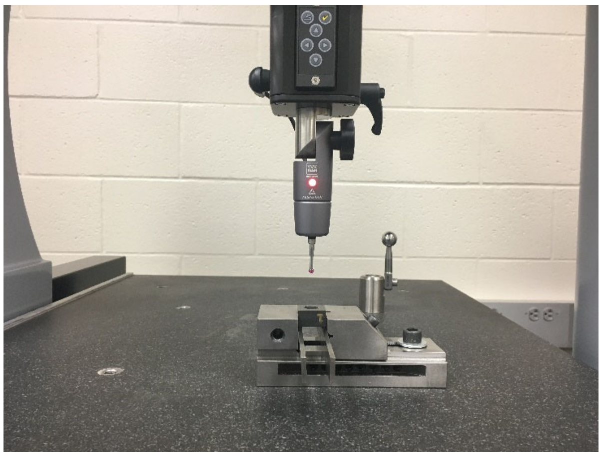
where,

D_{max} is the maximum diameter of delamination, and

D is the diameter of the hole.

Figure 3.11 Nikon SMZ800 Microscope to measure delamination

Roundness and diameter error was measured by TESA Micro-Hite 3D coordinate measuring machine as shown in Figure 3.12. A 4mm probe was used to measure the above-said parameters. The part to be measured is set on parallels to maintain constant height and was clamped using a bench vise to prevent any movement. Measurements were taken at depths of 1 mm, 4 mm, 7 mm and 12 mm of the workpiece. At each measurement (or depth), 10 points were taken by the probe. The probe records the coordinates at different points through the depth of the hole and determines the average values of diameter and roundness.



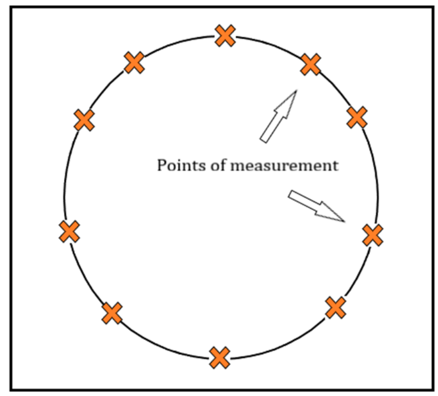


Figure 3.12 Measuring diameter and roundness using TESA Micro-Hite 3D coordinate measuring machine

The surface roughness of the part was determined using Zygo NewView 7300 Optical Surface Profiler, shown in Figure 3.13. The device is connected to a computer and using MetroPro software, the surface roughness of the drilled hole surface can be determined.

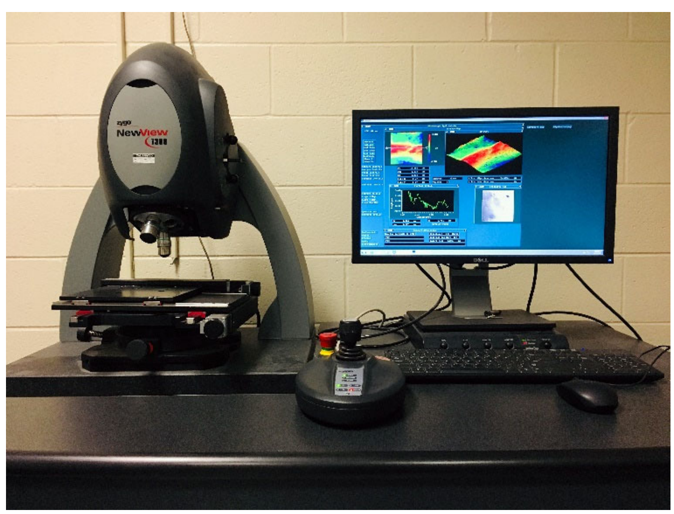


Figure 3.13 Zygo NewView 7300 Optical Surface Profiler to measure surface roughness

The mechanical property of the composite was studied by measuring hardness along the depth of the drilled hole. M-scale Rockwell hardness was used to measure hardness since it is the most popular scale used for plastic and soft materials (Gopinath et al., 2014). Figure 3.14 shows Sun-Tec Rockwell type hardness tester. The test was carried out using a 1/16" ball indentor by applying a major load of 100 kg on the drilled specimen. The corresponding hardness is then recorded on the digital scale of the device.

Figure 3.14 Rockwell type hardness tester

Surface integrity assessment was carried out by taking subsurface images of the part using a Nikon Epiphot 300 Metallurgical Microscope connected to a computer with Leica application suite as shown in Figure 3.15. The drilled samples were cut in half and cold-mounted using Struers' EpoFix epoxy resin mixed with a hardener in a ratio of 25:3 by weight. The specimens were then ground using SiC grinding papers of 220, 500, and 1200 grit size. Finally, the specimens were polished on Pace Technologies' Goldpad Stainless Magnetic Polishing pad with Buehler MasterPrep 0.05μm sol-gel alumina suspension. The resulting specimens were then observed under the microscope to get micrographs which were analyzed for any subsurface defects.

Figure 3.15 Nikon Epiphot 300 Metallurgical Microscope for surface integrity assessment

This chapter provided a complete description of the research methodology and devices used. The results thus obtained are discussed in detail in the next chapter.

CHAPTER 4

RESULTS AND DISCUSSION

This chapter presents the research findings when drilling CFRP under different cooling conditions. A comprehensive evaluation of thrust force and torque, delamination damage, diameter error and roundness, hardness, surface roughness and sub-surface damage is carried out.

4.1 Thrust force and torque

One of the main objectives of this study is to examine the influence of feed rate and cooling conditions on induced thrust force and torque when drilling CFRP. The quality of the part produced depends on the above-mentioned factors which in turn depend on the machining parameters. Figure 4.1 shows typical thrust force and torque profiles when drilling CFRP at 0.2 mm/rev feed.

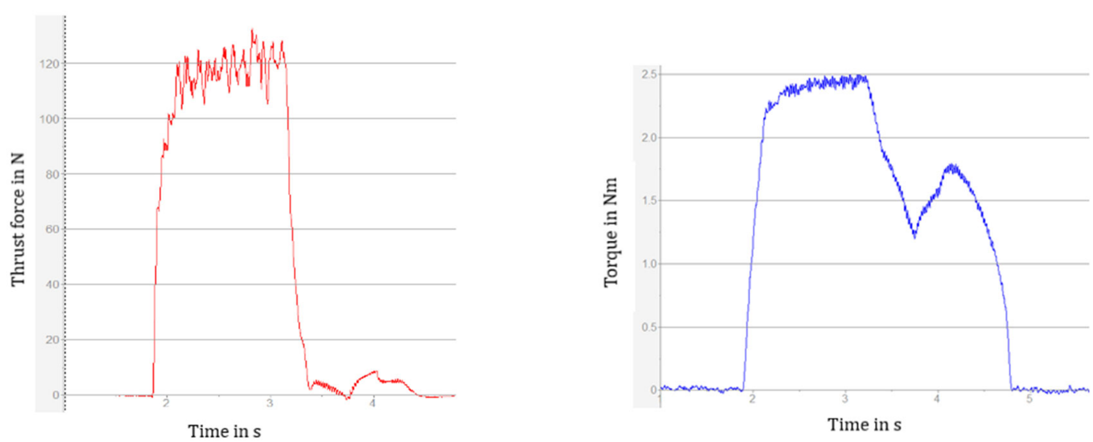


Figure 4.1 Thrust force and torque profiles from Dynoware

The thrust force and torque developed highly depends on the machining condition i.e., dry or using any coolant/ lubricant.

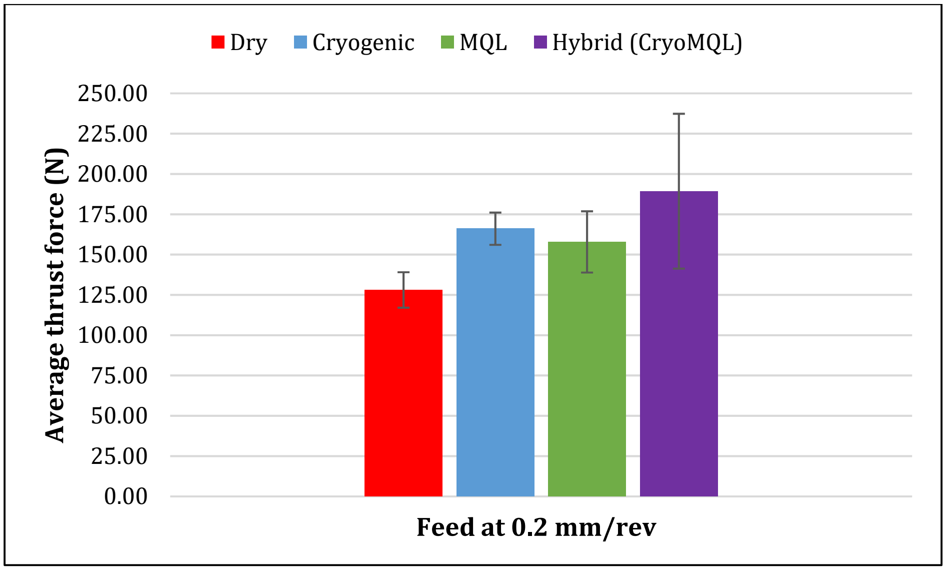
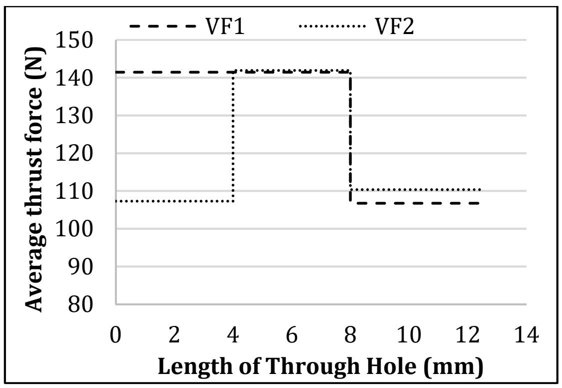


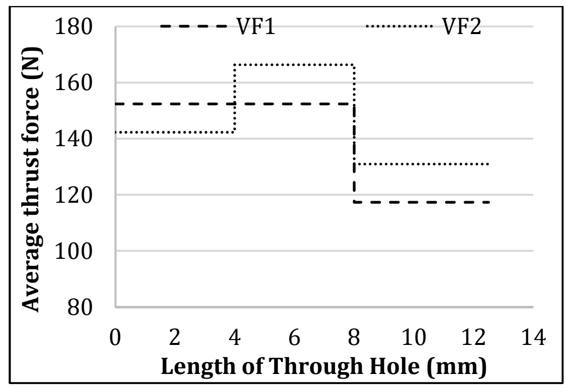
Figure 4.2 Influence of cooling conditions on average thrust force at *f* = 0.2 mm/rev

As seen from Figure 4.2, drilling under hybrid condition induces the highest thrust force among all the cooling conditions considered. The heat generated during dry drilling softens the matrix thereby inducing lower thrust force (Basmaci et al., 2017). Whereas under LN_2, the material properties of the composite i.e., Young's modulus and tensile strength increase, which causes a surge in the thrust force induced (Reed and Golda, 1994). Additionally, given the inverted drilling setup, the liquid lubricant delivered through the coolant holes of the drill bit clogs the free flow of chips, exerting more pressure and surges the thrust force eventually, which is also the cause for increase in thrust force under MQL condition. As per the above figure, the average thrust force under hybrid drilling is found to increase by 48% compared to the dry drilling condition. The thrust force under cryogenic and MQL condition were higher than in dry condition. It was found to increase by 30% and 23% respectively under cryogenic and MQL drilling.

