HOLE QUALITY ASSESSMENT OF DRILLED CARBON FIBER REINFORCED POLYMER (CFRP) PANEL USING VARIOUS DRILL BIT DESIGN

By:

MUHAMMAD FARIS SHAUQI BIN KAMARUZAMAN

(Matrix no.: 137842)

Supervisor:

Ts. Dr. MUHAMMAD HAFIZ BIN HASSAN

August 2021

This dissertation is submitted to
Universiti Sains Malaysia
As partial fulfillment of the requirement to graduate with honors degree in
BACHELOR OF ENGINEERING (MECHANICAL ENGINEERING)

School of Mechanical Engineering
Engineering Campus
Universiti Sains Malaysia

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ACKNOWLEDGEMENT

First thing first, my deepest gratitude to 'The Almighty God' for allowing me to do and complete with successful my Final Year Project (FYP) even in full of challenging times and a situation like doing this research during the Movement Control Order (MCO).

Next, I wish to express my thanks to my supervisor Ts. Dr. Muhammad Hafiz bin Hassan in regards to providing me with a wealth of insightful advice throughout this challenging journey. His understanding, valuable suggestions, wide knowledge in this project, giving moral support to me and proper writing guidance have provided a good basis for me to be successful in writing of final year project (FYP).

Besides that, my most thanks go to all academic and technical staff in the School of Mechanical Engineering, USM for giving their continuous assistance like time and also cooperation from the beginning until done of my experiment part.

Finally, I would like to express my deepest gratitude to my beloved parents, (Kamaruzaman bin Zainuddin and Normah binti Yatim), my siblings and friends for giving love, support and encouragement. Last but not least, for those who have directly and indirectly contributed to be the accomplishment of this challenging project, thank you very much for all.

Muhammad Faris Shauqi bin Kamaruzaman

August 2021

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AL	Aluminum alloy
ANOVA	Analysis of variance
CFRP	Carbon fiber reinforced polymer
CMM	Coordinate measuring machine
CNC	Computer numerical control
CV	Coefficient of variation
GFRP	Glass fibre reinforced plastic
HSS	High-speed steel
PCD	Polycrystalline diamond
RSM	Response Surface Methodology
Ti	Titanium alloy

LIST OF SYMBOLS

F_{tmax}	Maximum thrust force
R_a	Hole surface roughness
R^2	R-squared
D	Desirability
V	Spindle speed
f	Feed rate

PENILAIAN KUALITI JARINGAN PANEL POLYMER (CFRP) SENAR KARBON BERGERAK DENGAN MENGGUNAKAN GEOMETRI PELBAGAI JENIS BIT GERUDI

ABSTRAK

Penggerudian polimer bertetulang serat karbon (PBSK) sangat penting untuk mengekalkan daya tujah dan kualiti lubang walaupun setelah beberapa proses penggerudian. Kualiti lubang yang sangat baik diperlukan untuk proses penggerudian industri aeroangkasa untuk polimer bertetulang serat karbon yang sangat kasar (PBSK). Terdapat banyak gerudi putar yang memberikan prestasi yang baik dalam kualiti lubang tetapi selama dalam penyelidikan ini terdapat tiga geometri bit gerudi putar khas dari sudut sudut heliks, jarak utama, sudut titik dan sudut pahat, yang berlian polikristalin (BPK), tirus web, bit pengerasan digunakan dalam penggerudian panel PBSK Bit gerudi untuk badan utama bit gerudi terdiri daripada serbuk tungsten karbida yang menjalani proses penyinteran, dan untuk reka bentuk BPK alat pemotong terdiri dari PBK sementara untuk jaringan tirus dan pembakaran masih digunakan karbida tungsten. Objektif utama penyelidikan ini adalah untuk mengoptimumkan parameter penggerudian yang memberikan minimum daya tujah, minimum kekasaran permukaan lubang, minimum kesalahan diameter lubang, dan minimum delaminasi lubang untuk pelbagai reka bentuk bit gerudi untuk pengeboran lubang menggunakan kelajuan gelendong (rentang 1500 rev / min hingga 4500 rev / min) dan kadar feed (julat 0,05 mm / rev hingga 0.1 mm / rev) masing-masing. Hasilnya kemudian dinilai menggunakan analisis varians (ANOVA) untuk menentukan pelbagai reka bentuk bit gerudi khusus dari segi parameter penggerudian yang berbeza pada daya tujah maksimum dan integriti lubang lubang yang digerudi. Hasil kajian menunjukkan bahawa R1 (1500 rev / min dan 0.05 mm / rev) untuk PCD, R2 (1500 rev / min dan 0.075 mm / rev) untuk web tirus, dan R3 (1500 rev / min dan 0.1 mm / rev) untuk reka bentuk bit penggerudian memberikan parameter penggerudian terbaik dengan menghasilkan daya tujah paling sedikit. paling sedikit kekasaran permukaan lubang, nilai ralat diameter lubang paling sedikit, dan juga faktor pencabutan lubang paling sedikit. Kesimpulannya, daya tuju berkadar langsung dengan

kekasaran permukaan lubang, diameter lubang, dan faktor penebatan lubang ketika menggerudi bahan PBSK dalam satu operasi tembakan. Parameter penggerudian yang lebih tinggi dari setiap reka bentuk bit gerudi menghasilkan nilai yang lebih tinggi untuk semua tindak balas yang membuktikan bahawa reka bentuk gerudi putar perlu meningkatkan dari segi geometri untuk memberikan persembahan yang baik untuk semua percubaan.

