HOLE INTEGRITY OF CARBON FIBER REINFORCED EPOXY COMPOSITES USING COMBINED PUNCHING AND DRILLING TECHNIQUES

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UNIVERSITI SAINS MALAYSIA

2019

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by

MOHD SAFIE BIN ABDULLAH

Thesis submitted in fulfilment of the requirements for the Degree of Master of Science

April 2019

ACKNOWLEDGEMENT

Alhamdulillah, all praise to Allah SWT, who has answered all my prayers and eased the completion of this research work.

I am indebted to my supervisor, Assoc. Prof. Dr. Ahmad Baharuddin Abdullah for his insightful mentoring throughout the project. With his guidance, I was able to conduct the research systematically and be able to complete it in a timely manner. I also would like to thank to my co-supervisor Assoc. Prof. Dr. Zahurin Samad for the financial support provided by the Research University Grants (RUI). My appreciation also goes to the research members in the Metal Forming Lab, School of Mechanical Engineering, USM, who have provided support in terms of technical knowledge related to the project. Not forgetting, the technical and support staff at the School of Mechanical Engineering, USM, who have assisted in sample preparations, analysis and experimentations. Their contributions are greatly appreciated.

Special thanks go to my family and friends, especially my parents, Abdullah bin Hassan and Nurhani binti Yaakob for their encouragements and confidence in me to complete the study successfully.

Finally, I would like to acknowledge and express my gratitude for the financial support provided by Graduate Research Assistance (GRA) scheme, USM, for the tuition and subsistence allowances throughout the duration of the study.

Mohd Safie bin Abdullah

April 2019

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LIST OF ABBREVIATIONS

ASTM	American Society for Testing and Materials
AWJM	Abrassive Water Jet Machining
CFRP	Carbon Fiber Reinforced Polymer
CD	Conventional Drilling
CNC	Computer Numerical Control
CMM	Coordinate Measuring Machine
CV	Coefficient of Variation
DHS	Defense Hole System
EDM	Electro Discharge Machining
EDD	Electro Discharge Drilling
FRP	Fiber Reinforced Polymer
GFRP	Glass Fiber Reinforced Polymer
HAZ	Heat Affected Zone
ILSS	Interlaminar Shear Strength
IPF	Initial Ply Failure
IPFL	Initial Ply Failure Load
MMCs	Metal Matrix Composites
NDT	Non-Destructive Test
OD	Orbital Drilling
PCD	Polycrystalline Diamond
RPM	Revolution Per Minute
SEM	Scanning Electron Microscope
SD	Standard Deviation

UTM	Universal Testing Machine
VATD	Vibration-Assisted Twist Drilling
WJM	Water Jet Machining

LIST OF SYMBOLS

C	Punch-Die Clearance
D	Specimen Hole Diameter
d	Fastener or Pin Diameter
E	Specimen Edge to Hole Center Distance
HV_{20}	Hardness Value
L	Specimen Length
Ra	Surface Roughness
t	Specimen Thickness
W	Specimen Width
℃	Degree Celsius
E^{br}	Bearing Chord Stiffness
F^{IPF}	Bearing Strength at Initial Ply Failure
K	Factors of Double-Shear Tests
P	Load in Newton (N)
P^{max}	Load Maximum in Newton (N)
%	Percentage
Ø	Puncher Diameter
σ^{br}	Bearing Strength/Stress
ε^{br}	Bearing Strain
δ	Extensometer Displacement
$\Delta\sigma^{br}$	Changes in Bearing Strength/Stress
$\Delta\varepsilon^{br}$	Changes in Bearing Strain

KEUTUHAN LUBANG GENTIAN BERTELULANG KARBON EPOKSI KOMPOSIT MENGGUNAKAN GABUNGAN TEKNIK RICIHAN DAN PENGGERUDIAN

ABSTRAK

Penggunaan polimer bertetulang gentian sejak tahun kebelakangan ini meningkat dalam industri, kebanyakannya didalam struktur automotif, pesawat udara, dan maritim berikutan oleh nisbah kekuatannya kepada berat, tempoh fatig yang baik, rintangan kakisan dan sifat kebolehan pembuatannya. Salah satu kelebihan utamanya adalah strukturnya mudah dibentuk (acuan) kepada bentuk siap. Walaubagaimanapun, struktur ini masih memerlukan sendi untuk membentuk produk akhir. Ini adalah penting apabila reka bentuk produk terlalu rumit untuk dibentuksiapkan dalam satu acuan atau struktur memerlukan pemeriksaan kerap dan penggantian untuk penyelenggaraan. Maka, penggunaan sendi mekanikal dalam struktur komposit tidak dapat dielakkan untuk memasang siap kepada produk akhir. Keupayaan sendi mekanikal (sendi gegelung, sendi pin, dan sendi rivet) bergantung kepada kualiti lubang. Ini adalah kerana, beban dipindahkan antara sendi melalui pengikat, lalu menyebabkan konsentrasi tekanan menjadi tinggi di sekitar lubang dan pengikat. Penggerudian konvensional merupakan teknik asas utama yang digunakan untuk menebuk lubang pada panel komposit. Tetapi disebabkan oleh ketumpulan mata alat, kualiti lubang yang dihasilkan terjejas. Pada masa yang sama kos akan meningkat disebabkan kekerapan pengasahan mata alat. Daripada kajian yang lepas, teknik ricihan dicadangkan. Tiada masalah berkenaan dengan ketumpulan tetapi kualiti lubang pula menjadi masalah utama. Kajian ini membentangkan kajian eksperimen untuk membandingkan kualiti lubang yang terhasil daripada teknik penggerudian konvensional dengan teknik cadangan gabungan (ricihan + penggerudian konvensional) pada polimer bertelulang serat karbon (CFRP). Kesan kedua-dua teknik (teknik gabungan dan penggerudian konvensional) kepada kualiti lubang dan prestasi telah dinilai dengan menjalankan ujian eksperimen kekasaran permukaan dan kekuatan galas. Pengukuran kekasaran permukaan dilakukan melalui panjang persampelan 3.6 mm di sepanjang empat titik kuadran dinding lubang. Ujian galas telah dijalankan menggunakan lekapan yang diubah suai. Mod kegagalan yang dihasilkan dari eksperimen dikira dan dibandingkan dengan kajian literatur. Hasilnya mengesahkan bahawa penggunaan teknik gabungan dalam pembuatan lubang pada CFRP hampir sama dengan penggerudian konvensional sahaja dari segi kekuatan galas an, mod kegagalan, dan juga kekasaran permukaan.