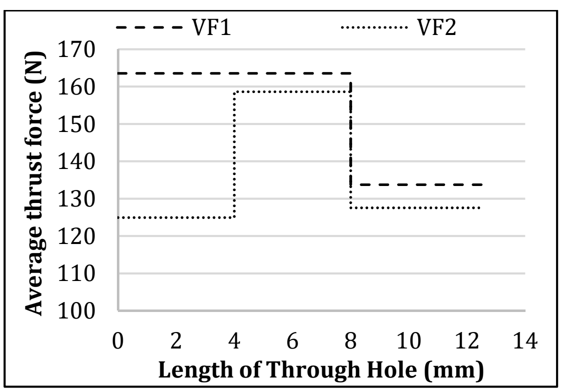
Figure 4.3 shows the variation of average thrust force for all cooling conditions under VF1 and VF2. As evident from the figure, feed rate influences the thrust force induced and agrees with previous work where researchers have shown that decreasing the feed decreases the thrust force when drilling CFRP (MaojunLi et al., 2018). With the feed rate decreased from 0.2 mm/rev to 0.05 mm/rev, the thrust force was found to decrease by 25%, 23%, 18% and 17% under dry, cryogenic, MQL and hybrid conditions respectively. Similarly increasing the feed in VF2 increased the thrust force by 32%, 17%, 26% and 18% under dry, cryogenic, MQL and hybrid conditions respectively.



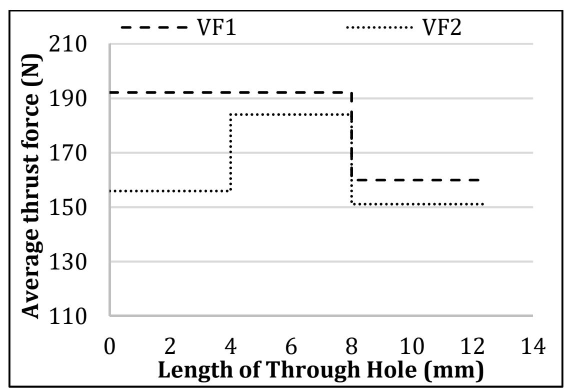
Dry



Cryogenic



MQL



Hybrid

Figure 4.3 Variation of average thrust force for all cooling conditions under VF1 and VF2

A similar trend was found in torque readings. As seen in Figure 4.4, cryogenic machining produced the highest torque among dry and MQL, the reason being the same as explained before for thrust force. The average torque was seen to increase by 6% under cryogenic medium. However, it was observed that the torque under MQL reduced by 10%. This may be due to the fact that MQL provides lubrication during the process which reduces the friction between tool-work interface, thereby reducing the torque developed.

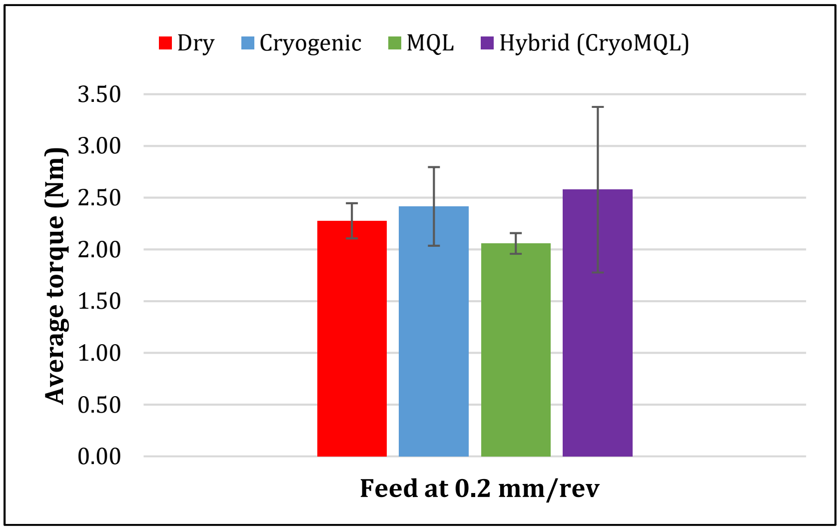


Figure 4.4 Influence of cooling conditions on average torque at *f* = 0.2 mm/rev

On the other hand, there was an abnormal increase in torque under hybrid machining. This may be explained based on Figure 4.5. Since MQL lubricant is fed in the direction opposing gravity, it offers resistance to the flow of chips; thereby clogging the machining zone. Further, under the influence of cryogenic medium, it increases the friction in the cutting zone thereby escalating the torque developed during the process.

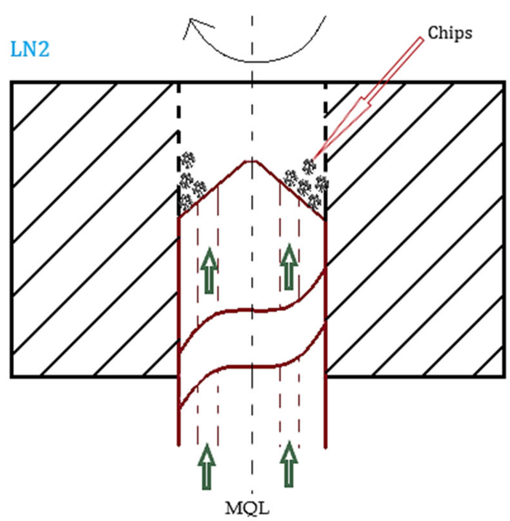
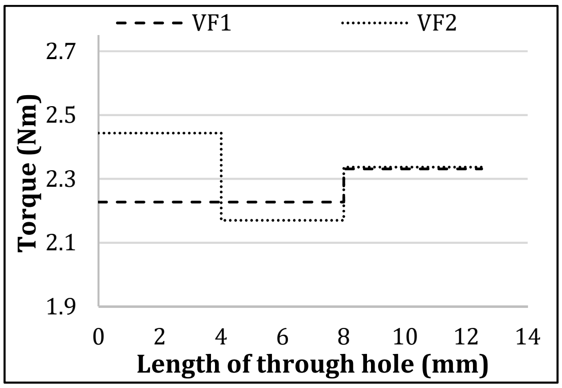
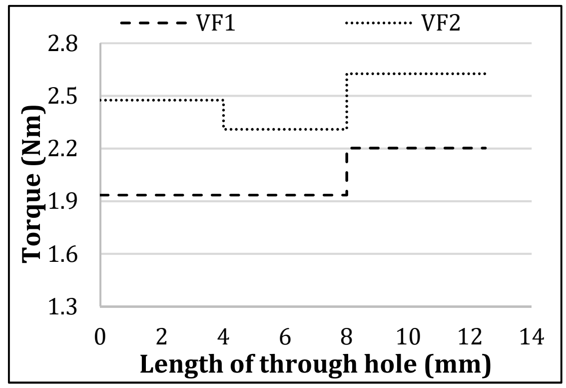


Figure 4.5 Illustration of torque developed under hybrid condition

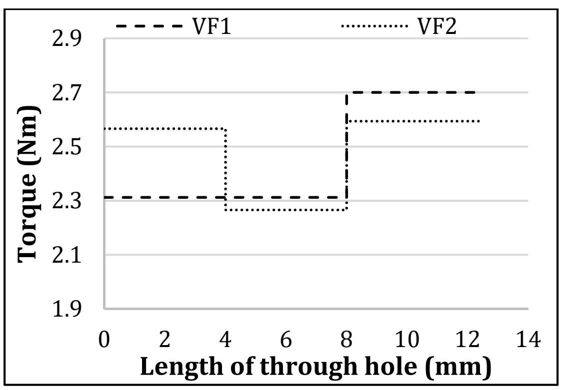
However, varying the feed rate did not yield much change in the magnitude of average torque as compared to the variation in average thrust force as seen in Figure 4.6. This shows that feed rate has a marginal influence on torque developed during the process.



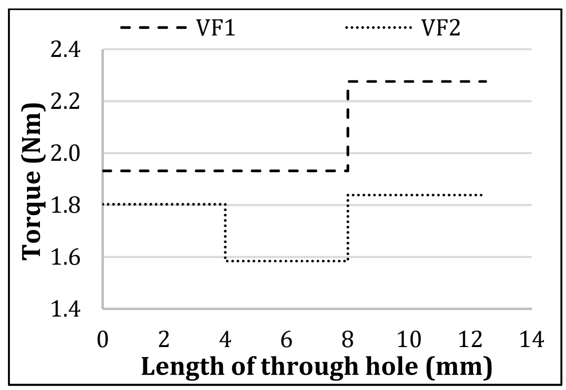
Dry



Cryogenic



MQL



Hybrid

Figure 4.6 Variation of average torque for all cooling conditions under VF1 and VF2

To summarize, feed rate plays an important role in inducing thrust force. Additionally, cooling condition certainly affects the machining forces when drilling CFRP.

4.2 Delamination assessment

Delamination is the most critical process induced defects which occur when machining composites affecting the fatigue strength of the material thereby deteriorating the assembly tolerances (Gaitonde et al., 2008). The delamination extent around a hole in composites is determined by measuring the maximum diameter of the damaged zone. A dimensionless factor called the delamination factor is used to quantify this damage and is defined as;

$$F_d = D_{max} / D \qquad (4.1)$$

where,

D_{max} is the maximum diameter of delamination, and

D is the diameter of the hole.

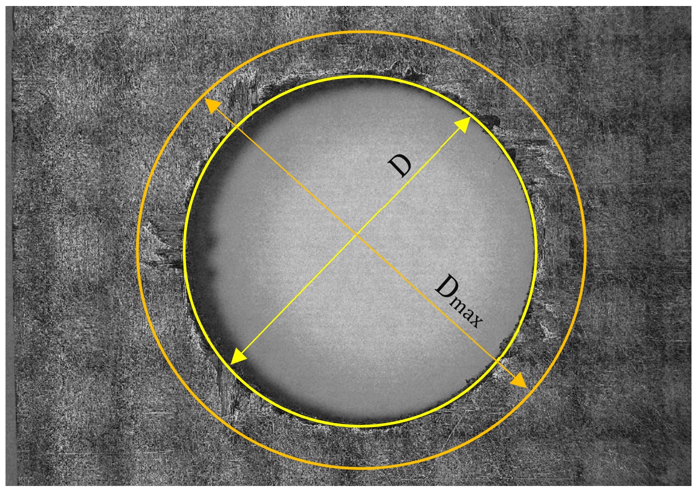


Figure 4.7 Assessment of the delamination factor

Assessment of the delamination factor can be carried out at the entry side and the exit side of the hole. A detailed assessment of delamination is presented in the following section.

4.2.1 Entry delamination

Entry or peel-up delamination occurs when the fibers get peeled up separating the upper laminates from the bulk material. The peeling force causing this effect is a function of the friction between tool and workpiece and tool geometry (Ho-Cheng and Dharan, 1990). Due to the higher point angle of the drill used in this work, entry delamination was found to be larger and may be even added because of the tool being uncoated resulting in higher friction between the tool and workpiece that occurs when using uncoated drills. This trend was also reported by Feito et al. (2014).