HOLE QUALITY ASSESSMENT OF DRILLED CARBON FIBER REINFORCED POLYMER (CFRP) PANEL USING VARIOUS CUSTOM TWIST DRILL GEOMETRIES

ABSTRACT

Drilling the carbon fiber reinforced polymer (CFRP) is crucial to maintain thrust force and hole quality even after several drilling processes. Excellent hole quality is necessary for the aerospace industry's drilling process for highly abrasive carbon fiber reinforced polymer (CFRP). There have many twist drill that gives the good performance in hole quality but during in this research three different of custom twist drill bit geometries in term of helix angle, primary clearance, point angle and chisel angle, which are polycrystalline diamond (PCD), tapered web, burnishing drill bit was used in the drilling of the CFRP panel. Those drill bits for the main body of the drill bit were made up of powder tungsten carbide that undergoes the sintering process, and for PCD design the cutting tool is made up of PCD while for tapered web and burnishing is still used tungsten carbide. The main objective of this research is to optimize the drilling parameter that gave the minimum of thrust force, minimum of hole surface roughness, minimum of hole diameter error, and a minimum of hole delamination for various drill bit designs for the hole drilling using spindle speed (range of 1500 rev/min to 4500 rev/min) and feed rate (range of 0.05 mm/rev to 0.1 mm/rev) respectively. The result was subsequently evaluated using the analysis of variance (ANOVA) to determine the various custom drill bit design in terms of different drilling parameters on the maximum thrust force and the hole integrity of drilled hole. The finding indicates that the R1(1500 rev/min and 0.05 mm/rev) for PCD, R2 (1500 rev/min and 0.075 mm/rev) for tapered web, and R3(1500 rev/min and 0.1 mm/rev) for burnishing drill bit design gave the best drilling parameter by generating the least thrust force. least of hole surface roughness, least hole diameter error value, and also least hole delamination factor. In conclusion, the thrust force is directly proportional to the hole surface roughness, hole diameter, and hole delamination factor when drilling a CFRP material in a single shot operation. The higher of drilling parameter of every single

drill bit designs produced higher value for all responses that prove that it design of twist drill need to improvise in term of geometries to give the good performances for all try.

CHAPTER 1
INTRODUCTION

1.1 Overviews

Drilling is a cutting process to cut or enlarge a hole of circular cross-section in materials by using a rotary cutting tool, which is named a drill bit. The drilling is one of the most common operations needed for post-processing components made from carbon fiber-reinforced polymer (CFRP) materials. Screws and rivets are often used in the assembly process to assemble the CFRP stack with other materials(Zhen yuan Jia et al., 2021; Hou et al., 2020). Although the majority of CFRP components are manufactured in the near-net form to minimize work, additional manufacturing, such as drilling, is still needed for the post-processing work

Commonly in the aerospace industry uses the drilling process to drill holes on the composite laminates which are primarily used in structural components of various aircraft instead of metal alloys (Liu, Tang, and Cong, 2012). CFRP is commonly used in various aircraft structures due to its special characteristics which are low weight ratio, high strength compared to much metal steel, good fatigue strength, and resistance to corrosion (Tsao and Chiu, 2011). The adoption of carbon fiber in aircraft is because of the drive to increase fuel efficiency and to improve the aerodynamic performance of aircraft (Shyha et al., 2011). However, when drilling fiber-reinforced composites, there are typical problems such as internal delamination, micro crack, fiber frying, and epoxy burn-off (Lin and Chen, 1996). The composite's structural integrity will be affected, the strength against fatigue will reduce and have a poor result of assembly tolerance and can easily be damaged.

Furthermore, CFRP materials are difficult to undergo machining which gives the result in a different type of damage such as fiber pull out and the fiber-matrix debonding. because of their material discontinuity, inhomogeneity, and anisotropic nature(Hou et al., 2020). Thus, before the cutting process of this kind of material, cutting tools and optimal drilling parameters should be chosen wisely or it can lead to various modes of damage to the materials and the cutting tools (Iliescu et al., 2010).

In the modern aerospace industry, stack-ups of composite and metal alloys were introduced in the manufacturing sectors due to enhance the characteristics of the new-generation structure and try to do continuous development of mechanical assemblies favoring saving in energy (Xu, Mkaddem, and El Mansori, 2016). Single-shot drilling of stack-up material which may be a combination of metal and non-metal material (without need prior drilling, deburring, and reaming) has become the answer to machine this material and this research become the topic by the researcher in recent years due to increasing demand for higher manufacturing productivity and efficiency (Kuo et al., 2014). Aluminum and Titanium are the most metal alloys chosen for stack-up with composite due to their low density, high strength, easy machining in Al not in Ti, and good thermal conductivity compared to the other metal.

Several drill geometries have been studies by previous research which is the geometry (twist drill, saw drill, core drill, step drill, candle stick drill, brad drill, and dagger drill) have an effect on thrust force, delamination, and bearing test result (Ismail et al., 2016). Other than that, drilling parameters (feed rate and cutting speed, and drilling method) are also an important factor that can influence the holes' diameters error and its quality during the single-shot drilling process.

Thus, this study will identify and understand the influence factor of drilling on CFRP composite materials. It aims to define the main effect of the relationship between drilling parameters using various customized drill bit designs. Selecting appropriate drilling conditions in terms of feed rate and spindle speed to the various tool geometry drill bit is very important to reduce damage on the material induced by the drilling process and get a better quality of hole during the drilling process.

1.2 Research Background

In an aircraft manufacturing process, they are involving more holes' processes for each aircraft for assemblies the component(Wen, Xia, and Choy, 2011). Drilling is one of the familiar processes to make a hole for riveting or screwing on the CFRP material especially in aircraft industries assemblies. The single-shot drilling technique is widely applied to composite materials like CFRP. The method of drilling, drill bit as the main tool of drilling, and proper selection of drill geometry are the most important in the drilling of

CFRP material to give the best performance during the drilling process and in the subsequent analysis.

In industry especially in the aircraft industry, they are facing much of the challenging situation in producing the perfect with the optimum and consistent hole quality (Venkateshwaran and Elayaperumal, 2015). It is because the aircraft industry is very strict about every machining process and future process to ensure the product's safety and ability to be used by civilians. With the special characteristic of CFRP material, it has resistance from corrosion and high strength to the weight ratio are highly preferable in the aircraft industry. Even though they are highly specialized, the effects of the drilling process, such as delamination and micro-cracks, must be focused on by controlling all drilling parameters to ensure top performance.

Due to the sensitivity of the CFRP material structure when going through a specific machining process, the CFRP specialist continues to identify the best drilling parameter with different geometry of drill bit to give the best hole quality result. It is because of the effect of drilling such as hole delamination and micro crack which led to major cracking on the CFRP material or stack up like aluminum and titanium alloy in the certain pressure and condition. To get the best hole, they need the best drilling parameter for each drill bit design, as well as a run of the experiment to optimize the drilling parameter. So this is will be some research that will carry out on the quality hole of one-shot drilling by using different drill bit designs such as polycrystalline diamond (PCD), tapered web, and burnishing drill bit design with some selection of drilling parameters such as spindle speed and feed rate which that focus into. The thrust force is recorded for knowing the maximum thrust force exerted during drilling of CFRP material. Hole surface roughness, hole diameter error, and hole delamination are the element of responses for the analysis process for knowing the optimized drilling parameter for each drill bit design.