HOLE INTEGRITY OF CARBON FIBER REINFORCED EPOXY COMPOSITES USING COMBINED PUNCHING AND DRILLING TECHNIQUES

ABSTRACT

The use of the fiber reinforced polymer (FRP) has been increased in recent year in many industries, mostly in automotive, aircraft and marine structures due to strength to the weight ratio, better fatigue life, corrosion resistance and tailored-made properties. One of major advantage is that structure can be moulded easily to the net shape. However, there is still a need to joint to assemble the composite structures into the final product. This is essential when the design of the product is too complicated to be moulded into single part or the structure need a frequent inspection and replacement for maintenance. Therefore, to assemble the structures together, the use of mechanical joint in composite structures is inevitable. The capability of the mechanical joints (bolted joint, pin joints, and rivet joints) depends on the hole quality and performance since the load transmitted via fastener give rise to stress concentration around the hole-fastener boundary. Drilling is the most common technique in hole making technique of composite panel. But due to wear, quality of the produce hole is severely affected. At the same time cost will increase as the frequent regrinding is required. From previous study, punching was proposed. Wear problem is not an issue in punching, but hole quality become the major issue. This experimental study aims to investigate the quality of hole prepared via conventional drilling technique and the combined technique (punching + conventional drilling) on carbon fiber reinforced polymer (CFRP). The effect of the both hole making techniques (combined technique and conventional drilling) to the hole quality and performance were evaluated by conducting experimental based on surface roughness and bearing strength. The surface roughness measurement was performed over a sampling length of 3.6 mm along at the four quadrant points of the hole wall. A bearing test a was conducted using modified fixture. The failure modes resulting from an experiment are quantified and compared to literature. The results confirm that the use of the combined technique in hole making on CFRP is almost similar to the conventional drilling alone in terms of bearing strength and failure mode as well as surface roughness.

CHAPTER ONE

INTRODUCTION

1.1 Research background

Composite material is defined as combination of two or more constituent materials which lead to a development of a material far superior than the properties of the individual constituents (Khayal, 2017; Aleksendrić & Carlone, 2015; Fragassa, 2017) . In recent year, composite material has begun to replace metallic material due to enchanced in strength to the weight ratio, thermal stability and resistance to enviromental degradation (Amir et al., 2016; Islam et al., 2015; Kim & Lee, 2016). The use of composite material in engineering structures today has spread into a wide range industry especially automobile, aircraft and marine industries (Arif et al., 2017; Kumar & Reddy, 2014). Composite materials are assembled as composite structures either by mechanical joint or bonded joint (Jadee & Othman, 2011). Due ease of access in assembly for inspection and maintenance, mechanical joint are preferred over bonded joint. In mechanical joint, composite material is assembled either via bolted joint, pinned joint or riveted joint (Lopez et al., 2017; Puchała et al., 2015). These joint required holes to resemble the structures and parts. Moreover, the joints efficiency is highly dependent on the quality of produced holes (Ashrafi et al., 2016). Since the quality of the holes is always associated with the damaged induced during drilling processes, therefore, there are a great effort of improving the quality and performance of the existing conventional processes besides introducing a new developed method in order to provide solution to the challenges facing the industry.

Research effort that have been done regarding hole making technology in composite material will be further discuss in chapter 2. Since most of the existing method produces hole in laminated composite is by drilling and involved direct contact between the workpiece and cutting tool (except for those related to unconventional method), the tool facing extreme tool wear. The defect in hole making processes associated with drilling induced damage due to the tool wear including the time needed to regrind the tool, caused the manufacturing cycle time and production cost increase (Raj & Karunamoorthy, 2016). Aside from drilling, punching in composite area show a great potential and have been studied by a number of researchers. However, the application of punching in composite material is new, and only a few work have been conducted and not well established as the punching on metal. In some cases, punching exceed expectation over drilling in term of time, speed, versatility, and cost (Wang et al., 2016; Klocke et al., 2017). However, punching in composites material is challenging due to having different mechanical/physical properties for the multi-phase structures.

Previous researcher have covered the studies of punching in composite laminates mostly in term of hole quality. This includes the evaluation of hole damage by measuring delamination factor, hole roundness, cut neatness, wear and hole edge quality which will be further discussed in literature. However, the evaluation of hole performance (i.e. bearing test) in punching are not commonly found in literature. Both hole quality and performance are important for assembly of composite structure to ensure the safety of the joint connection. Hence, it is necessary to study extensively in this area especially the hole performance in punching technique to evaluate the bearing strength characteristic to determine the limit that can be achieved before failure.

1.2 Problem statement

One of the most severe challenges in hole making on composite is the occurrence of induced damage, which could results poor bearing strength of the hole. The capability of the joint depends on hole quality because the load transmitted via fastener gives rise to stress concentration around the hole fastener boundary. Hence, it is important for the hole to be strong enough and good in surface quality. At present, most of the manufacturer used conventional drilling in hole making operation. Due to intense machining operation of composite materials, the cutting tool suffer rapid tool wear which degraded tool life, thus, uneconomic production cost, production rate and damage to the product. However, wear is not an issue in punching. Addititionally, punching showed a great potential in hole making on laminated composite compare to drilling in term of time, speed, versatility, and cost. From previous studies, there is a significant different in quality of punched holes compared to drilling. Anyhow, the punching technique depicted its potential to replace drilling as the overall condition of the hole is still within the acceptable range such as roundness and delamination level. Therefore, potential of the hole prepared by punching can be further explored by determining the strength of the holes.