Table 4.1 shows the optical images of entry delamination under different machining conditions. It can be seen that, under the highest feed rate, cryogenic and hybrid conditions caused more severe delamination compared to dry machining. Additionally, there were even higher amounts of fraying, and chipping that occurred under these conditions as shown in Figure 4.8.

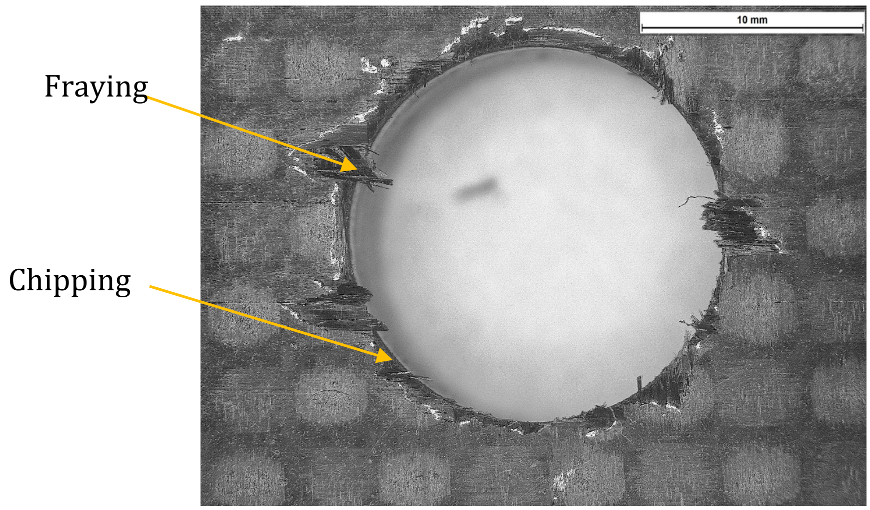


Figure 4.8 Fraying and chipping on the entry side under cryogenic and hybrid conditions

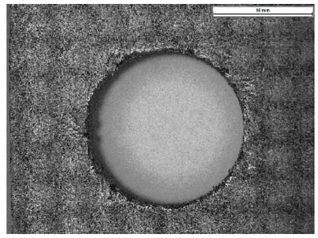
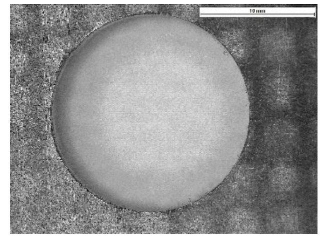
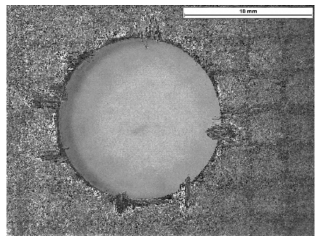
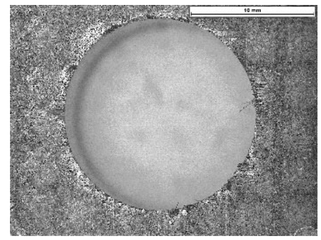
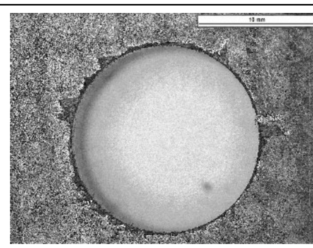
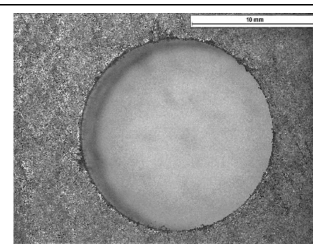
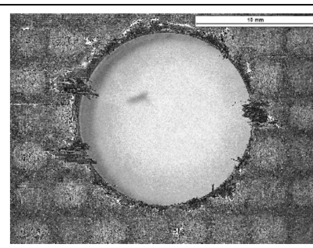
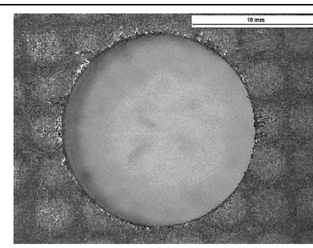
Cooling condition	*Entry feed at 0.2 mm/rev*	*Entry feed at 0.05 mm/rev*
Dry		
Cryogenic		
MQL		
Hybrid		

Table 4.1 Entry delamination under different cooling conditions

The variation in delamination factor with respect to feed rate and cooling conditions is presented in Figure 4.9. As it can be seen, delamination under cryogenic and hybrid drilling was slightly higher compared to dry drilling and was 11% and 8% higher respectively.

Similar result was found in the case of MQL, where the delamination factor was 7% more than that under dry machining. Also, MQL performed better compared to cryogenic and hybrid machining probably due to the fact that MQL provides better lubrication thereby reducing the peel-up delamination. Another observation that can be made is, under VF2 where the feed rate was the lowest, the composite experienced lesser delamination for all the cases compared to that at a higher feed rate of 0.2 mm/rev. This agrees with results from other researchers that delamination highly depends on feed rate. Also, the delamination data follows the trend displayed by thrust force i.e., higher the thrust force higher is the delamination.

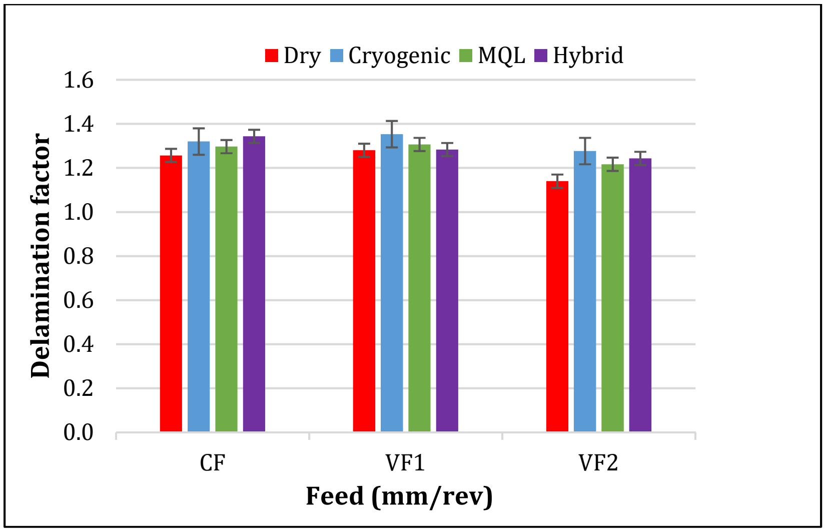


Figure 4.9 Entry delamination factor under different feed and cooling conditions

4.2.2 Exit delamination

Exit or push-out delamination occurs when the drill approaches the end of the workpiece and the uncut chip thickness becomes smaller thereby decreasing the resistance to deformation. This causes the inter-laminar bond strength to give away to the machining load causing delamination (Ho-Cheng and Dharan, 1990).

Table 4.2 shows the optical images of exit delamination under different machining conditions. It can be seen that, under the highest feed rate, cryogenic condition gave more severe delamination as compared to any other condition. Additionally, there were even fraying, and chipping that occurred under this condition as shown in Figure 4.10.

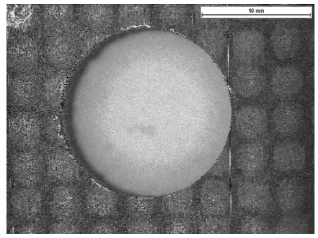
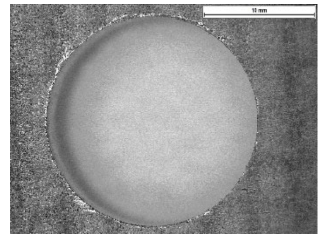
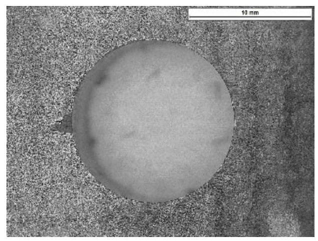
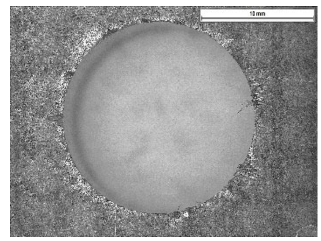
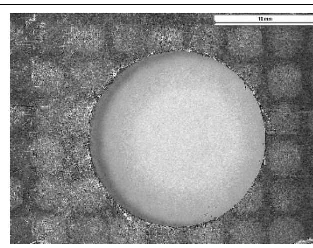
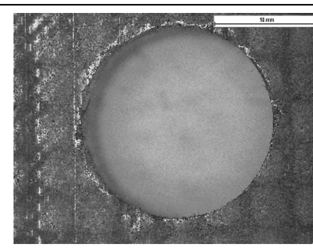
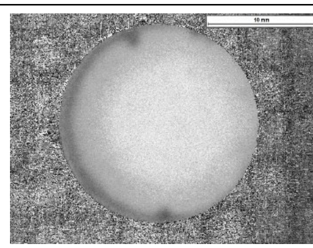
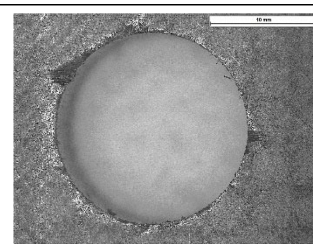
Cooling condition	*Exit feed at 0.2 mm/rev*	*Exit feed at 0.05 mm/rev*
Dry		
Cryogenic		
MQL		
Hybrid		

Table 4.2 Exit delamination under different cooling conditions

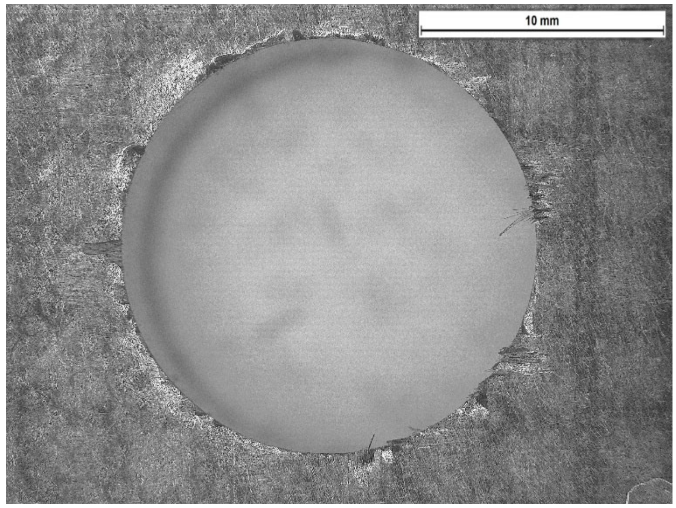


Figure 4.10 Fraying and chipping on the exit side under cryogenic condition

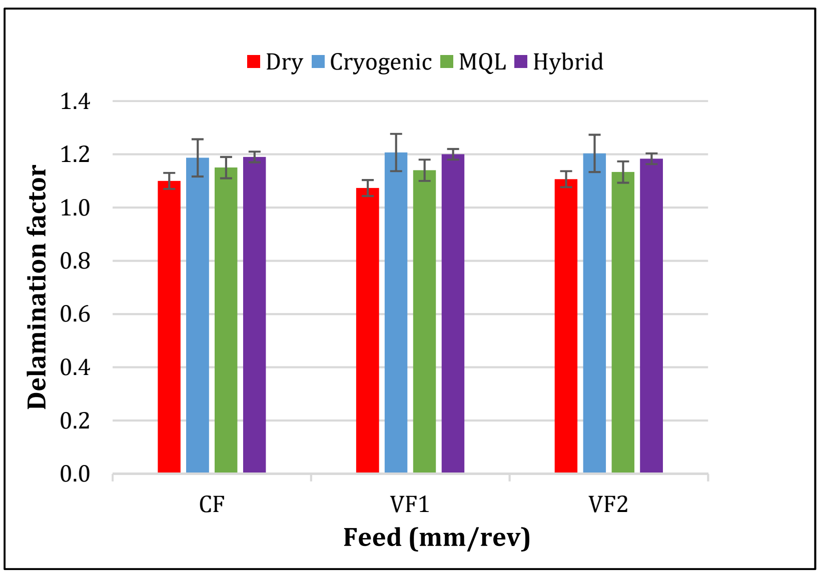


Figure 4.11 Exit delamination factor under different feed and cooling conditions

The variation in the delamination factor with respect to feed rate and cooling conditions is presented in Figure 4.11. As it can be seen, cryogenic process induced the highest magnitude of delamination and was about 12% higher than dry machining. This was followed by hybrid and MQL machining which produced 8% and 6% higher delamination than under dry machining. This may be because of the higher horizontal forces which will be induced when MQL is involved (Meshreki et al., 2016,).

