INNOVATIVE TOOL FOR COMPOSITE MACHINING IN AEROSPACE APPLICATION

LUQMAN HAIKAL BIN MOHAMAD NIZAR

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INNOVATIVE TOOL FOR COMPOSITE MACHINING IN AEROSPACE APPLICATION

by

LUQMAN HAIKAL BIN MOHAMAD NIZAR

(Matrix no.: 143524)

Supervisor:

Ts. Dr. Muhammad Hafiz bin Hassan

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LIST OF ABBREVIATIONS

CFRP	Carbon fiber reinforced plastics
SEM	Scanned Electron Microscope
CMM	Coordinate Measuring Machine
DOE	Design of Experiment
GFRP	Glass fiber reinforced plastics
DLC	Diamond-like carbon coating

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ABSTRAK

Peningkatan permintaan untuk bahan termaju termasuklah plastik bertelulang gentian karbon (CFRP) telah memberi cabaran baharu kepada syarikat pembuatan dalam memastikan bekalan mencukupi dan dapat dikeluarkan dalam masa yang paling singkat, terutamanya bagi industri pesawat komersial. Proses pemesinan CFRP ke bentuk akhir memerlukan pelbagai proses termasuk menggerudi, memangkas dan memuka, menyebabkan banyak masa perlu diambil dalam proses pemesinan kerana mesin perlu dihentikan bagi memberi ruang kepada proses penukaran mata pemotong. Penggabungan banyak mata pemotong ke dalam satu mata pemotong akan memansuhkan proses penukaran mata pemotong, dan mengurangkan masa pembuatan CFRP. Masa pembuatan yang rendah dan pengunaan mesin yang lebih efisien semestinya membantu pihak pembuat dalam memenuhi permintaan dari pelanggan. Penyelidikan yang telah dijalankan ke atas mata pemotong dengan julat kadar suapan 0.05-0.15mm/rev and julat kelajuan putaran 2500-10000rpm telah memberi lebih kefahaman terhadap respon yang telah diperoleh dalam eksperimen ini. Pengenalan salutan di permukaan mata pemotong telah membantu meningkatkan prestasi mata pemotong dari segi jangka hayat dan juga kualiti pemesinan. Tiga objektif penyelidikan ini telah tercapai, iaitu respon kualiti pemesinan daripada kombinasi parameter telah berjaya diteroka dengan jayanya. Industri pesawat komersial dapat mengambil manfaat daripada penyelidikan ini dari segi kualiti pemesinan dan semestinya mempunyai potensi yang baik dalam mengurangkan kos pembuatan.

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ABSTRACT

The rise of demand for advance materials including CFRP has pose new challenges for manufacturers to ensure sufficient and timely supply of parts, especially for commercial aircraft industry. Machining CFRP panels into net shape require numerous processes such as drilling, trimming and facing, making it a time-consuming process, as machine needs to be stopped to accommodate tool change process. By combining multiple tools into a single tool bit, the tool change process could be eliminated, which effectively translate into lower cycle time of CFRP machining. Having a lower cycle time and higher machine efficiency helps manufacturers to cope with the demand from customers. Conducting research using combined tool bits with a feed rate range of 0.05-0.15mm/rev and rotational speed range of 2500-10000rpm allows further understanding on the responses obtained in the experiment. Introduction of coating layer onto the tool bit helps to boost the tool bit performance in terms of tool life and also quality of machined parts. The three objectives set for this research were met, whereby the set target of effect of machining parameters to the quality performance of CFRP panel has been successfully explored. Commercial aircraft industry may benefit from this research as the results obtained in positive in terms of machining quality, and surely has the potential of reducing the overall manufacturing cost.

CHAPTER 1

INTRODUCTION

1.1 Background study

The rise of demand for carbon fiber reinforced plastics (CFRP) on different applications poses new challenges for manufacturers to meet the requirement of the industry. Due to the nature of CFRP, it is impossible to fabricate CFRP into its net shape. As with current practice, CFRP panels are manufactured into near net shape, then processed through machining into its final shape and form. Common machining process for CFRP include drilling, trimming, and facing. The time-consuming process of CFRP panel manufacturing of has resulted in great loss in terms of time and resources for CFRP consumers, including commercial aircraft manufacturers. The presence of COVID-19 as a global pandemic has greatly impacted the production of CFRP panels, equally impacting the production of commercial aircrafts. Currently, major commercial aircraft manufacturers are struggling to meet the orders of aeroplanes by its customers. Two major aircraft manufacturers, Airbus and Boeing are not spared from the worldwide implications. It was reported that as of May 2022, Boeing are struggling to clear their production backlog of 5142 aircrafts. Airbus have even greater backlog, in which a total of 7037 aircraft orders are yet to be delivered. Analysts have forecasted based on the pre-pandemic capacity (2019 production performance for Airbus, 2018 production performance for Boeing) that it would take Airbus 8.2 years to clear the backlog, while Boeing needs 6.4 years to clear its booking sheet. Forecasting the backlog clearance using 2021 performance of both companies has yield an even worse result, which is 11.5 years for Airbus and 15.1 years for Boeing. It is obvious that the commercial aircraft industry is in dire needs of production ramp-up to meet the customers demand, and small improvements would eventually contribute to the efficiency and productivity increase in the industry. The commercial aircraft industry is actively looking into ways to lower the manufacturing cycle time and also reduce manufacturing cost. Any improvement that will boost the manufacturing capacity is surely welcomed by the manufacturers in the industry.