1.3 Problem Statements

Multiple-step drilling of CFRP composite material is commonly used in the assembly of the structure of aircraft to reduce delamination of the composite panel during the drilling process. A single-shot drilling process of CFRP material would help the operator to reduce the drilling time and increase production capacity. By the previous work of experimental and statically analysis of drilling and the work pieces, there had less work that combined the study of the effect of every different drill bit geometry and machining parameter on a single shot drilling on the CFRP composite. Much previous work concerns the effect of drilling parameters(Shu et al., 2021) and using coated carbide(Zhen yuan Jia et al., 2020) for achieving good hole quality. However, there is less work about the relation of different customize geometry drill bit with material parameters (thickness of material, hardness of material and type of the material).

To date, the delamination still not fully covered and the issue to overcome the delamination still not be solved. By referring to the current research by Zhen-yuan Jiaa et al,(2020) state that the delamination by using the step drill and twist drill with specific geometries as the cutting tool for drilling the CFRP in the range of 5% to 50%, which half from the nominal,1.0. Also that by end of the research conduct by Hao et al,(2021) also have the high delamination where is 18% from the nominal, while Angelone et al,(2021) there also was recorded the result of delamination by using the innovative drill bit was more than two times from the nominal of diameter hole, it because of the effect of high vibration of the drill bit during the drilling process. This kind of phenomenon happened because there does not do the optimization for the drilling parameter for that drill bit. This process is very important to define the characteristics of the customized geometry of the drill bit and drilling parameter that contribute to give better hole quality on the work pieces.

In this research, the aim is to overcome the previous and the current problem that exists on research when doing the drilling of CFRP material by proposing and introduces the new design of the drill bit for improving the hole quality. Also in this research, the optimization process for drilling parameters like spindle speed and feed rate, has been done for each drill bit which that contribute in giving the best hole quality among another drilling parameter. In doing the drilling analysis there has some factor that contributes to the delamination factor value which is thrust force value, it because both of it have the interrelation in giving the best hole quality. So, technically in this research is to minimize thrust force which also contributes to giving the minimize of hole quality like delamination factor and surface roughness directly.

1.4 Research Objectives

The general objective of this study is to optimize the customized drill bit geometry that compromises the drilling of composite material in order to produce good hole quality in the drilling process. In order to achieve this aim, three specific objectives were set out as follows:

1. To identify the effect and interaction of drilling parameters (spindle speed and feed rate) to the thrust force and temperature distribution during the drilling process.
2. To investigate the relationship of thrust force and temperature distribution to the hole integrity in terms of hole diameter error, hole surface roughness, and hole delamination.
3. To optimize drilling parameters (spindle speed and feed rate) for all drill bit types to conduct the single-shot drilling process on a CFRP panel with a good hole quality.

1.5 Scopes of project

In this project, a single CFRP is chosen as the base material of workpieces to be drilled by using the various customize drill bit designs and drilling parameters. The main goal is to utilize the thrust force characteristics produced during drilling as an indicator for the hole quality study. In doing this study, there will find out the optimized drilling parameter for every drill bit type that can give the best hole quality in the single-shot drilling of CFRP material. In order to achieve that, the characteristics of the CFRP were studied and the characteristic operating range in the drilling process was discovered. In doing the holes' quality assessment analysis, there have some methods that will be used to calculate the holes' quality which is by monitoring the force signature generated from the dynamometer during the drilling process, taking temperature using the thermal imaging camera, and doing the offline measurement like hole surface roughness by using coordinate measure machine (CMM) and hole diameter error and also hole delamination by using Alicona Infinite. The analyzing the data from the experiments conducted have been done to study the cause of each problem how the phenomenon occurs during the drilling process on the CFRP material. After all the data has been carefully analyzed, the optimization steps are conducted to find out the drilling parameter that giving the minimum of thrust force, lowest hole surface roughness, lowest diameter error, and lowest delamination by using the analysis of variance(ANOVA) for every design of drill bit.

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

Carbon Fiber Reinforcement Polymer (CFRP) is one of the composite materials developed with special properties for critical applications such as those found in the aerospace industry. Generally, CFRP material (Figure 2.1) has been used in building structural applications, especially in aircraft industries. It is because this composite material has an excellent strength-to-weight ratio, damage tolerance, fatigue, and corrosion resistance. Indirectly it will reduce the weight of the aircraft body and also will reduce the lift force in bringing up the plane. So, indirectly it also will reduce the fuel consumption and make the plane more fuel-efficient than other planes that do not use this material.

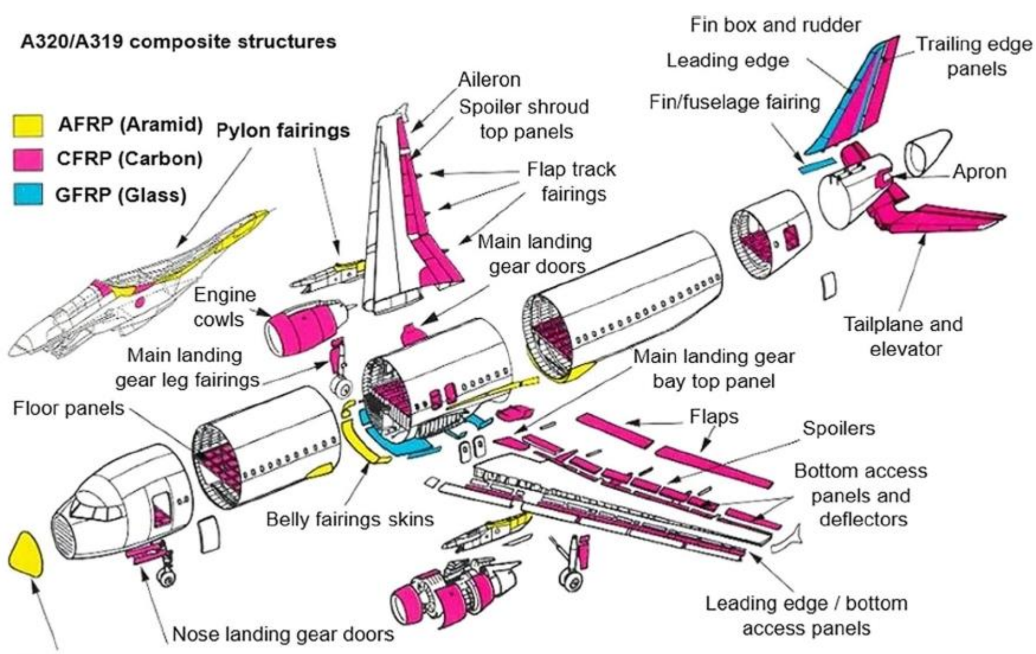

Figure 2.1 Carbon fiber reinforced polymer(CFRP) distribution on the aircraft body(A320/A319)(Aamir et al., 2019)