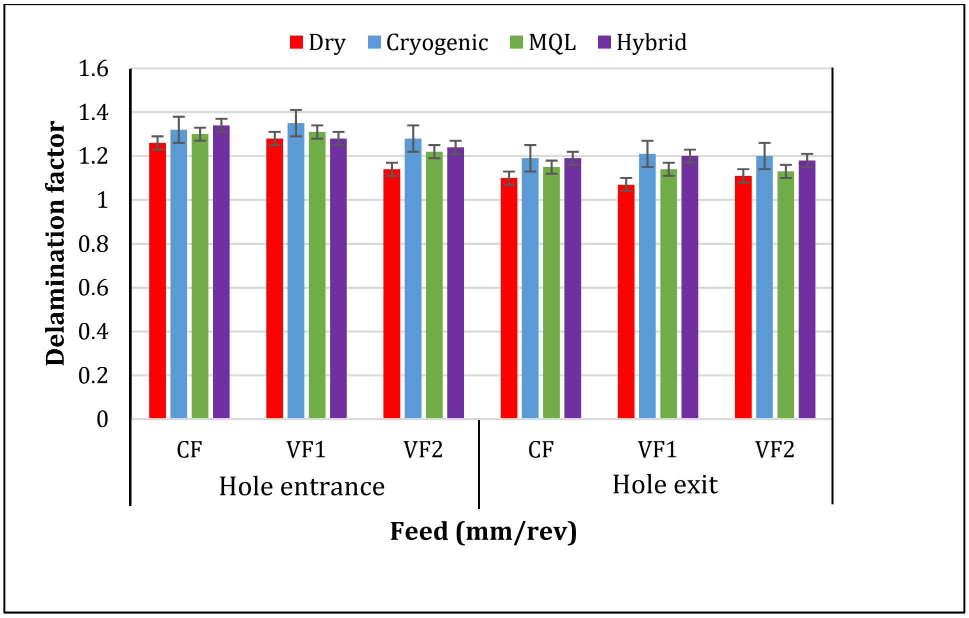


Figure 4.12 Delamination factor at hole entrance and exit

Figure 4.12 summarizes the positive impact of adopting variable feed rate. The delamination factor at exit is lower following the low feed rate compared to the hole entrance. With respect to the least amount of damage that occurred following the drilling process, dry drilling under VF2 outperformed all other conditions. Additionally, the technique of variable feed rate resulted in reduced fraying and spalling of fibers in the composite.

4.3 Hole quality and surface integrity assessment

4.3.1 <u>Hole diameter and roundness</u>

Hole diameter in composites plays a crucial role in the mechanical assembly of parts, especially in the aerospace sector which require tight diametric tolerances. The effect of the various cooling strategies on drill hole diameter will be explained in this section.

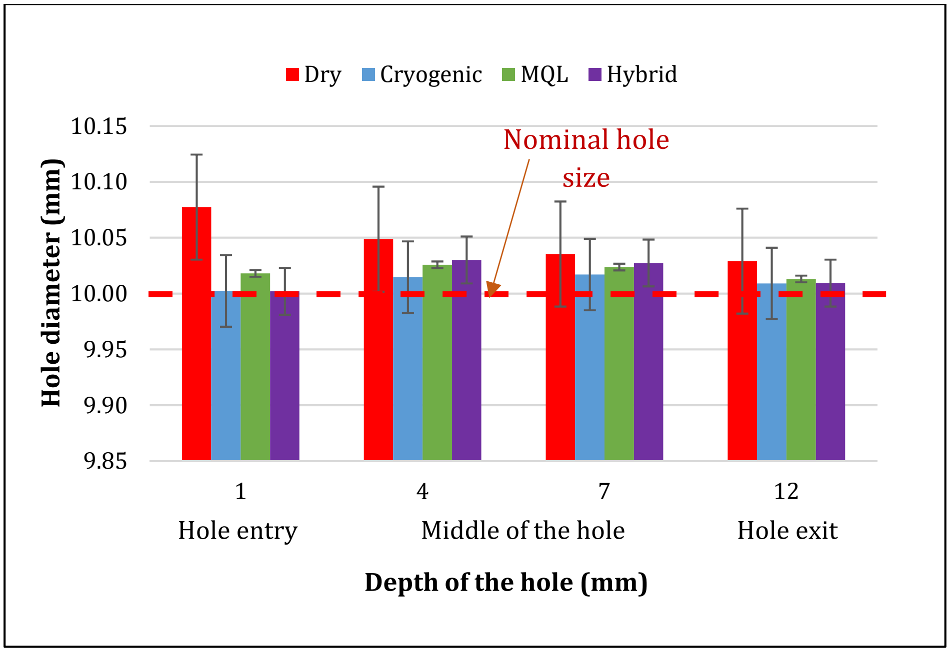


Figure 4.13 Hole diameter along the hole depth for various cooling conditions at 0.2 mm/rev feed

Figure 4.13 shows the variation of hole diameter along the depth of the drilled hole at constant feed of 0.2 mm/rev. As it can be seen, holes produced were generally oversized under all conditions. The hole machined under dry condition had the largest size amongst all the conditions. Due to higher cutting temperatures involved in dry drilling, the drill bit undergoes severe expansion leading to bigger sized holes. Additionally, dry drilling exhibited bell-mouthing effect i.e., hole with a larger entry diameter curving inward through the depth of the hole as shown in Figure 4.14. A similar trend was observed by Hayajneh, (2001).

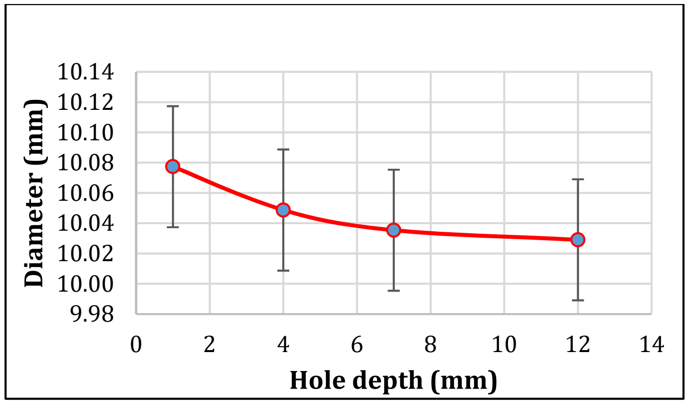


Figure 4.14 Bell-mouthing under dry condition

Holes under the other three cooling/ lubrication modes had less diameter error and cryogenic cooling in particular, gave the best results. However, unlike bell-mouthing, barreling effect was found under these conditions as shown in Figures 4.15, 4.16 and 4.17. Under all these conditions, the diameter of the hole increased at the entrance up to the middle and decreased at the hole exit. While the deviation was between +2 µm and +17 µm under cryogenic condition, MQL and hybrid had deviations ranging between +13 µm and +26 µm and +2 µm and +30 µm respectively. With respect to the average diameter of the drilled holes, all the three cooling conditions achieved the recommended tolerance range of ±20 µm to ±40 µm (Sandvik Coromant).

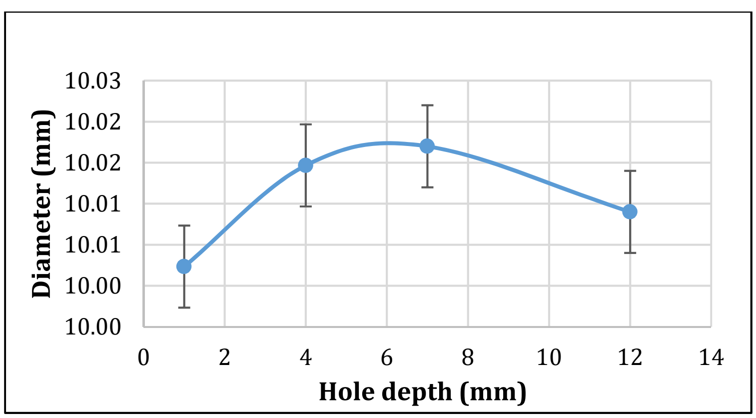


Figure 4.15 Barreling under cryogenic condition

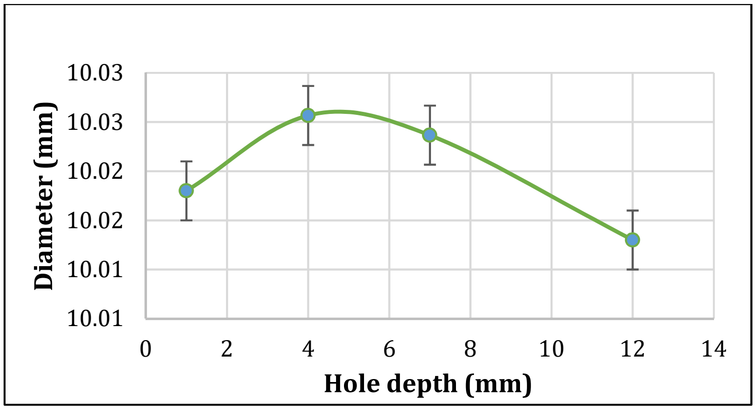


Figure 4.16 Barreling under MQL condition

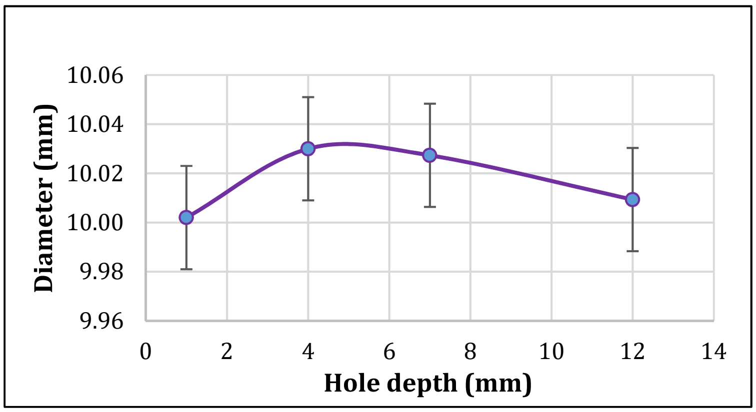


Figure 4.17 Barreling under hybrid condition

The effect of varying the feed rate on hole diameter is shown in Figures 4.18 and 4.19. It can be observed that lowering the feed minimized the diameter error and the diameter of the hole was closer to the nominal diameter. As in the previous case, cryogenic drilling minimized the hole diameter error to the maximum extent as compared to all other cooling conditions. All the holes produced under VF1 and VF2 under all the four conditions were within the tolerance level except for dry under VF1.