Machining of CFRP panels pose several challenges in terms of defects to the product. Delamination, peel-up and push-down mechanisms, micro cracks and matrix burning are some of the defects usually found on CFRP panels. Among the mentioned defects, delamination is considered as the most critical defects, as it is reported to account around 60% of part rejection of CFRP. The reason for rejection of CFRP panels due to delamination is because it results in poor tolerance of assembly and reduced structural integrity of the panel itself (Boccarusso et al., 2019). Other than that, processing CFRP into its net shape also require multiple processes before it is finally formed into its net shape. Typical process includes trimming and drilling. In the current practice in the industry, each process will have its own tool. Therefore, tool change is needed every time another process is taking place. Tool changes possess its own disadvantage, which is related to the total machining time. Tool change will cause down time to the machine, whereby the process needs to pause to accommodate for the change of tool. Reducing or eliminating tool change process will surely improve the overall processing time of CFRP panels, reduce waste that is associated with waiting time, and increase the efficiency of the machine.

Having said that, this project intends explore possibilities to resolve the above-mentioned issues to allow for further advancement of CFRP machining processes. Reviewing previous research for current CFRP machining that is currently being practiced in the industry will help to further understand the advantages, limitations and constraints faced by the industry. Proposing solutions for the problems will help the industry to progress and open more possibility for further application of CFRP in more industries. To come out with viable solutions, the performance of the proposed solutions are analyzed and presented in this research. Based on previous works, the usual performance of CFRP machining including delamination, roughness, hole diameter error and tool wear are included in this research.

1.2 Problem statement

Drilling CFRP panels poses several problems in terms of defects including delamination and poor roughness, which may lead to part rejection. Due to the nature of CFRP panels, it is not possible to repair the defects found on the panel, which means panels with defects will be scrapped, causing loss of resources and financial loss to the manufacturers. Processing of CFRP panels into its net shape involves several machining processes. The quality issues associated with machining of CFRP leads to loss to manufacturers. Ensuring the CFRP to be produced of highest quality requires extensive study of machining parameters. Different process requires different tool, which will result in machine downtime to accommodate tool change after each machining process. This causes the increase of cycle time in the CFRP machining process. Purchasing multiple tools also would significantly add to the operation cost of the CFRP manufacturer. The current practice in the CFRP manufacturing industry of using multiple tools is not contributing to the boost of capacity greatly needed by the commercial aircraft industry with its huge number of production backlog. Existing studies have yet to propose and produce a solution to the multiple issues associated with machining of CFRP, which means there are rooms for improvement in the CFRP machining process

1.3 Research objectives

Generally, the objective of this research is to allow for excellent quality machining finish that are within the standard set by the industry. Achieving the target requires three specific objectives to be met, including:

- To obtain a suitable machining parameters to machine a CFRP panels by using single bit for various types process.
- To investigate the effect of machining parameters to the quality performance of CFRP panel.
- To study the coating application at a constant machining parameter for tool life improvement while machining a CFRP panel.

1.4 Scope of research

For this study, the research focused on the effects of manipulating machining parameters towards the quality of machined surfaces of the CFRP panels. With that said, the research started by determining relevant parameters based on literature review of previous works. Then, the range of parameter values were determined. After verifying the parameters, the machining process were executed. All the machining processes were executed in a dry cut condition, which means no coolant or lubricant assistance were deployed. Four tool bits were used in this research, with all the three tool bits having the exact same geometry and properties. The fourth tool bit used in this experiment is coated with diamond-like coating on the cutting surface. Its performance is compared with the uncoated tool bit with the best set of parameter for tool improvement analysis. The experimented panel on the other hand is uni-directional CFRP with an average thickness of 3.5mm. To maintain the integrity of the captured data, the machined surface was ensured to be free from any impurities. This was done by vacuuming the chips formed after each machining processes. Relevant responses were observed and identified, and related data were collected for further analysis. Among the responses that were analyzed include hole roughness, trimming roughness, facing roughness, entry delamination, exit delamination, trimming gap, chip size, and tool weight. Interactions between parameters to responses were investigated for better understanding of the research.

1.5 Organization of thesis

Five chapters are included as a part of this thesis. The thesis starts with chapter one, which includes the background study, problem statement, research objectives, and scope of research. Chapter two consist of literature studies of related topics including workpiece materials, drill bit materials and also machining parameters including feed rate and spindle speed. In chapter three, research methodology was discussed to include the machining set of parameters and machining processes including workpiece placement. Other than that, details of materials used in the project and the tools used are also presented. The quality performance assessment such as delamination, roughness and hole diameter error are including in this chapter. Chapter 4 will then present the results and findings of the research. The results were also discussed further to include trends and relationship between interactions of variables. Some of the results analyzed in this experiment include hole delamination, trimming gap, roughness, hole diameter error and tool wear analysis. Finally, the conclusion is presented in chapter five of this thesis. The objectives of this experiment are determined whether it is met or not. Recommendation for further studies were also presented in the last chapter.