The drilling process in the composite material especially CFRP is the familiar machining process, which mainly for assembling the structural component to the main part of the aircraft body. In attaching the two parts, drilling will be the best machining process in allowing rivets and screws for part assemble (Zhen yuan Jia et al., 2020; Hou et al., 2020). Drilling composite materials, whether in single composite or stack up the composite, such as CFRP, CFRP/Al/CFRP, and CFRP/Ti, each has its own set of challenges due to the different elements of material to ensure the internal structure is not disrupted by the drilling process, which is not the case when drilling metallic materials. A proper drilling parameter selection with the drill bit as the cutting tool is a critical parameter because it reduces damage such as hole delamination, micro-crack, and geometry effect(Zhenyuan Jia et al., 2020).

Delamination is a major concern when drilling laminated composites. This phenomenon occurs when the thrust force from the drilling process exceeds the interlaminar fracture toughness of the layer, causing poor drilling and affecting part assembly. Delamination will take place and occurs during the entrance (peel-up) of drilling and exit(peel-down) of drilling. Peel-up and peel-down are the possible delaminations that occur in drilling which can be looked at by rough eyes and clearly under special equipment such as Alicona infinite. These effects are causes of the drilling process to the composite material (Krishnaraj et al., 2012). Furthermore, inter delamination occurs during the drilling process of the laminated composite material, and this type of delamination is critical because it initiates internal micro-cracking, which can lead to major cracking under certain conditions such as high pressure and high temperature(Tan et al., 2019). Figure 2.2 illustrates the mechanism of the delamination when drilling process of general composite.

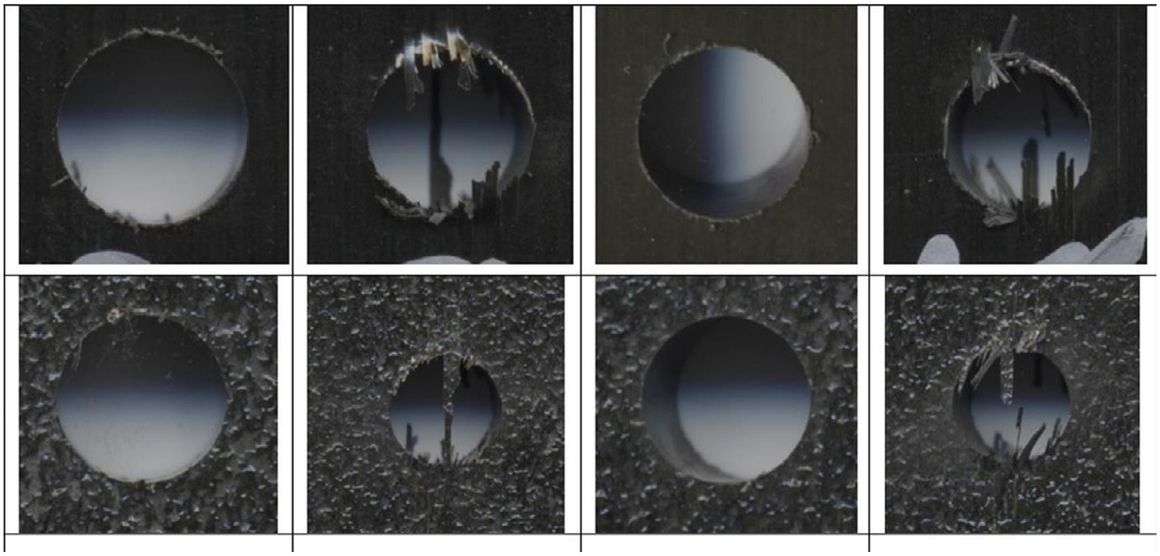

Figure 2.2 Typical hole delamination produced by the drilling process (Eneyew & Ramulu, 2014)

2.2 Type of aircraft composite panel

Globally, composites are in extensive demand due to their wide range of applications and superior properties over conventional materials. GFRP materials are chosen over traditional materials due to their unique properties such as high strength-to-weight ratio, high fracture toughness, high specific modulus of elasticity, thermal resistance, and lightweight. (Nayak et al., 2021). GFRP is typically drilled for aircraft body assembly, although there are several effects of GFRP drilling, including matrix cracking, thermal degradation, fiber breakage, spalling, and delamination (Malinowski et al., 2021). CFRP is usually the same has characteristics as GFRP which high in mechanical strength. Both of these types of composite have a unidirectional type, which is typically used for flat panel applications, and a woven kind, which is utilized for complex shapes that require a greater degree of fabric flexibility and will conform to the appropriate shape(John & Kumaran, 2020). Other than GFRP, QFRP composite is a kind of material with anisotropic and nonuniform properties at different fiber orientations, the stresses and strains were different, and the processing performances were highly dependent on the fiber orientation(Z. Liu et al., 2021).

In the aircraft industries there used several elements in build the aircraft body like glass fiber reinforced polymer (GFRP), quartz fiber reinforce polymer (QFRP), and also carbon fiber reinforced polymer (CFRP) and there have some metal and glare (Figure1.1) to build up the aircraft. There have some important reasons for choosing this kind of material in build the aircraft. It is because of the characteristic of the material which has light in weight which can help the lifting force and can save the fuel consumption and they also have high corrosion resistance.

2.3 Drill bits

2.3.1 Twist drill design

Drilling kinematics is the process of using a rotating drill bit to create or enlarge existing round holes in a workpiece(Ismail et al., 2017), and drill bits are cutting tools used to create cylindrical holes, typically with a circular cross-section(Material & Geometry, 2015). The spiral (or rate of twist) in the drill bit controls the rate of chip removal and access of a cutting fluid with the aid of one or more cutting lips and flutes. As can be seen, the most common type of drill bit used in the industrial field is the twist drill bit, which comes in a variety of designs depending on the application. The varying parameters which will contribute to the twist drill geometric design in term of helix angle, primary clearance, point angle and chisel edge angle and the most important is the design of the drill bit itself like burnishing and tapered web.