1.3 Research objectives

Based on mentioned above, the present research is aiming at adressing the following three objectives:

1. To analyze experimentally the bearing response on how the specimen exhibit under load, as well as into the effect of different hole making technique (punching and conventional drilling) of CFRP to the loading trend (pattern of graph), bearing strength and failure mode of the hole under tensile loading. From that point, a reliable

experimental data of both conventional drilling and punching can be attained and will be a guideline to compared with the second research objective.

2. To evaluate the performance of the combined technique (punching and conventional drilling) in terms of bearing strength and surface roughness of the hole. The result of experiment will be compare to the conventional drilling as a benchmarks.

3. To investigate the effect of hole diameter (5 mm diameter and 10 mm diameter) to the bearing strength and failure mode of combined technique (punching and conventional drilling) and conventional drilling.

1.4 Scope of study

The experiment were conducted according to the ASTM D 5961 Procedure-A, double shear with single pin loaded. The specimen is obtained from part of an aircraft wing panel of a commercial aircraft. The material used is carbon fiber epoxy prepreg (FIBREDUX 6268C-833-45) using autoclave for curing. For this study, the parameter considered are the type of hole making technique (conventional drilling, punching, and combined technique) and geometry configurations (E/D ratio and W/D ratio). The geometry configurations were fixed for all tested specimens. The output is focused on bearing data including bearing load, bearing strength and bearing chord stiffness, loading trend, and failure mode type. The measurement of the bearing test is done by internal displacement transducer recorder built in system of an INSTRON 3367 UTM with 30 kN loading capacity. For the failure mode analysis, it will be observed at macro level as recommended by the standard, which will be captured using an Andonstar ADSM201 HDMI 1080P Full HD USB Microscope.

1.5 Research significance

The contributions from this research work are:

i. The understanding of the different behavior of bearing strength characteristic and surface quality of the hole with different type of hole making method.

ii. The results can be used to possibility of developing a new machine by implying combined technique (punching and conventional drilling) for hole making.

1.6 Thesis outline

The aforementioned research objectives will be addressed in the thesis according to the following outline:

1. Chapter 1 presented general view about study and outline the scope of study regarding to the research problem stated.

2. Chapter 2 will discuss the research work in available literature review of the hole making technology of fiber reinforced polymer (FRPs) and the overview of the mechanical joint, standard test and bearing failure mode in laminated composite. This review will circumscribe a complete picture of hole making technology as well as the problem facing of each of them.

3. Chapter 3 will describe the whole research steps involve. The chapter also explains in detail the procedure to carry out the experiment.

4. Chapter 4, there are two experiments will be discuss according to priority. Experiment I and Experiment II will answer research objectives. In order to quantify the improvement of the combined technique, the results of the combined technique will be compared to the results of conventional drilling.

5. Chapter 5 will present the main conclusion of the entire research finding, as well as recommendations for the future research work.

CHAPTER TWO

LITERATURE REVIEW

2.1 Research background

The use of a mechanical joint in composite structures has grown steadily in recent years since it is a promising technique in terms of cost and accessibility for inspection, maintenance, and repair work compared to adhesive joint (Dutton et al, 2004). However due to structural discontinuities in joint geometry, the load transmitted via fastener give rise to the stress concentration around the hole-fastener boundary and might cause the premature failure of the entire structures (Tsukasa et al., 2010). Unlike ductile materials, composite laminates are brittle, non-homogeneous, multi-phase structure and anisotropic in nature (Panchagnula & Palaniyandi, 2017). For that reason, stress concentration are not relived by localized yielding compared to metals.

Since the performance of the mechanical joints is highly depending on the hole quality such as hole geometry, hole integrity and countersink geometry, therefore, a thorough understanding of hole making operation is necessary. This chapter presents a comprehensive review of hole making technology and overview of the mechanical joint, standard test and bearing failure mode commonly found on laminated composite panel.

2.2 Hole making technology

In the manufacturing industry, most of the structures applications, consists of a large number of holes having different diameters, type of hole (round holes, counter-boring, countersinking, honing, reaming, lapping, and sanding), depth and surface finish mainly for assembly purposed. As technology advances, the complexity of the profile, hard materials, high productivity, low cost, smooth surface finish and closer in dimensional accuracy and tolerance has led to the development of new hole making technology.

There are many types of machining based technology that have been developed as the demand for composite applications continues to rise. The method of hole making on composite could be divided into two, namely, machining and non-machining methods as shown in Figure 2.1. Machining can be further divided into traditional and non-traditional methods. Although several non-traditional machining operations such as abrassive water jet machining (AWJM), electro discharge machining (EDM), and laser beam machining (LBM) have been suggested, drilling operation remain as the method of preffered hole making on the composite material by manufacturer and still significant (Ariffin et al., 2009). The composite material, mostly very abrasive and since the drilling operation involves direct contact between tool and workpiece, cause, the tool suffers extreme wear and formed a huge amount of heat, which lead to degrade tool life and most importantly the hole quality (Peng et al., 2013). Under drilling operations, there are conventional drilling (CD), high speed drilling (HSD), grinding drilling (GD), vibration-assisted twist drilling (VATD), and Orbital drilling (OD), which will be further described in the next sub-section. Among these drilling operations, conventional drilling with twist drill bits is the first operation attracting extensive attention and studied elsewhere (Amir et al., 2016).

The next section will further elaborate the technologies in holes making based on illustrated diagram shown in Figure 2.1. The machining technologies will be emphasized on the traditional machining operations, focus on various drilling operations, while other machining such as milling will be explained in brief, For the non-traditional machining technologies, the elaboration will be brief. The non-machining technologies i.e. punching will be discussed in detail.