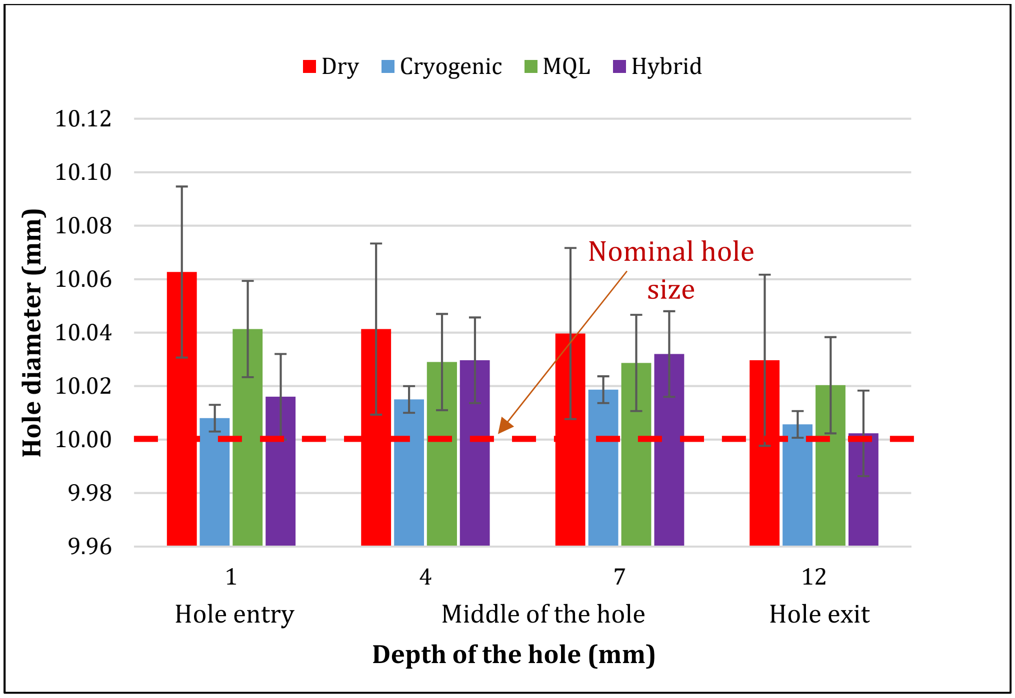


Figure 4.18 Hole diameter along the hole depth for various cooling conditions under VF1

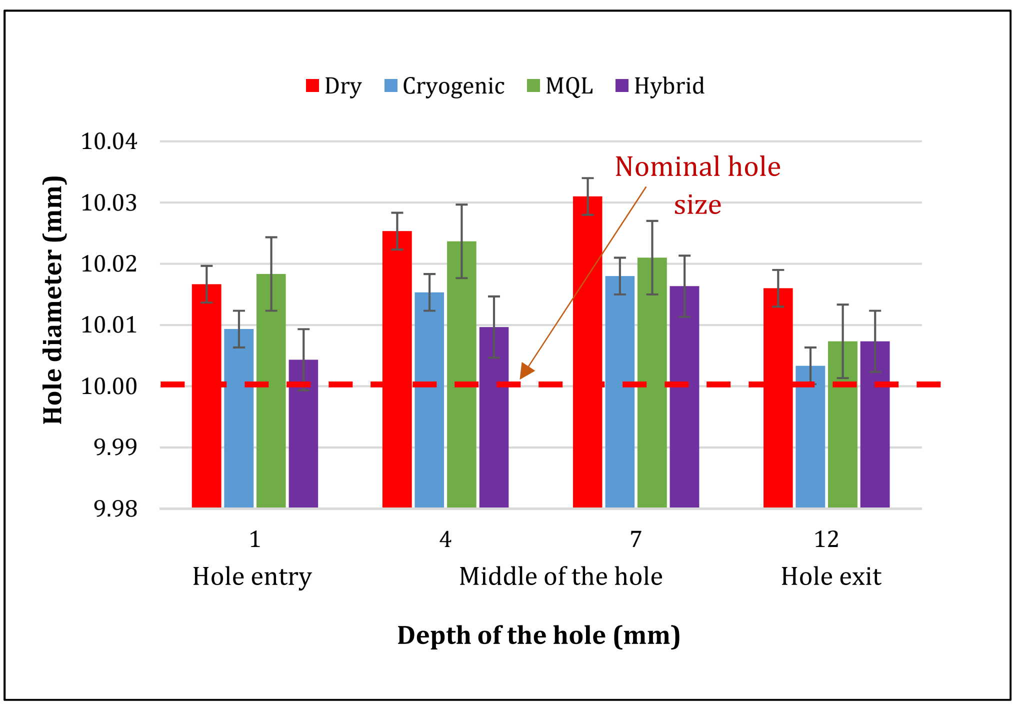


Figure 4.19 Hole diameter along the hole depth for various cooling conditions under VF2

Roundness of the hole is a measure of how closely the hole cross-section matches a true circle. Figures 4.20, 4.21 and 4.22 shows the roundness measurement results from all three feed conditions. It was found that the average roundness values ranged between 14.67 µm and 25 µm. VF2 produced holes with the least roundness error under all the conditions except for hybrid and may be because of higher radial forces induced due to the effect of the liquid lubricant in the cryogenic environment. The radial forces in drilling significantly contribute to the roundness error of the hole (Chandrasekharan, 1996). Comparing the effect of cooling conditions on roundness of the hole, cryogenic machining produced the best results among all the conditions considered.