2.3.2 Drill bits material selection

There have several material of drill bit which contribute different function in drilling such as carbon speed steel, high speed steel(HSS), titanium coated drill, cobalt drill bit, carbide tipped drill bit and polycrystalline diamond drill bit as in Table 2.2. Every type of drill have their life performing which depend on the hardness, toughness, wear, thermal resistance and the coating that used on the drill bit (Aamir et al., 2019). When selecting a suitable drilling tool material, it is critical that the tool's hardness value be greater than the hardness value of the workpiece so that the tool can drill and remove the unwanted area of the workpiece without causing wear and tear to the drilling tool. The hardness values of various types of drilling tools and stacked up material are shown in the table below. Based on the table, can conclude that all type of drill bit has high hardness than the CFRP material which have tend to drill the material but if stack on descending order PCD will the higher hardness continue by tungsten carbide and HSS.

Table 2.1 Hardness of drill bits and laminate composite (CFRP) material

Type of material	**Drill bit type**	**Material drill bit**	**Function**	**Vickness hardness (HV)**
Drilling tool	High-Speed Steel Drill Bit (HSS)	carbon steel	wood metal drilling	750
	Tungsten Carbide	Carbide-Tipped	-fiberglass reinforced plastic -nonferrous heavy metals	1600
	Polycrystalline diamond (PCD)	Diamond	-glass -ceramic	6000
Laminate composite (CFRP material)			Workpiece material	180

The performance of the drill is based on the toughness of the material, resistance to heat, wear, and hardness. In making the best quality drill, it must have characteristics that can avoid the fastest break, wear and maintain the toughness of the material due to high temperature during drilling. The Figures show the hardness and toughness of different materials. The least hardness tooling material is (high-speed steel) HSS but has the most toughness property since the sharp deformation temperature is 700^{o}C. While polycrystalline diamond (PCD) is the hardest tooling material but has the least toughness which will deform around 600 ^{o}C(Ismail et al., 2017). In the selection of the cutting tool material, the most important criteria are the hardness and toughness of the material.

Hardness is the ability of a material to resist deformation and resistance to indenter penetration. The hardness of the material is measured due to the ability to maintain the hardness at a high temperature during drilling. While toughness is the ability of a material to absorb energy and plastically deform without fracturing. The higher toughness of the material is measure due to the ability can withstand the shock load and crack during vibration in the drilling process

According to some researchers, the tool material is chosen based on the number of holes and the size of the hole that the drill bit can make. High-performance carbide drills have the highest penetration rate and the shortest cycle time, but they are expensive. As a result, if the number of holes to be drilled is small, it is preferable to use a cost-effective alternative such as an HSS drill. In terms of hole size, it is best to use an HSS drill if the hole is between 12 mm and 24 mm in diameter, as it is more expensive to manufacture carbide drills larger than 12 mm(Ismail et al., 2017). Other researchers state, when compared to HSS drills, helical flute carbide drills perform better due to their higher hot hardness (Zhenyuan Jia et al., 2020). Furthermore, in the aerospace industry, the high number of holes and hardness of the drilling workpiece lead to the use of tungsten carbide as a drilling tool.

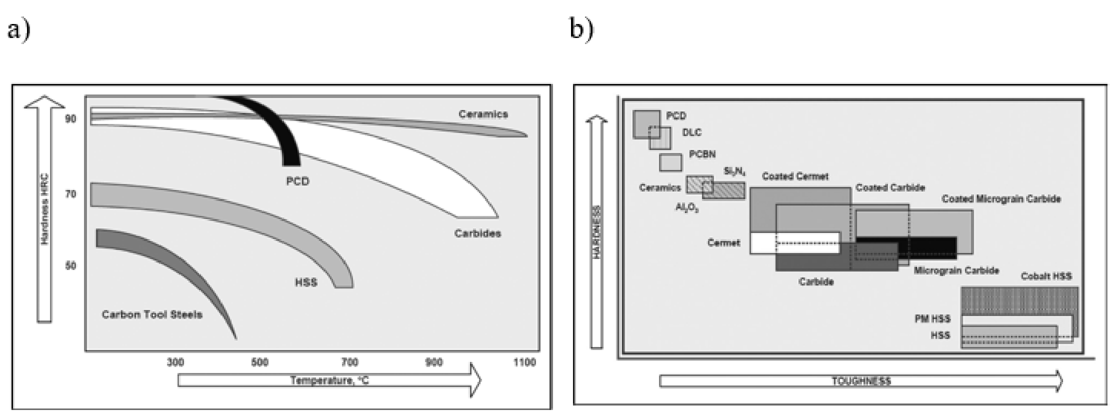

Figure 2.3 Relationship between a)hardness of drill bit material and temperature b)hardness and toughness of drill bit material (Ismail et al., 2017)

Tungsten carbide or another name is tungsten tetra-carbide if the crystal structure is hexagonal, as Figure 2.5. That contains equal parts of tungsten and carbon atoms. The fine grey powder is the basic form of the tungsten carbide. Sintering is the process where the powder is compressed into forming a shape (Shabgard & Najafabadi, 2014). The combination of the tungsten and cobalt content are depending on the toughness and hardness required. By using the right combination of these two elements and another internal improvement it will allow the best performance. High melting point and high boiling point is the special characteristic that makes it high strength of material and resistance to high temperature. It is very abrasion resistant and also can withstand higher temperatures than HSS tools.

Tungsten carbide is very suitable for drilling the composite material because it can maintain a sharp cutting edge even when drilling several holes and generally will produce a better surface finish than HSS even in the same drilling parameter. Also can undergo a fast machining process due to the temperature resistance. Drilling by using the tungsten carbide's drill bit will least wear or do not consider wear, different when using the HSS's drill bit had been considered wear just only drill one hole.