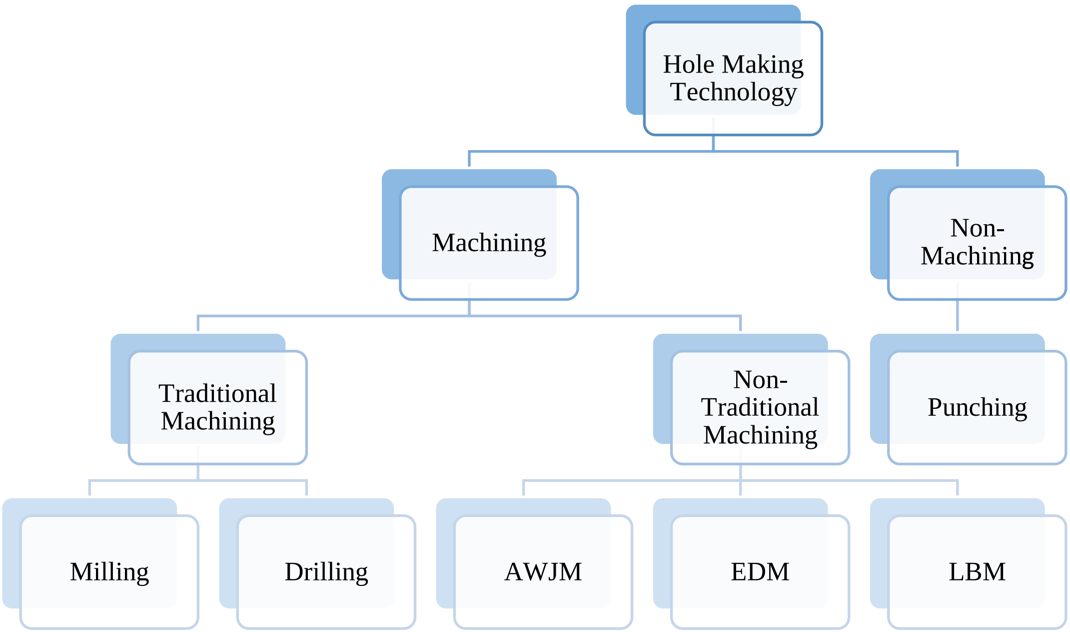

Figure 2.1: Technologies in the holes making

2.2.1 Machining

a) Conventional drilling

The conventional drilling operation of FRP laminates is the first drilling operation that draws an extensive investigation by many researchers compared to others. Majority of the research work on conventional drilling of FRPs is focused on experimental investigation to study the input variable such as drilling parameter (spindle speed and feed), drill bit geometry, drill bit material, a type of composite material, and diameter size) on the output variable such as hole quality (delamination, surface roughness, and roundness), thrust force, and bearing strength of the hole (Liu et al., 2012). Most of the drilling operation is using twist drill bits and other special drill bit (step drill bit, center drill bit, dagger drill bit) as the cutting tool . However, twist drill bit by far the most used as a cutting in drilling operation (Tsao & Hocheng, 2005; Wei et al., 2013). Hole making in conventional drilling consist of multiple stages of drilling before produces hole with a specific size of the diameter. If the diameter of the hole relatively large, a pilot hole with a small diameter may have to be drilled at the first stage and then enlarge it to the final size with a larger tool as shown in Figure 2.2 (Dalavi et al., 2016). This is to avoid the high stress concentration at the hole boundary of the workpiece material and to keep the damage to the minimum (Tsao & Hocheng, 2003; Tsao, 2006).

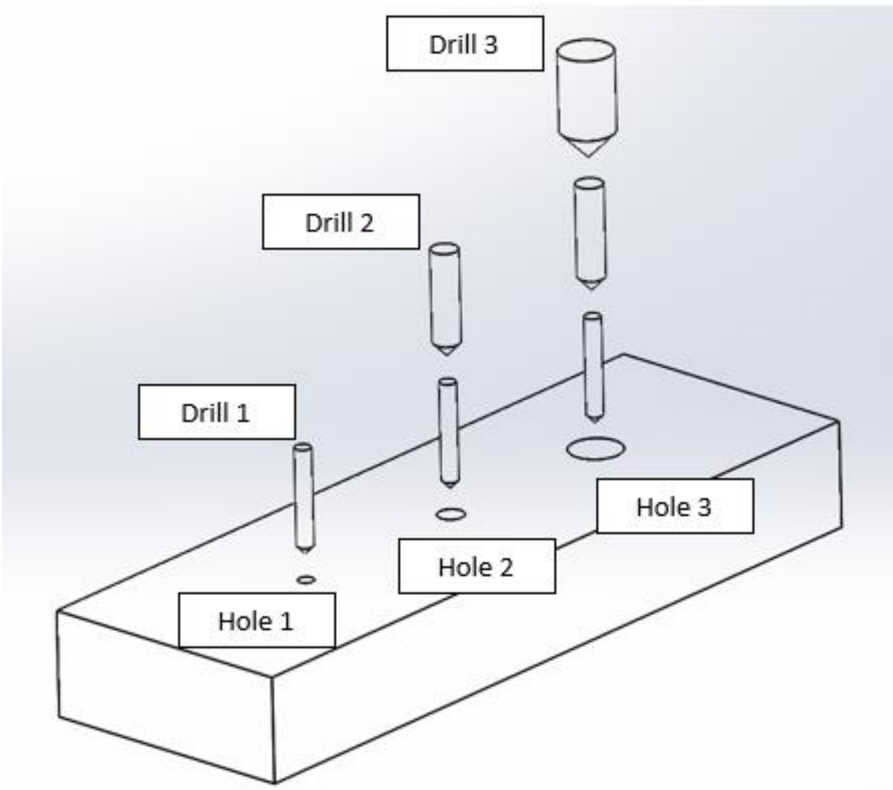

Figure 2.2: Multiple stages to drill a hole on workpiece (Sketch using SolidWorks)

b) High speed drilling

Continuous development of the cutting tool (material and geometry) has enabled a reduction in cutting time and improved the productivity (Liu et al., 2012).