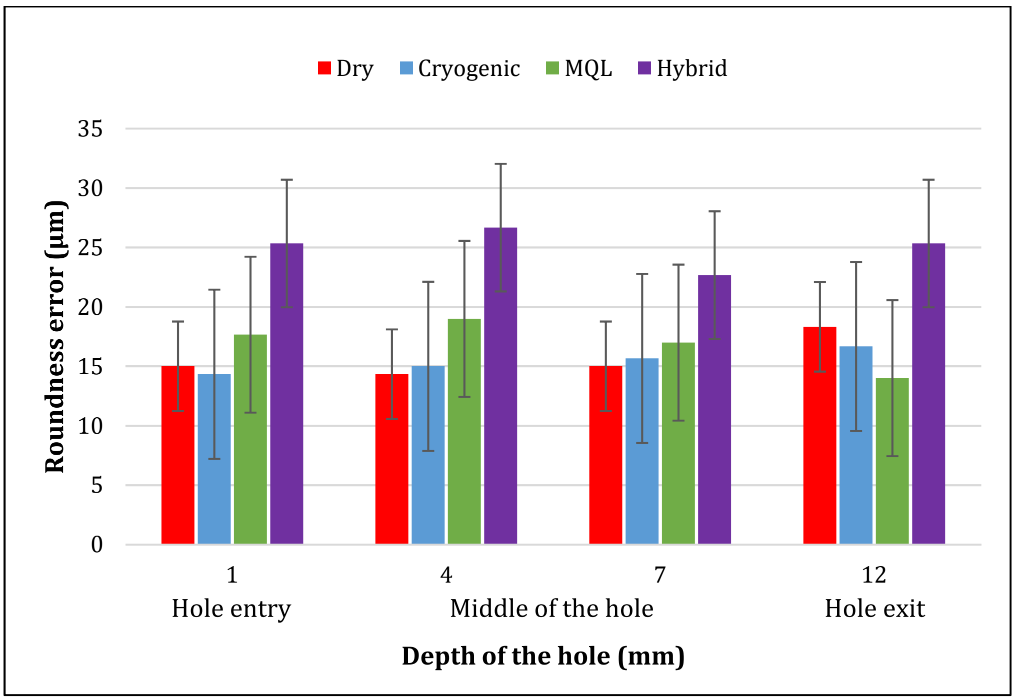


Figure 4.20 Hole roundness error comparison at 0.2 mm/rev

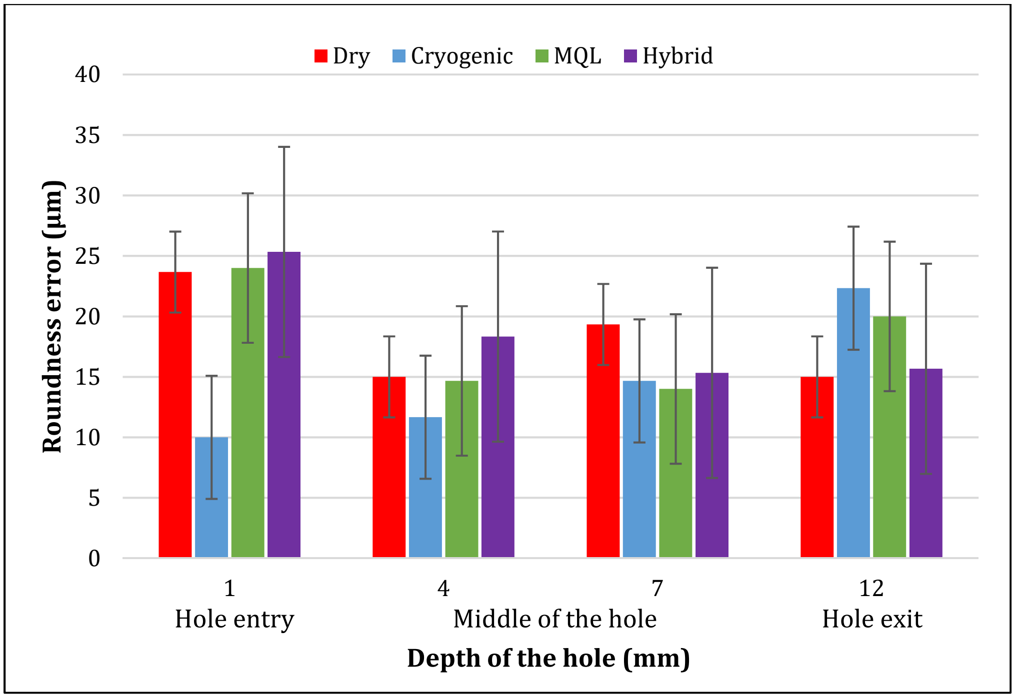


Figure 4.21 Hole roundness error comparison under VF1

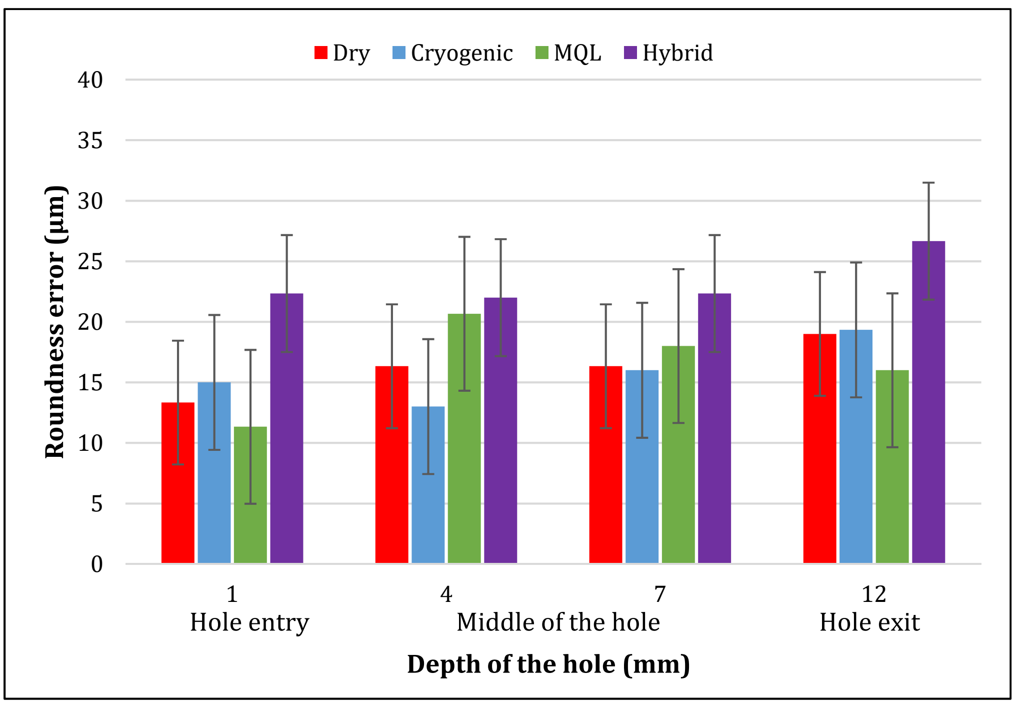


Figure 4.22 Hole roundness error comparison under VF2

4.3.2 <u>Surface roughness (R_a)</u>

The surface roughness values obtained from Zygo are shown as a function of feed rate in Figures 4.23, 4.24 and 4.25. The surface roughness was measured at entry, mid-section and exit position of the hole surface. The average R_a values under dry condition is found to be around 1.41 – 3.2 µm, while around 0.76 – 1.98 µm, 1.11 – 2.42 µm and 1.06 – 2.07 µm under cryogenic, MQL and hybrid conditions respectively. It is evident that cryogenic drilling produced a much better surface amongst all the cooling conditions considered. Since the composite behaves like a brittle material under cryogenic temperatures, it prevents the thermal damage on the hole surface and also improves the chip breakability which results in smooth surface (Morkavuk et al., 2018). This was followed by hybrid and MQL machining wherein the temperatures in the cutting zone were maintained due to the cooling effect produced. The surface topography in Figure 4.26 clearly shows the surface quality of the hole under all machining conditions.

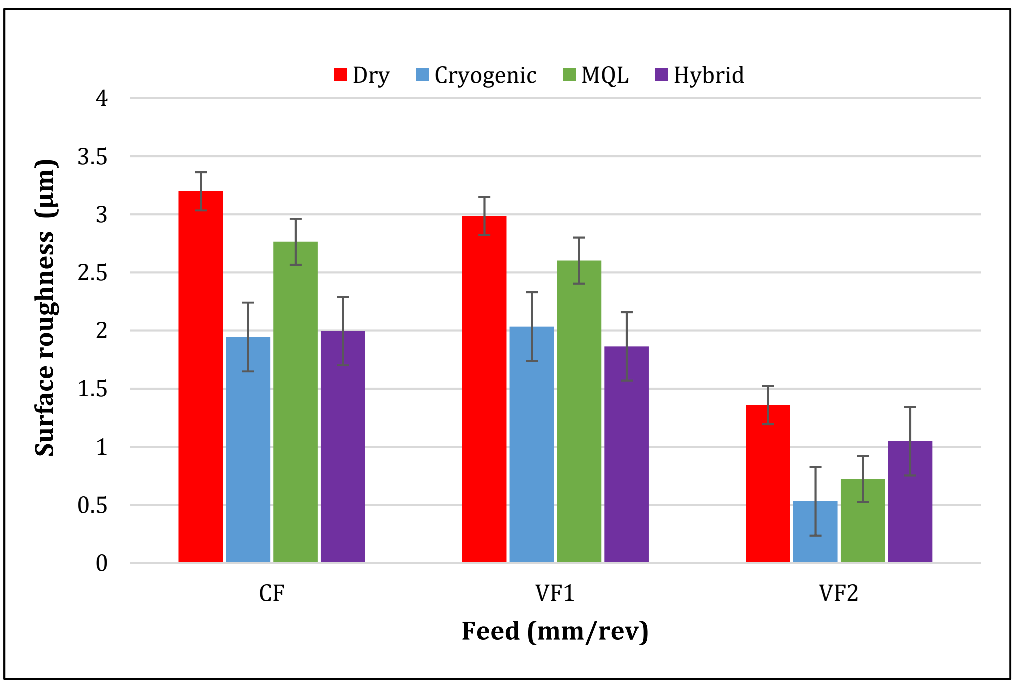


Figure 4.23 Surface roughness variation Vs feed at hole entry

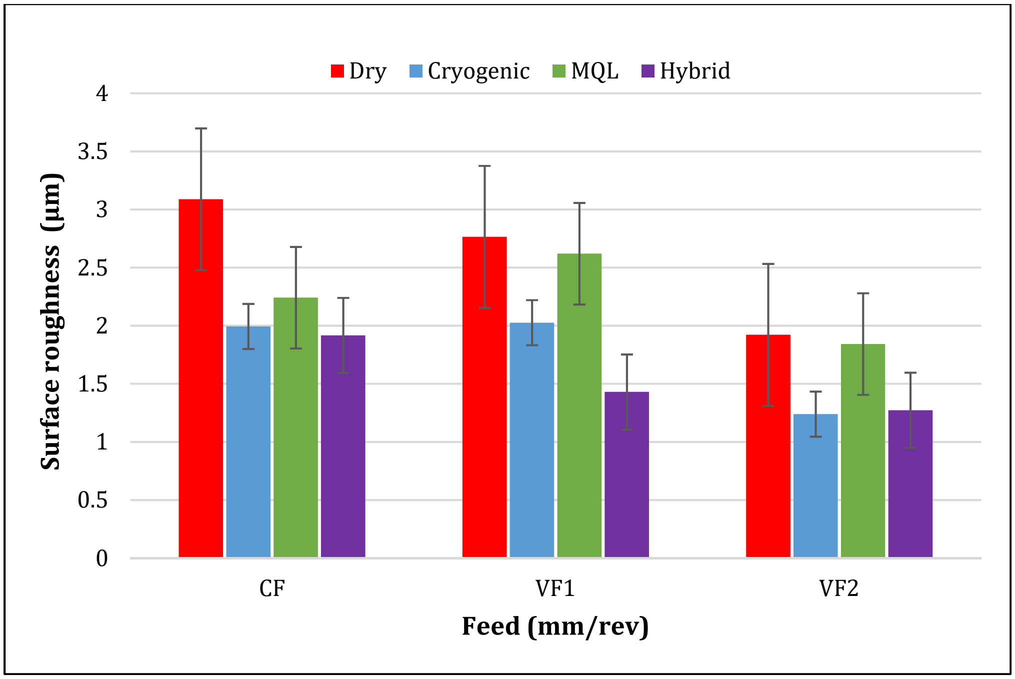


Figure 4.24 Surface roughness variation Vs feed at mid-section of the hole

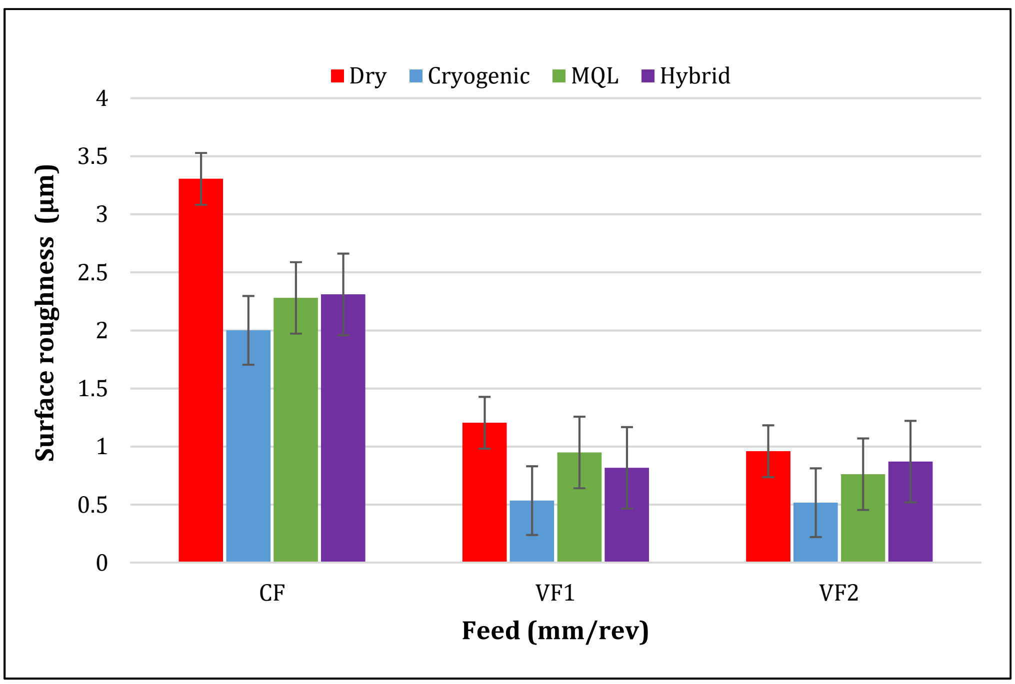


Figure 4.25 Surface roughness variation Vs feed at hole exit

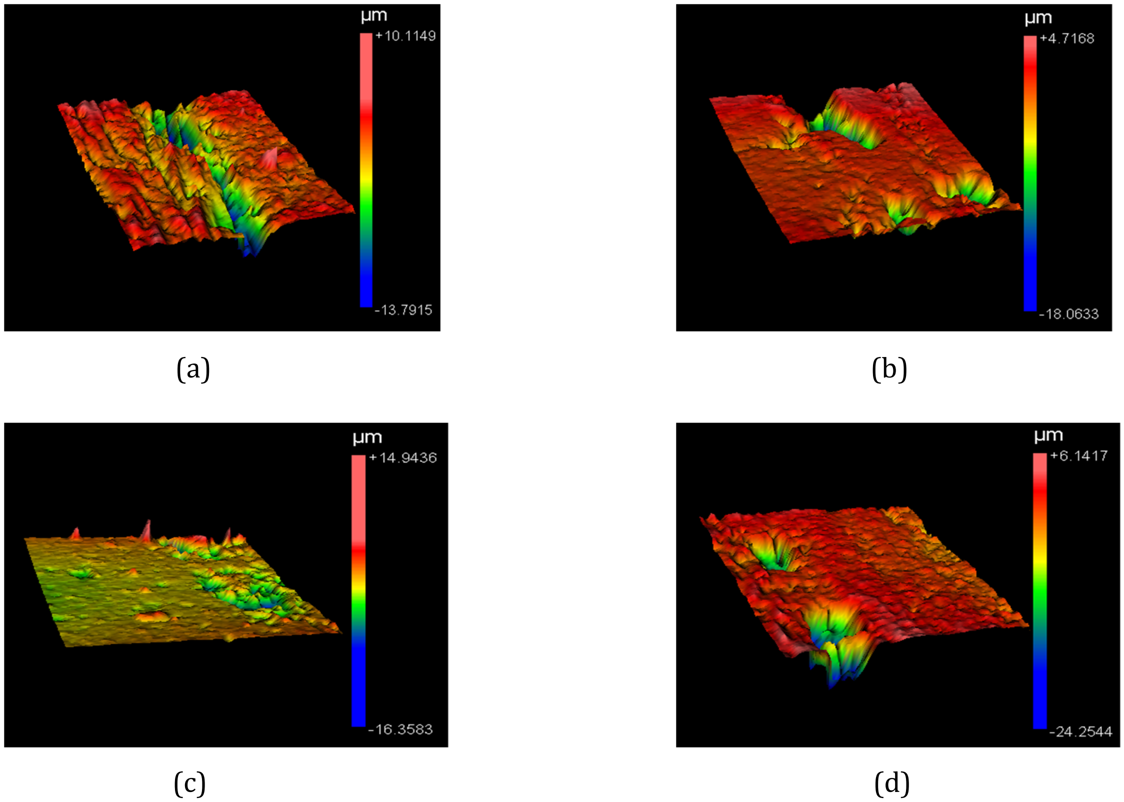


Figure 4.26 Surface topography of hole surface under (a) Dry, (b) Cryogenic, (c) MQL and (d) Hybrid conditions