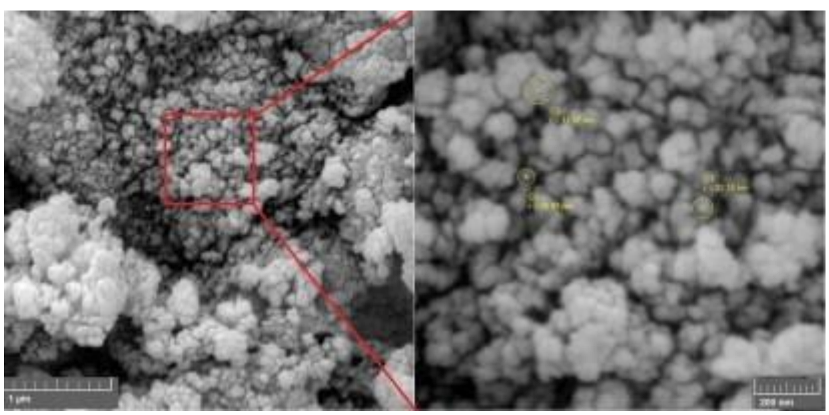

Figure 2.4 A nano-structural of Tungsten Carbide

2.4 Drilling of Carbon Fibre Reinforced Polymer (CFRP) material

Since carbon fiber reinforced polymer (CFRP) composite material offers excellent strength to weight ratio, damage tolerance, fatigue, and corrosion resistance, they are gradually replacing the conventional material and currently makeup 50 % of the structural weight of aircraft. To assemble the aircraft body especially for composite materials like CFRP, drilling is the common and best machining process than other processes like punching. It is because the punching process will give high consistent force to the overall fiber layer to make the hole on the CFRP material. Even punching process is one of an efficient and economical process for producing a hole in structures for functional requirements. However, it cannot make a good performance for making a hole either in the entrance or exit of the surface of CFRP material, as shown in Figure 2.3, where the flange can be seen at the exit side of CFRP(Ho & Yanagimoto, 2018). But in the drilling process, it is cut layer by layer and the possibility of damage is lower than punching. However, the structure of the CFRP consists of two parts, the cutting tool selection and the drilling parameter which correspond to the machining process quality.

By referring Table 2.1, is a summary table for the type of material used from the previous research. Most of the researchers (Eshetu et al., John et al., and Xu et al.,) are focus on the feed rate which in the range of 0.01mm/rev to 3.2 mm/rev, cutting speed in a range between 750rev/min to 6000 rev/min with the constant diameter of the drill bit by choosing the high quality of cutting tool material like a polycrystalline diamond (PCD), uncoated solid carbide twist drill and solid carbide twist drill. The high strength-to-weight ratio of CFRP necessitates using a specialized cutting tool to achieve high hole quality. It is because to ensure the cutting tool will giving the best performance and tend to reduce the wear on the cutting tool, even have drilled several holes.

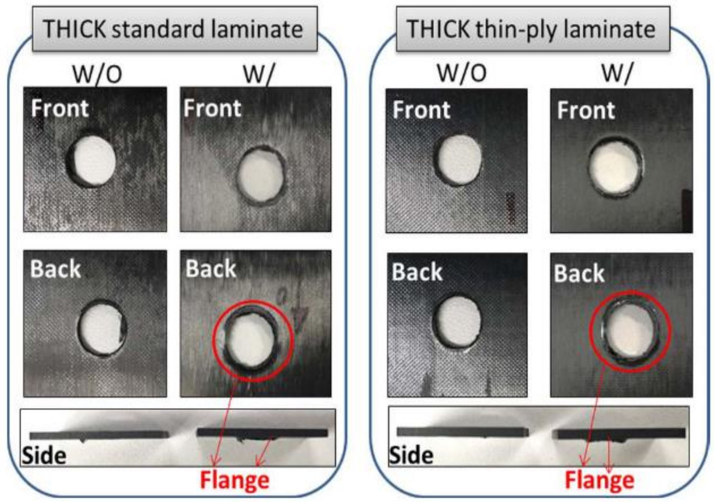

Figure 2.5 The illustration of the punching process on the CFRP material (Ho & Yanagimoto, 2018)

They have a state that, the thrust force value, torque, and the delamination effect on the CFRP will increase significantly, but tend to decrease gradually with increasing to the spindle speed or cutting speeds. Because of that, the proper selection of the drilling parameter is needed, for giving an ideal result in the drilling of CFRP material either in thrust force measurement or the hole quality effect (Nayak et al., 2021). Isbilir & Ghassemieh,(2013) also has concluded that the increase of thrust force drilling torque is due to the increase of the spindle speeds directly. D.F.Liu et al,(2012) were presented their study of drilling CFRP using the various drill bit geometry with different drill bit materials. Which they have related the quality of the hole during the drilling operation to the various drill bit type. The various of drill bit type is used as a step, slot, core, twist and brad drill bit type which that gave the different result in delamination factor because every type of drill bit has different of tendency and ability in the drilling of CFRP material. While Tamura & Matsumura,(2021) state that feed rates have a greater impact on thrust force, push-out delamination. Lower feed rates result in less thrust force and push-out delamination, while higher feed rates result in holes that are closer to the nominal diameter. And to reduce the thrust force of the drilling process of CFRP material the lower point angle is needed as proposed by Wei et al,(2016a).

Table 2.2 Tabulation of drilling parameter in drilling the CFRP composite material

Author	Tool material	Diameter of drill bit, mm	Cutting speed, rev/min	Feed rate, mm/rev	Thickness material, mm
Xu et al (Xu et al., 2018)	Solid carbide	6.35	750, 1000, 1250, 1500	0.01,0.02, 0.03,0.04	5
Eshetu et al (Eneyew & Ramulu, 2014)	Polycrystalline diamond (PCD)	6.35	1500, 3000, 4500, and 6000	0.064,1.28,1.92,2.56, 3.20	6.35
John et al (John & Kumaran, 2020)	Solid carbide	6.352	2000-4000	0.01-0.03	5
Li et al (Li et al., 2014)	Diamond coated solid carbide	6.38	90	0.2,0.4	-
H.Zhang et al (H. Zhang et al., 2021)	Solid carbide	6	2000-8000	0.005-0.02	5
D.kim et al (Kim et al., 2016)	Solid carbide and PCD	9.525	-	-	7.62