There are few basic requirement need to take into account in high speed drilling, namely, concentric system (related to tool material behaviour when operate at different cutting speed), tool material, coating material, flute geometry, and coolant delivery (Zelinski, 2018). The main purpose of the high speed drilling technology is suppose to produce less delamination in a short time with a single shot drilling (Uhlmann et al., 2016). Similar to the conventional drilling, it is the most promising drilling operation that leads to better performance and improved the quality of the hole. Unlike others drilling operation, high speed drilling is carried out at very high spindle speed and results in reduction of the delamination (Gaitonde et al., 2008; Karnik et al., 2008). However, increasing the speed literally increase the power consumption of the machine operation and tooling cost due to the wear and causes the total machining cost became very expensive (Ocena & Cieplnego, 2015).

As the speed goes higher usually 5 to 10 times more than conventional drilling, the rate of temperature increase and the composite laminates are prone to thermal damage (Hosono et al., 2009). At the higher temperature, which exceed the epoxy melting temperature, the heat buildup from the friction contact between the tool and the workpiece soften the matrix epoxy and evaporated into the air which known as matrix burn out and cause only fiber left. This results in interlaminar delamination (Khashaba & El-Keran, 2017). Not only that, it is also shortened the tool life span (Rawat & Attia, 2009b). Since the temperature significantly effects the hole quality and tools (Isbilir & Ghassemieh, 2013), there comes coolant which offering conclusion to the temperature issues. Nowadays, most applications of high speed drilling came with high pressure coolant flow system to avoid catastrophic thermal damage to the workpiece instead of removing chips (Dhar et al., 2006). Yet, the aerospace manufacturing industry is moving toward high speed drilling under dry conditions with optimum cutting parameter due to economic and environmental reasons (T. Singh et al., 2016). Dry drilling conditions might be a better choice for the thin composite laminates because of short contact time which decrease the heat buildup.

c) Grinding drilling

Grinding drilling also known as core drill is one of the drilling operation that reduce delamination damage to the finest. The idea of the grinding drilling is focusing on the periphery of the hole. There is no chisel edge that acting on the pre-drilling like a normal drill bit since the center of the drill bit is hollow. The absent of chisel edge reduces thrust force, and hence delamination (S Jain & Yang, 1994; Jain & Yang, 1993). It was found that by increase the number of teeth on core drill can lower the cutting force. Therefore the author proposed the cutting tool with hollow shaft by coating it with certain grit size of diamond material (Tsao & Hocheng, 2007b). Diamond material has an extremely high thermal conductivity which can provide good conduction of heat to remove from the cutting edge and extend the tool life . In previous research, the preferable grain of the processes over the carbide material due to diamond provides high abrasive wear resistance. The different grain size of coated material also influences the surface quality of the hole and the heat distribution over the matrix of the hole boundary. The result of the investigation shows that by increase the grain size, results in lower thermal load and allow the heat to dissipate more efficient. On the other hand, it was shown that finer grains has improved the surface quality of the hole (Biermann et al., 2017). There are different type of geometry for core drill bits and each of them serve different purpose. The Figure 2.3 shows a different design of core drill bits.

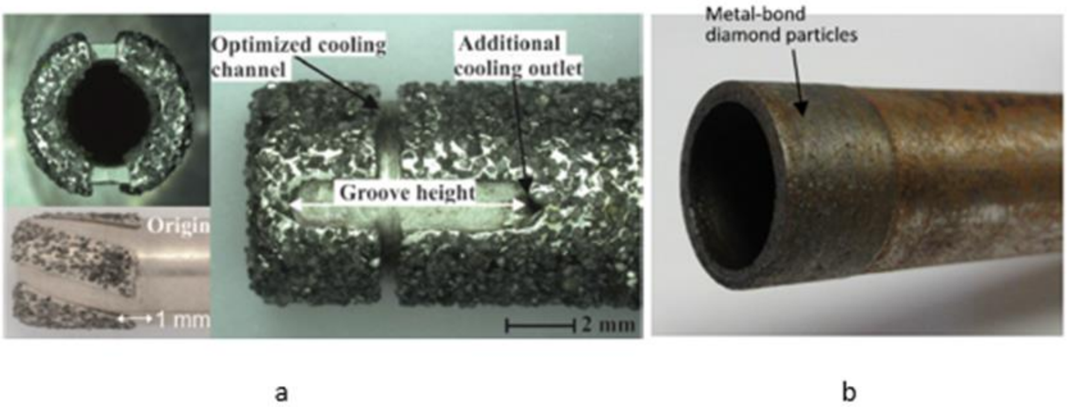

Figure 2.3: Different design types of core drill bits (Biermann et al., 2017; Liu et al., 2012)

An extention improvement of cutting mechanism of micro-core drilling has been made by introducing a shear mechanism at the cutting edge of the core drills using novel tool design (defined cutting edge using polycrystalline diamond, PCD). The conventional core drills (randomly distributed micro grains) are simply using electroplated diamond abrasive micro-core drill produces an abrasive/rubbing action which results in random cutting edge geometry (negative rake angle, protrusions, densities). This defieciency of the random cutting edge geometry is not the best solution for machining parameter. According to the result of the research, a novel micro-core drill reduce drilling force and temperature by 36% and 11% over conventional core drills, respectively. In addition to these findings, the evaluation of the novel micro-core drill produces holes with greater edge definition and surface quality (Butler-Smith et al., 2015). Figure 2.4 shows the image of (a) Conceptual design of laser generated PCD core drill and (b) SEM image of laser generated tooth profile in PCD and profilometric measurement image of its geometry .