Regarding the effect of feed rate on surface roughness, it was found that decreasing the feed rate improved the surface roughness characteristics as summarized in Figure 4.27. This is attributed to the fact that decreasing the feed decreases the heat generation and hence tool wear resulting in improved surface roughness (Palanikumar, 2008). It was noted that similar results were obtained by Joshi et al., (2018). Additionally, R_a near hole exit was found to be lower than that at the entrance may be due to the ploughing/ polishing effect that takes place under lower feeds of 0.05 mm/rev (MaojunLi et al., 2018). Furthermore, it was found that all the four cooling conditions achieved the recommended surface roughness value of < 4.8 µm (Sandvik Coromant).

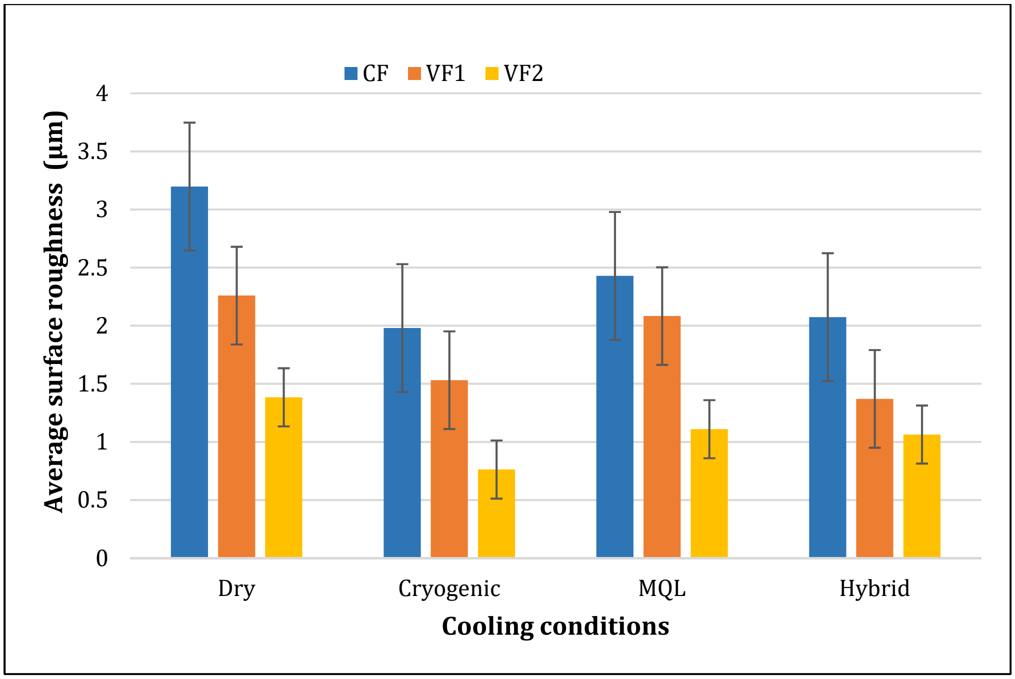


Figure 4.27 Effect of varying the feed rate on surface roughness under all cooling conditions

4.3.3 Hardness

The drilled samples were tested for hardness on Rockwell scale as per the ASTM D785 standard. M-scale is generally used for hardness measurement of plastics and soft materials and composites being similar, the same scale was used for measurement (Gopinath et al., 2014). Figure 4.28 shows the hardness as a function of feed rate under different cooling conditions. Under constant feed conditions, dry drilling produced higher hardness. However, under variable feed, the other three cooling conditions exhibited better hardness characteristics. Specifically, cryogenic drilling offered improved hardness. This is because of longer cutting time involved in variable feed leads to an increase in the modulus of the material as discussed before under the influence of cryogenic temperature. The hardness being a function of modulus of the material (Srinivasa and Bharath, 2011), increases with it.

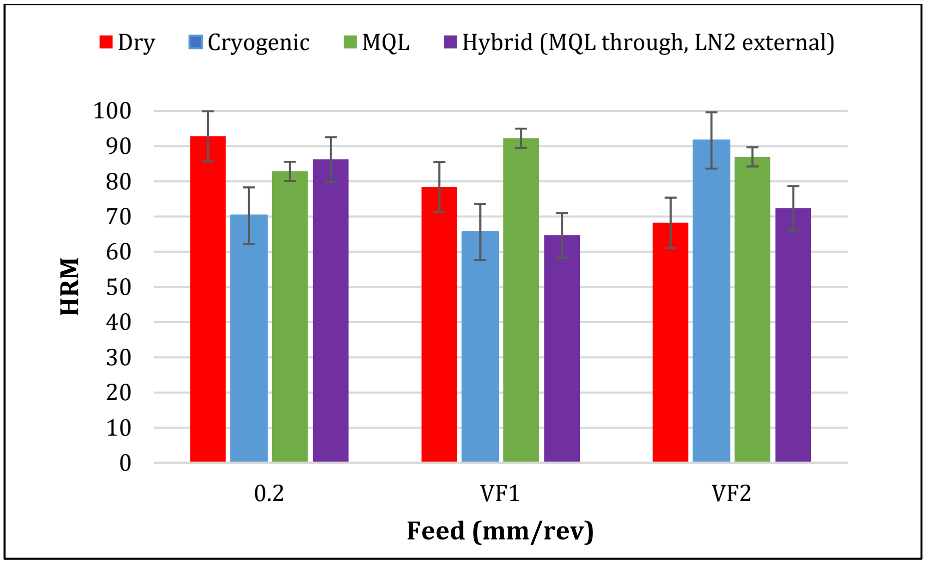


Figure 4.28 Hardness Vs feed under different cooling conditions

4.3.4 Sub-surface damage analysis

Surface integrity plays an important role as it exhibits the impact of surface properties and condition upon the product performance, longevity, and reliability (Astakhov, 2010). Composites, which are a class of significant materials in the aerospace industry need to be analyzed for subsurface damages after machining. The advantages of conducting sub-surface analysis is that any subsurface defects in the form of fiber/matrix pullout or fiber/matrix loss or internal cracks can be discovered and analyzed.

Figure 4.29 shows the typical cross-section of the composite specimen. As mentioned before, the composite used in this study have fibers oriented along 0˚ and 90˚ which can be clearly seen in the micrograph below.

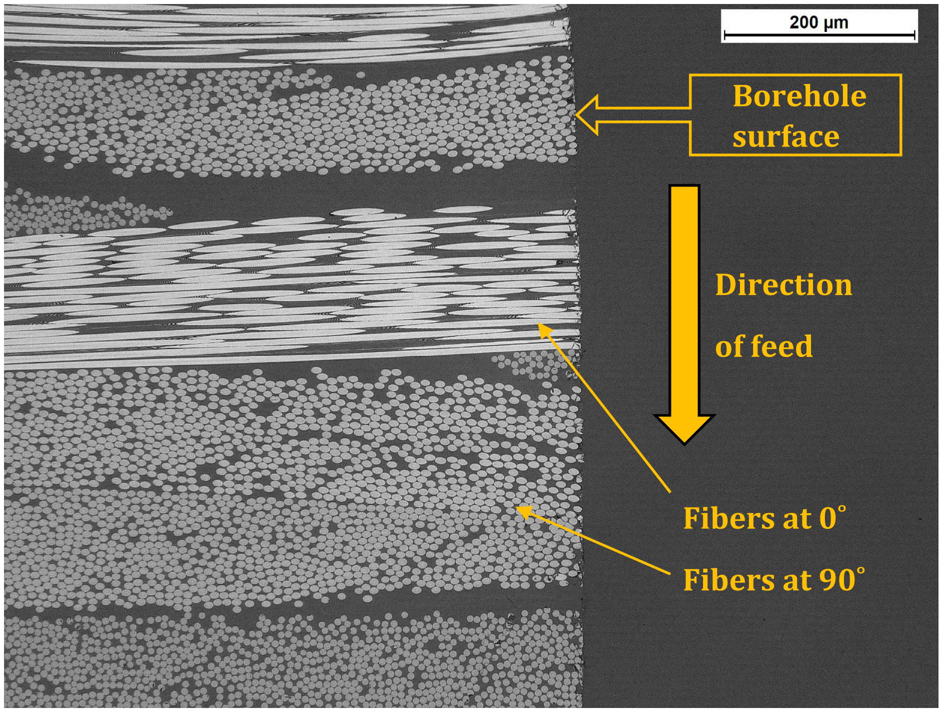
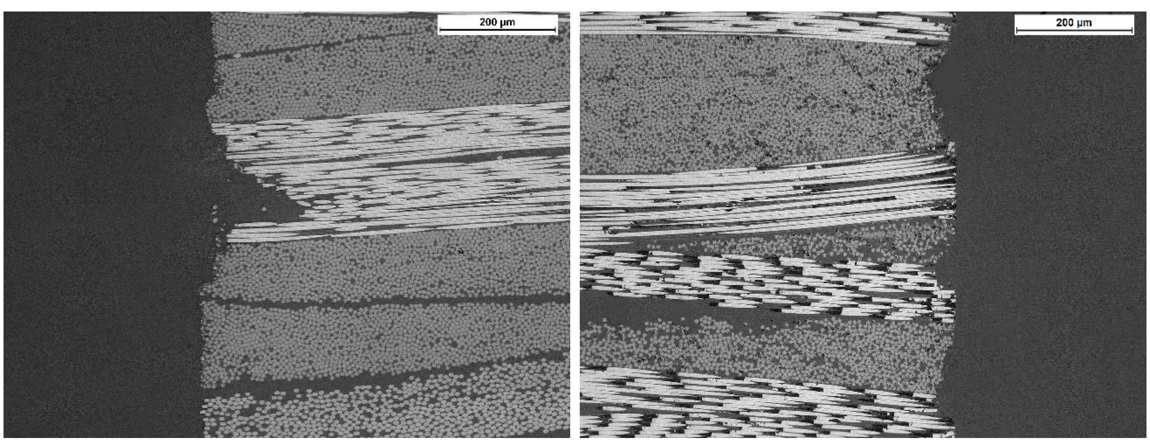
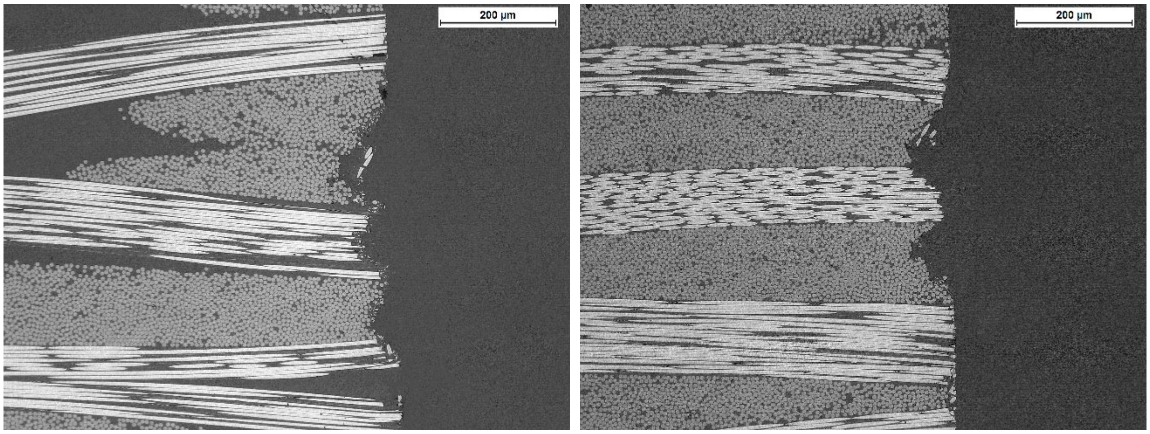