2.5 Single Shot Drilling of laminate composite material (CFRP)

CFRP is a laminate composite material which very sensitive to the process. To drill the CFRP material, they need the proper selection of process parameters like spindle speed, cutting tool, and the feed rate which contribute to the effect and the quality of the hole. In most of the research before, As the basic responses, the thrust force study is used as a benchmark to evaluate the drilling quality of stacked-up materials. Aamir, Muhammad Tolouei-Rad, Majid Giasin, was concluded that the best drilled-hole quality and minimal damage during CFRP drilling, is by lowering feed rates and high cutting speeds favoring acceptable performance and minimum torque, minimum thrust force, and minimal delamination. According to the result by Krishnaraj, Vijayan Prabukarthi, the thrust force at the low spindle speed (12000 rev/min) which the higher thrust force even in low feed rate whereas the higher spindle speed (20000 rev/min) which the lowest thrust force even in low feed rate. This is because of the higher impact of the fiber and reduced effective clearance angles of the drill, thereby creating frictions between the CFRP which make the higher thrust force. Due to this paper that was explained, in the drilling of the laminate composite material especially for drilling CFRP material, the machining parameter like feed rate contributes to the quality of the hole based on the chip formation. While for spindle speed-wise, thrust force reduces with high spindle speed because the cutting resistance of epoxy was lower with higher cutting edges temperature(Ameur et al., 2017).

2.6 Effect of drilling parameters and cutting tool on thrust force

Thrust force is the signature generated by a dynamometer in real-time while monitoring the drilling operation of a laminated composite material such as CFRP. Based on the tabulation of data in Table 2.3, the thrust force in drilling CFRP material using various materials such as PCD and solid carbide and drill bit designs were recorded during drilling the CDRP material. The thrust force generated while drilling CFRP as shown in Table 2.3, is within the range of 25 N to 584 N. Eneyew Ramulu,(2014) was drill the CFRP by using PCD drill bit type with the range of 1500-6000 rev/min and the feed rate 0.064-0.32mm/rev was recorded the thrust force in the range 25 N – 170N. It can maintain the minimum thrust force while drilling CFRP because of the properties of the PCD which have high hardness and have low resistance in the drilling process. It was proved by Wei et al,(2016b), which the maximum thrust force still low which is recorded in the range 80N-140N. Ramesh et al,(2014), H.Zhang et al,(2021), and Sur & Ekran,(2020) which they have been drilled the CFRP material by using solid carbide drill bit type with the range of spindle speed of 750 – 8000 rev/min and the feed rate of 0.005-0.2 mm/min were recorded 60N – 584N. The thrust force by using tungsten carbide is lower than PCD because of the different values of hardness drill bit material.

` Wei et al,(2016b) was stated that the thrust force using the PCD drill bit was affected by drilling parameters, especially the feed rate. The thrust forces will be increased with the elevation of the feed rate. While for Eneyew Ramulu,(2014) had mentioned that, the maximum thrust force is more influenced by the feed rate rather than the spindle speed. For drilling CFRP by using the solid carbide, Sur & Ekran,(2020) stated that by increasing the feed rate, the thrust force decreases. From that was shown that the drilling parameter was contributed to the value of the thrust force in the drilling of CFRP material.

Table 2.3 Tabulation of Thrust Force for Drilling on CFRP and CFRP/Al

No	Author	Tool Material	Diameter Tool, mm	Parameter		Maximum Thrust Force, (N)	Hole quality assessment
				Spindle Speed, rpm / m/min	Feed Rate, mm/rev		
1	**Eneyew Ramulu,(2014)**	PCD	6.35	1500-6000	0.064 - 0.32	25 - 170	-hole delaminatiom -hole surface roughness
2	**Ramesh et al,(2014)**	Solid carbide	10	750 - 1250	0.05-0.15	274.06 - 584	-hole surface roughness
3	**Sur & Ekran,(2020)**	Solid carbide	8	995 - 2984	0.1-0.2	60 -140	-hole delamination -hole surface roughness
4	**Norcahayo et al,(2018)**	Solid carbide	8	1000-2000	0.05-0.15	30-178	-hole delamination
5	**Zhang et al,(2015)**	Solid carbide	5	3500	0.05	100	-hole delamination -hole surface roughness
6	**Wei et al,(2016b)**	Solid cabide Coated CVD Diamond	6.35	2500-7000	0.02-0.08	80-140	-hole delamination
7	**H.Zhang et al,(2021)**	Solid carbide	6	2000-8000	0.005-0.02	85-110	-hole diameter error

2.7 Effect of drilling parameters and cutting tool on the hole quality assessment

Drilling of the CFRP material to make holes may affect the quality of the hole directly, as some researchers concluded that abrasion was the strongest wear mechanism observed in CFRP/AL drilling, which is due to the highly abrasive properties of carbon fiber (Montoya et al., 2013). Some also mention that more damage and surface roughness in CFRP composite during drilling process by using uncoated carbide drills and was concluded that to produce the minimum of the surface roughness it needs the proper selection of drilling parameters like controlling the feed rate and the spindle speed while machining (Shahabaz et al., 2020). Geier & Pereszlai,(2020) was found that every different design of the cutting tool will be contributed to the hole surface roughness, if the surface roughness of the drill bit is higher the surface roughness will be higher directly.

On the topic where the hole drilled diameter of CFRP material are not same but just little it because Wang et al,(2017) was mention that every hole that produces will smaller than the drill bit diameter. In addition, they also conclude that the middle hole diameter of the drilled hole will be larger than the entry and the exit because of high vibration during the drilling process. This statement also supports by L.Zhang et al,(2015) which concluded that in the drilling of the CFRP material, the hole diameter of the drilled hole was shrinking 5 μm and this phenomenon only can be reduced by controlling the chisel edge angle.

The design of the tool geometry has a significant impact on the thrust force generated during the drilling process of laminate composite materials such as CFRP. There are four factors which are considered in tool geometry, which are the point angle, helix angle, chisel edge angle and primary clearance and also the much important is the material of drill and the design of the drill bit which that the main factor which that will influence to the thrust force, temperature and also the hole quality of the drilled CFRP material. Heisel & Pfeifroth,(2012) was stated that increasing the point edge angle will lead to the increasing of the thrust force and the bur formation. Wei et al,(2016) also mention that the increase in the helix angle and the chisel edge led to a decrease in the thrust force and the torque (Wei et al., 2016a). Jaafar et al,(2019) discovered that when a higher feed rate is used, a drill with a higher helix angle suffers from chipping of the primary cutting edges. If drills with lower helix angles have a stronger cutting edge and are less prone to chipping, but they result in higher cutting forces and temperatures which can see based on the chip formation distribution while drilling process on the CFRP material (Jaafar et al., 2019). Lastly, the primary clearance must be maintained to prevent the drill flank from rubbing against the workpiece. A large clearance angle extends tool life by reducing friction, but as the clearance angle increases, the tool's strength decreases(Zou et al., 2020).