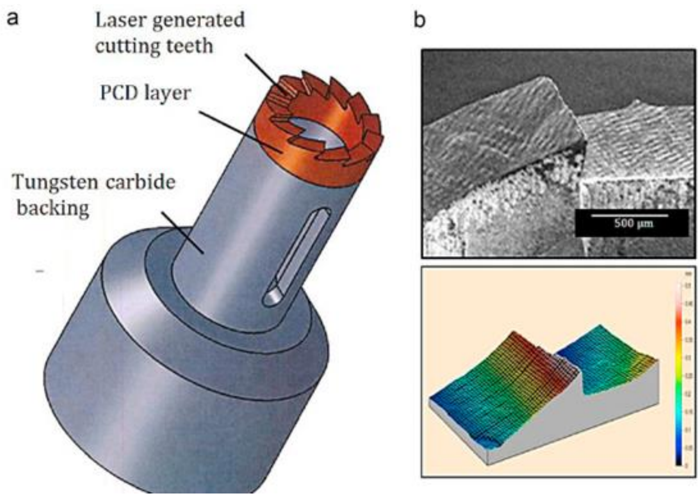

Figure 2.4: (a) Design of novel PCD micro-core drill (b) SEM image of laser generated tooth profile in PCD and profilometric measurement image of its geometry (Butler-Smith et al., 2015)

d) Vibration-assisted twist drilling

Vibration-assisted twist drilling (VATD) is another branch of vibration cutting that uses vibration in the drilling process and it is different from conventional drilling operation. There are three directional modes of vibration that occur in a drilling process, namely axial, lateral and torsional. These are the three direction drill move when it's run on the surface of the workpiece. Most of the conventional drilling are continuous axial motion of the drill bit toward the workpiece. This continuous motion of the drill generates heat by the friction contact between the tool and workpiece and the temperature rises as the drilling progress. In VATD, the process added small-amplitude, low/high-frequency tool and superimposed with conventional feed in axial motion with controllable intermittent intervals. This allows the intermittent separation and contact between the tool and the workpiece, which reduces the contact area and led to decrease in frictional force (Wang et al., 2004). So by comparing VATD over conventional drilling, VATD have a unique characteristics such as impacting, separating, changing speed, and changing angle in the whole drilling process (Wang et al, 1987). In general, this process interrupted continuous contact between the tool and workpiece and exhibit a great potential in improving the cutting ability of a chisel edge and restraining the skidding of a chisel edge, surface roughness, thrust force, delamination, and extend the tool life while maintaining process productivity (Zhang et al., 2001; Babitsky et al., 2004). It has been reported that in some research by analyzing the VATD and conventional drilling, the thrust force reduces by around 40% compared to conventional drilling. Therefore, implementing the VATD can reduce the delamination in drilling composite laminates (Arul et al., 2006a).

e) Orbital drilling

Orbital drilling (OD) has huge potential alternative to conventional drilling for minimizing damage in composite laminates. OD particularly effective for hole-making operations in laminate materials, such as CFRP/aluminum and CFRP/titanium used in aerospace applications which need precise dimensional accuracy and tight tolerances (Zhao et al., 2015; Yagishita & Osawa, 2016). The working principles of OD can be described in three basis motions, spindle rotation, feed, and orbital rotation, as shown in Figure 2.5. Combining three of these motions created spiral/ helical rotation of the cutting tool. As the cutting tool spin in it's own axial direction, then the tool simultaneously moves offset (in lateral direction) to the desired hole diameter. By calculating the desired offset, single cutting tool can be used to drill any diameter larger than the tool's diameter (Iyer et al., 2007). Thus, its essentially reduces the need of multiple tool to drill a single hole and also eliminating the time for tool changeover. During the OD process, the tool is in partial contact between the workpiece and this action enables the performance of heat extraction become more efficient. Additionally, normal mechanism of other mechanical drilling , the tool move straight concentric in axial motion to the laminates which results in high pressure at the center of the machine hole. However, in the OD operation, the tool move in helical feed motion which put reduction of the pressure in the center of the hole while machining. Consequently reduces the matrix resin from burnout in heat-affected zone (US 6,773,211 B2, 1986). The cutting tool material commonly used in OD process is Polycrystalline diamond (PCD) and carbide end mills. These advantages of the OD significantly decreased total cycle time can increase the productivity and profitability (Sultana et al., 2016).

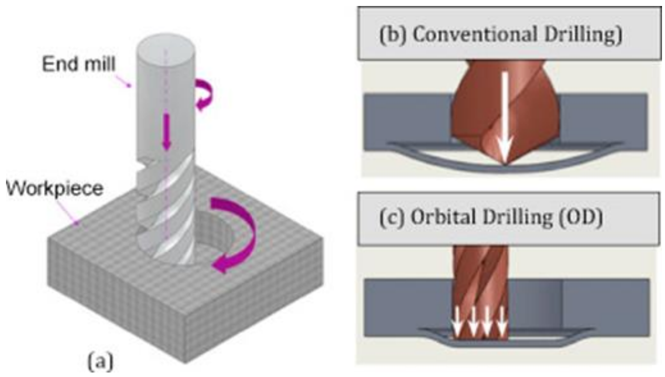

Figure 2.5: (a) Tool motion in orbital drilling; (b) and (c) deflection of the last ply in CD and OD, respectively (Sadek et al., 2012)

f) Milling

Milling is a machining process that uses rotating cutter containing number of cutting edges to remove the material. Milling operation is done by using milling machine which consist of motor driven spindle mounted to the milling cutter, and reciprocating adjustable worktable which mount and feed the workpiece. Milling machine can be used for boring, slotting, circular milling dividing, and drilling (US Army, 1996; Od, 1988). Recent work from researchers reported that, the used of end milling in hole making on composites laminates results in better surface quality (minimum surface roughness, minimum difference in upper- and lower-hole diameter) compared to the conventional drilling if the cutting quality is become a primary choice (Ali et al., 2013). The investigation of the effect of machining parameters setting to the surface roughness during end milling of CFRP-Aluminum composite laminates by (Nurhaniza et al., 2016) showed that, the optimal cutting parameters combination for good surface finish is high cutting speed, low feed rate, and low depth of cut.

g) Unconventional machining

Generally, the unconventional machining technique is defined as a group of processes that remove excess material by various techniques involving mechanical, thermal, electrical or chemical energy or combinations of these energies, but do not use a sharp cutting tool as the case for traditional manufacturing processes. Among the many unconventional machining techniques, a few will be discussed in this sub-section, namely abrasive water jet machining (AWJM), electro discharge machining (EDM), and laser beam machining (LBM).