Figure 4.29 Micrograph of the CFRP sample showing fiber orientations

Machining conditions play a significant role in maintaining the sub-surface quality of the composite. Micrographs of the specimen under constant feed rate of 0.2 mm/rev are demonstrated in Figure 4.30 for all cooling conditions.



Dry Cryogenic



MQL Hybrid

Figure 4.30 Micrographs under all cooling conditions at constant feed

As it can be seen, dry drilling had the deepest sub-surface damage extending up to 176 μm. The high cutting temperatures involved in dry drilling lead to thermal softening of the matrix which results in weakening the support for fibers. This eventually lead to fiber pull-out and consequently due to the removal of fibers, cavities are created which increase the surface roughness of the machined surface (Basmaci et al., 2017). This validates the results obtained in Section 4.3.2. Additionally, the fibers at the surface oriented at 90˚ were bent to newer orientations between ~30˚ and ~60˚ leading to oval shaped cross-sections as shown in Figure 4.31. Similar results were reported by Brinksmeier et al. (2011). However, cryogenic drilling gave the best result among all the conditions considered, wherein damage was confined to a maximum of 61 μm depth from the surface. The lower temperatures involved in cryogenic machining increase the bonding strength between the matrix and fiber leading to fewer defects, like fiber pull-out (Basmaci et al., 2017). This results in machining smoother surfaces under cryogenic condition and is validated in Section 4.3.2. Damage up to a depth of 96 μm and 92 μm were observed under MQL and hybrid cooling respectively. When using MQL, the temperature in the cutting zone will be reduced resulting in higher material strength and higher resistance to interlaminar damage. This results in less sub-surface damage (Barnes et al., 2013).

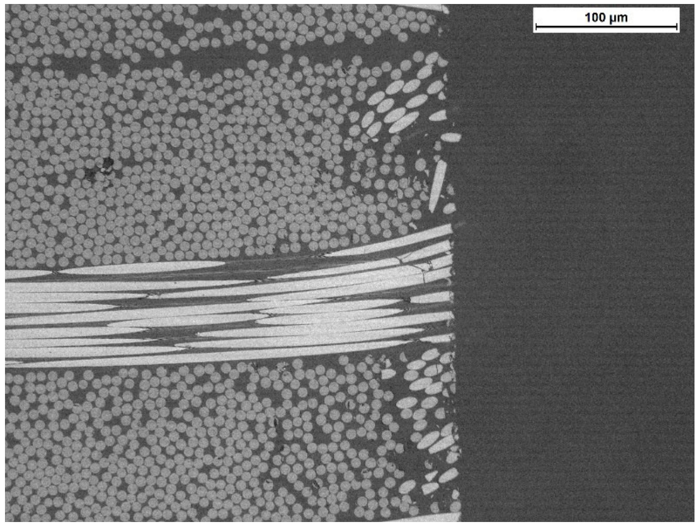
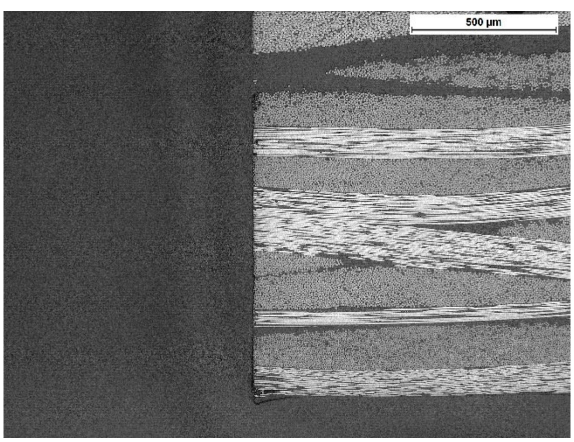
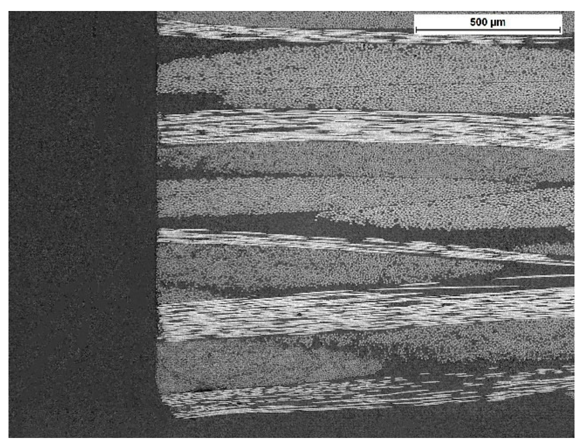


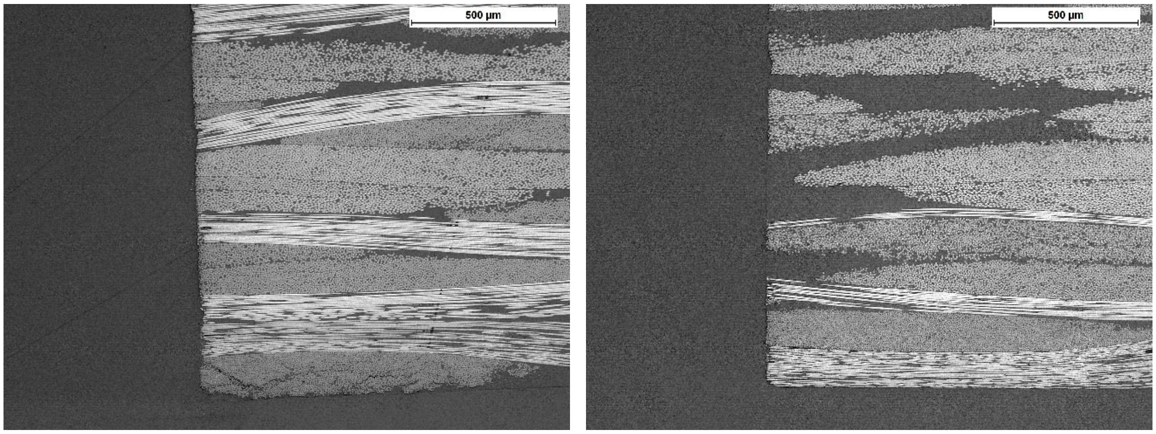
Figure 4.31 Fiber bending under dry condition

The technique of variable feed rate improved the sub-surface quality of the composite. Lowering the feed rate resulted in surfaces with almost no damage. Figure 4.31 shows the micrograph of the hole surface under all cooling conditions at lower feed rate of 0.05 mm/rev. This corresponds to better surface roughness characteristics at hole entry and exit as explained in Section 4.3.2.





Dry Cryogenic



MQL Hybrid

Figure 4.32 Micrographs under all cooling conditions at lower feed

This chapter provided an in-depth analysis of the effect of machining conditions on part quality and surface integrity when drilling CFRP. The major observations found in this study will be summarized in the next chapter.

CHAPTER 5

CONCLUSIONS AND FUTURE WORK

5.1 Conclusion

This thesis investigated the machining performance of CFRP in terms of thrust force and torque, part quality based on delamination, and surface integrity assessment based on diameter error and roundness, surface roughness, hardness and sub-surface damages through systematic investigation of drilling CFRPs under different cutting parameters and cooling conditions involving dry, MQL, cryogenic and hybrid (CryoMQL) techniques and analyzed the process performance under each condition.

The conclusions from this research work can be summarized as follows:

- The thrust force and torque developed highly depends on the machining condition i.e., dry or using any coolant/ lubricant. Cryogenic and hybrid drilling induced higher magnitudes of thrust force and torque among all the cooling conditions considered due to the fact that the Young's modulus and tensile strength increases under cryogenic cooling thereby increasing the drilling forces. Variable feed rate did show a positive effect on thrust force. However, varying the feed rate did not yield much change in the magnitude of the torque as compared to the variation in thrust force. This shows that feed rate has a marginal influence on the torque developed during the process.
- Entry delamination damage was found to be more severe under cryogenic and hybrid machining than under dry condition. However, exit delamination factor was higher in cryogenic medium followed by hybrid and MQL drilling. Following the impact of varying

the feed rate on thrust force, similar results were found in delamination. Lowering the feed resulted in reducing the delamination damage.

- Cryogenic drilling produced the best quality holes in terms of diameter and roundness error among all the cooling conditions because of the fact that temperature in the cutting zone will be reduced which maintains the life of the cutting edges. Also, varying the feed had positive impact i.e., lowering the feed minimized the diameter and roundness error.

- It was found that surface roughness under cryogenic drilling significantly improved since cryogenic temperature prevents thermal damage on the hole surface resulting in smoother surfaces. Also, MQL and hybrid gave better results than dry drilling. Additionally, decreasing the feed rate during the process resulted in improving the surface roughness characteristics.

- Sub-surface damages were found to be the highest under dry drilling and lowest under cryogenic drilling. The lower temperatures involved in cryogenic machining increase the bonding strength between the matrix and fiber which lead to fewer defects like fiber pull-out. Hybrid and MQL machining gave appreciable sub-surface quality. The effect of adopting variable feed rate was that lowering the feed resulted in surfaces with almost no damage at micro-level. The results obtained from sub-surface analysis was correlated with the surface roughness analysis under all conditions.

5.2 Future work

Based on the present research work performed, suggestions for future work can be elucidated as follows:

- Investigation of machining performance under hybrid cooling condition through conventional means i.e., rotating drill bit and stationary workpiece.
- Studying the effect of varying flow variables like pressure and flow rate when using MQL and cryogenic/ hybrid cooling condition on machining quality.
- Studying tool wear under MQL and hybrid condition and examining its effect on machining performance.
- Investigation of the effect of variable speed on the machining performance when drilling CFRP.

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