Drilling holes on the laminate composite material as CFRP material will give an effect on the hole quality especially in terms of the delamination. Delamination can occur in three areas which are entry, exit, and middle of the drilled hole. It is difficult to maintain the delamination factor value in drilled of the unidirectional laminate composite material. Figure 2.6, which described that the mechanism of push-down delamination that occurs while drilling of CFRP material (L. Liu et al., 2017). Norcahyo et al,(2018) concluded that the delamination can be minimized if proper control of the drilling parameter as the material of drill bit which has high hardness than the workpieces as a carbide twist drill, by lowering the spindle speed and by lowering the feed rate in the drilling of CFRP. L.Liu et al(2017), was used and mention that the delamination factor value can be used by using the diameter value. where D represents the actual diameter for drilled hole or drill and Dmax represents the maximum diameter for delamination area, as shown in Figure 2.6. They used the diameter formula to calculate the delamination on the CFRP material, which the maximum diameter for delamination divide by the actual diameter of the drill hole. Some researchers stated that the formula can be used, but they also stated that when the maximum diameter is used, all sides of the diameter are affected. Isbilir & Ghassemieh(2013) claims that using the maximum damage area increases the accuracy of the delamination factor value, where Amax is the damaged area after drilling and Anom is the drilled hole area as in Figure 2.7. They used the damage area formula to calculate the delamination on the CFRP material, which the maximum damage area divided by the actual area of the drill hole.

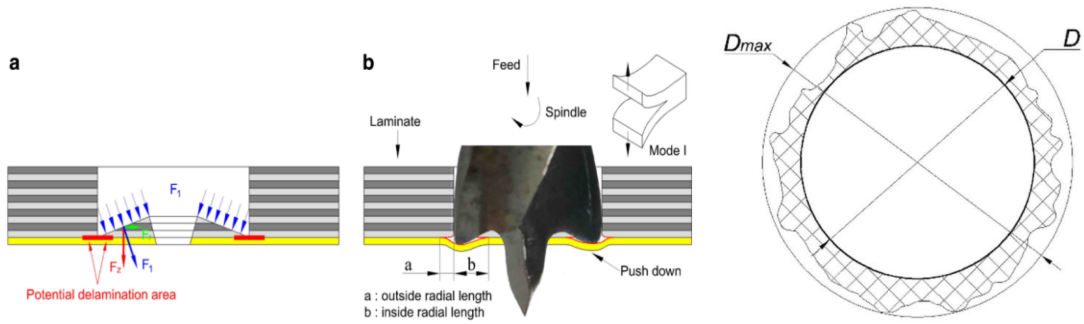

Figure 2.6 The mechanism of the delamination during drilling of CFRP material and the scheme diameter delamination (L. Liu et al., 2017)

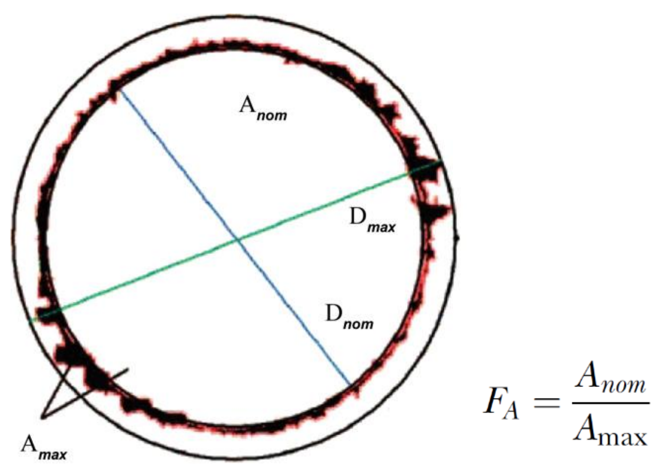

Figure 2.7 The scheme of damage area delamination(Isbilir & Ghassemieh, 2013).

2.8 Design of experiment

Design of experiment is the method used to collect data in experimental studies or research. The DOE's types to use were determined depends on the experimental goal and the practical limitation. The first type of DOE is response surface methodology (RSM), which is used to investigate the interactions between many explanatory variables and one or more response variables (L. Zhang et al., 2015). The main principle of RSM is to employ a sequence of optimal responses. Statistical approaches such as RSM can be useful in maximizing the production of a special variable or parameter by optimizing the operational component (Shahabaz et al., 2020). Premnath,(2019) was used RSM to experimented with study the effect of various machining parameters.

The Taguchi method is an example of DOE. Taguchi devised a specific design of orthogonal arrays to explore the full parameter space with a limited number of experiments (Vankanti & Ganta, 2014). Sur & Erkan,(2020) also state that the Taguchi method aims to optimize design parameters and improve product quality using statistical methods. use the Taguchi method to determine the optimum output parameters. Taguchi's major goal is to estimate the transformed experimental result in terms of the signal-to-noise (S/N) ratio(Shahabaz et al., 2020). It uses the S/N ratio as a measure of quality qualities that deviate from or approach the ideal values.

Vankanti and Ganta,(2014) were stated that analysis of variance (ANOVA) is a statistical technique for determining the degree of similarity or difference between two or more groupings of data. It is based on the comparison of the average value of a common component. Based on Eneyew & Ramulu,(2014), the analysis of variance (ANOVA) method is used to determine the effect of each variable on each of the responses evaluated. While Shahabaz et al,(2020) state that, using the ANOVA, can show the significant correlation between the result and the parameter that has been used.

2.9 Chapter summary

In this chapter, a review of the drilling parameter, design of cutting tool details, and detailed material cutting tool in the drilling of CFRP material have been reported according to the previous work done. As mention in this chapter, even by using the twist drill, step drill and so on they have still its limitation in the hole quality such as delamination, surface roughness, and the diameter error of the drilled hole to meet the stringent aerospace requirement. There are many various tools design and material has been employed to produce the best hole quality with achieving the minimum thrust force during drilling of the CFRP. So to achieve this objective, an experiment was conducted by using the different design of the drill bit which that was proposed in Chapter 3.