i) **Abrasive water jet machining (AWJM).** Abrasive water jet machining has been used in industry for such purposes and provided some advantages over conventional/mechanical drilling operation. AWJM offer the cutting process of the workpiece material such as no thermal effect, high machining versatility, high flexibility, small cutting force, and high productivity. Also issues like burr formation and delamination is almost negligible (Alberdi et al., 2013). AWJM use erosion mechanism as a working principles. A water jet of high pressure, high velocity, and abrasive slurry to cut the target material by means of erosion (Unde et al., 2014). In some research done to investigate the quality of the cutting hole of the GFRP, the author found that the quality of the hole in GFRP is highly dependen on the right choice of the cutting parameter in cutting process (Thongkaew et al., 2016). Another researcher carried out an experimental investigation using AWJM on the composite laminates and the finding of the research shows the delamination of the laminates can be reduced by reducing the jet speed but on the other hand, the piercing deteriorated (Ibraheem et al., 2015).

ii) **Electro discharge machining (EDM).** Electro discharge machining also known as spark erosion machining. The process basically removes the material using electric spark. There are 3 types of electro discharge machining, namely, die sinker EDM, wire EDM, and hole drilling EDM. In this sub topic of EDM, we will cover basic concepts of hole drilling EDM which is also called Electro-discharge drilling (EDD) (Singh et al., 2013). EDD is a process of hole making for electrical conductive material which hardens to machine. Machining of metal matrix composite (MMCs) using EDD is inevitable due to their high material hardness and wear resistance property. Conventional/mechanical drilling might not a suitable choice to employ in making of a substantial number of holes due to rapid tool wear. MMCs are composite material with at least two constituent parts, one being a metal necessarily, the other material may be a different metal or other material, such as a ceramic or organic compound. When at least three materials are present, it is called a hybrid composite (Abhishek et al., 2013). This makes drilling MMC become more difficult because each material has different properties.

iii) **Laser beam machining (LBM).** Laser beam machining (LBM) is a form of machining, in which a laser is directed towards the work piece for machining. LBM is one of the advanced manufacturing processes that capable to machining all ranges of material from metallic alloy to non-metal (Parandoush & Hossain, 2014; Patel et al., 2013). Therefore, LBM provides solution for critical problem which conventional/ mechanical drilling are not capable of. Material removal in LBM is a thermal material removal process that utilizes a high-energy, coherent light beam to melt and vaporizes particles on the workpiece in the focus point (Industries, 2015). The advantages of LBM such as improved end product quality, short processing time, non-contact process, cost reduction and small heat affected zone (HAZ) have made the used of it in many manufacturing industries (Dubey & Yadava, 2008). For cutting composites, the general types of lasers used are CO2 and neodymium yttrium aluminum garnet (Nd:YAG). Composite laminates having more than one constituent material which make it difficult to laser machining because the component of the composites have varied thermal conductivity (Meijer, 2004). This mean, in FRP, the power needed for laser to vaporize (cut) the fiber (CFRP or GFRP) is much higher than polymer (epoxy and etc). For this reason, it is important to set the laser cutting parameters (laser power, cutting speed, gas pressure, etc.) on the cut quality parameters (heat affected zone, surface roughness, kerf width, taper angle etc).

A few important selected research on traditional machining composite will be adress in this next few paragraphs. Many research had been carried out numerically and experimentally, in order to explain the defect induces during drilling FRP. The input process parameters like tool geometries, tool materials, and cutting parameters affect directly to the hole quality. Hole quality can be characterized on the basis of a few criteria, including delamination factor, out-of-roundness, cut neatness, surface roughness, damage surface layer, fiber fracture, burr formation, and crack (Khoran et al, 2014; Ragunath et al., 2017). However in composite laminates, damage due delamination is a highly concern in drilling. For example, it was reported that, the rejection of composite parts of the final assembly in aircraft industry is high as 60% due to drilling-induced delamination damages (Mehbudi et al, 2013). Since composites is a material which assembly of layers of fibrous composite material with liquid resin to form laminates stacking, presences of repeated cyclic stresses, impact and so on will cause layers to separate with significantly degrade the performance in bearing strength and stiffness along with structural integrity of material. This type of damage can occur from both top and bottom of composite surface and almost unseen (Ghrib et al., 2017). Figure 2.6 shows type of delamination that frequently occur during drilling of composites laminate.

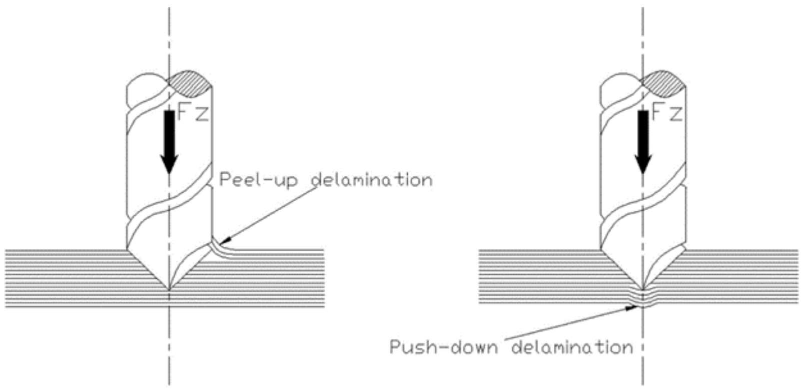

Figure 2.6: Delamination damage (Singh et al., 2013)

The relationship between the drilling parameters such as point angle, spindle speed and feed (input response) on the response variable thrust force and torque is subject matter in drilling laminates composite since the delamination damage always depend on these two response variables. The investigation on thrust force and torque in drilling was studied by (S Jayabal, 2010) and the author observed that the effect of the cutting speed on the cutting force is minor for the same drill material. On the other hand, the cutting force was found decrease with feed. The author concludes that to minimum the push down delamination, the feed needs to decrease at the exit. The result of the reducing in feed before exit has been prove effectively by (Li et al, 2014) and found that almost 80 % of the surface roughness value constantly to be lower at the exit.

(Khashaba et al., 2013) investigated the effect of drilling parameters (feed, speed and drill pre-wear) on the machinability parameters in GFRE. The author found that the drill pre-wear highly plays a part in thrust force. It becomes more noticeable at high-cutting speed and feed, resulting increase the delamination. It was further discussed that drilling at high speed and drill pre-wear turn the surface roughness value higher due to the increase in temperature caused by poor thermal conductivity in GFRE composites. In addition to the finding, the bearing failure of the specimen tested was due to the interlaminar shear failure contribute by the delamination.

Similar behavior was observed by (Shahrajabian et al., 2012). The author has been researched the effect of the machining parameter and tool geometry (spindle speed, feed, tool point angle) during the drilling process of CFRP laminates on the output response of surface roughness, delamination factor and thrust force. They used full factorial design of experiment and ANOVA to decrease number and cost of experiment. The result reveal that the surface roughness increases with feed and decrease with spindle speed. Moreover, thrust force increase with feed, and increases in cutting speed leads to decrease in thrust force. In addition, the delamination factor increases when both feed and tool angle point increase but decreases as a spindle speed decrease. Some author has been researched about the influence of the drill geometry toward delamination and he found that the thrust force changes with drill geometry and the delamination cause to be less at higher feed if proper drill geometry is selected (Hocheng & Tsao, 2006).

(Won & Dharan, 2002) studied the effect of the chisel edge and pilot hole in drilling CFRP laminates. The result of the experiment shown the chisel edge contribute to most of the total thrust force and can be reduced significantly using pilot holes and minimize the delamination. Similar study is done by (Tsao, 2006), he evaluated the importance of pilot hole on delamination by using statistical tools to find optimal cutting parameters. (Fernandes & Cook, 2006b; 2006a) was tried to investigate the thrust force and torque during drilling with “one shot” drill bit on carbon composite materials. Their objective was to extend tool life and improve hole quality. For that, an empirical model to calculate the feed under optimum thrust force was developed. This model is an extension from their early research experimentation of one-shot drill on CFRP by focusing on behavior of force and torque

Apart from hole quality, tool wear also influences the frequency of tool-regrinding and tool changes during machining, thereby, uneconomical production cycle and manufactures cost (Desai et al, 2013). (Dahnel et al., 2014) also state that, high temperature and tool wear are other considerations while machining hard material. The productivity rate of machine tools and machining costs depend on the failure of cutters, which due to intense machining processes as a result of the increase in dynamic force, cutting speed, magnitude of feed rate and depth of cut (Bhuiyan & Choudhury, 2015). Therefore, machine tools must go through many cutter replacement processes that ultimately result in the decrease of its output and economic efficiency. The wear mechanism and development in machining material can be differ due to many aspects, however, among all the possible wear, only abrasion, surface damage, and sometimes adhesion, are significant in FRP machining (Turan eet al., 2015).

Different authors have been studying different machining parameter concerning to wear during CFRP drilling. (Fujiwara, 2005) state that, the tool wear during cutting CFRP occurred is due to abrasive hard grain of carbon fiber broken into pieces and rub against tool flank. He also found that the rubbing is more intense as the cutting speed increase.

(Lin & Chen, 1996) studied the effects of increasing cutting speed on drilling characteristics of CFRP. In this investigation, they used both multifaceted and twist drill bit operated at high cutting speed (210 to 850 m/min) with drilling length of 13.5 mm, 59.4 mm and 94.5 mm. The results showed that the tool wear increases significantly as cutting speed increases. They also found that the average torque is slightly higher for multifaceted compared to twist drill. They concluded that tool wear is the major reasons this changes in force.

(Arul et al., 2006b) showed the used of low feed during machining contributes to the rapid wear of the cutting edge. They used high-speed steel (HSS) drill mounted to vibratory drilling and conventional drilling to evaluate the thrust force, flank wear and delamination factor on glass fiber-reinforced plastics composites. The experimental results indicated that the tool wear reduces as feed rate increases from 0.04 to 0.2 mm/rev.

The worn of the conventional drill bit during dry highspeed drilling of carbon composites studied by (Rawat & Attia, 2009a). In this investigation, they used standard tungsten carbide (WC) two flute drill to evaluate the wear mechanisms under high rotational speed (10000-15000 RPM). As a result, the abrasive wear has been found the main factor that cause WC drill bit deteriorate. Moreover, it has been observed that as the cycles is increase, the delamination and surface roughness also increase.(Park et al., 2011) conducted an experiment to find an optimal machining parameter for high speed drilling of CFRP to minimize the tool wear. The result showed the drill bit carrying less wear at 12000 rpm spindle speed and 0.137 mm/rev of feed.

(Tsao & Hocheng, 2007a) have performed an experiment to investigate effect of tool wear at the exit delamination when drilling CFRP. The author in his research used 6 mm diameter of high-speed steel twist drill bit with 181^o point angle. The results shown there is a correlation between tool wear and the thrust force. The thrust force is higher with increasing wear, thus the delamination more liable to occur. Moreover, they also comparing sharp drill with the worn twist drill and found that the delamination can be suppress for worn twist drill bit by using lower feed.

Regarding tool geometry influence on composite materials drilling, (Shyha et al., 2009) investigate the effect of drill geometry and process parameters when drilling small hole diameter on thick CFRP and they observed that the drill geometry and feed are the two main factors affecting drill life. They also claimed that, the used of uncoated stepped drill geometry at higher feed can increases the tool life in terms of the number of drilled holes. Another research concerned effect of tool geometry was studied by (Bahtiyar, 2012). They try to analyze the drilling performance of double point angle drill bits for fabric woven CFRP laminates using both uncoated and diamond coated carbide twist drill bits. They found that feed was the major parameter contribute to the tool wear, compared to cutting speed.

Finally, the behavior of coated versus uncoated drills was studied by (Wang et al, 2013). He conducted an experiment using three different drill bits (uncoated,