CHAPTER 2

LITERATURE REVIEW

2.1 Composite material types

Glass fiber reinforced plastics (GFRP) and CFRP are some of the most commonly used composite materials that have found numerous applications in various industries. CFRP and GFRP are desired for their excellent mechanical strength. Both CFRP and GFRP are formed with the combination of fibers such as carbon, Kevlar and glass with polymer matrix. Fibers are favoured for its characteristics of light in weight, sturdy and stiff that is able to provide high rigidity and durability to composite laminates. Polymer matrix on the other hand binds together the fiber and at the same time acts as an agent to spread loads to the fibers. It also acts as protection to the reinforced fibers from environmental damage throughout its service life.

2.1.1 Carbon fiber reinforced plastics

Carbon fiber reinforced polymers (CFRP) are heterogeneous and anisotropic materials. It does not exhibit plastic deformation when subjected under stress (Altin Karataş & Gökkaya, 2018). It has numerous properties that are favoured by industries as a material of choice. Popular properties include low weight to strength ratio, high fatigue, resistant to high temperature and does not oxidize due to absence of metal elements (Altin Karataş & Gökkaya, 2018). CFRP are made from stacks of weaved carbon fiber and layered together to form a single panel. The usual practice of layering involves stacking layers with different angle of orientation to allow for better distribution of force that acts upon the panel. Common orientation includes 0°, 45° and 90° (Zhang et al., 2021).

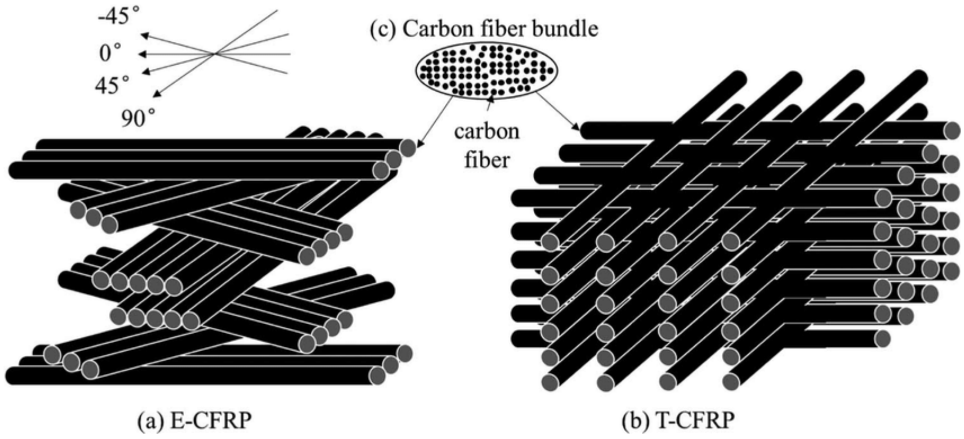

Figure 2.1: Orientation of carbon fiber in CFRP panel.

2.2 Drilling

Processing of CFRP often requires machining before obtaining its final shape and form. Typical machining process includes drilling. Drilling is often required on CFRP panels for assembly process. Taking CFRP panels for aerospace application for example, thousands of holes need to be drilled for assembling the panels to the body of an airplane (Araujo et al., 2021). With that said, drilling process needs to be executed carefully to avoid defects that could potentially cause rejection of the CFRP panels. It is a known fact that drilling parameters will directly affect the drilling surface formed on the CFRP panel (Joshi et al., 2018). Parameters such as spindle speed and feed rate are often considered during drilling process. Other than that, parameters of the cutting tool itself such as tool geometry also will have influence to the end result of the drilling process (Joshi et al., 2018). Based on the literature review, the drilling parameters used are 0.05-0.15 mm/rev for the feed rate and 2500-1000 rpm for rotational speed.

2.2.1 Drilling for manufacturing of commercial aircraft

Drilling is considered as one of the most significant machining processes in the aircraft manufacturing industry. This is because many parts of the commercial aircraft are assembled using riveting joints. Millions of holes need to be drilled in aircraft panels, and similar amount of rivets are then used as mechanical fasteners in the place of the drilled holes (Long et al., 2022). Drilling also has severe effect of an aircraft's structural integrity, performance, and the overall service life. As the commercial aircraft industry has been steadily on the rise due to customers demand of air travelling, commercial aircraft manufacturers have been on track to provide the best aircraft for airline service providers across the globe. Fulfilling the aviation industry standard of requirements in producing high quality CFRP panels with factors including roughness and delamination has always been a major challenge for commercial aircraft manufacturers. The unique properties of CFRP as advanced material that is totally different from traditional materials such as metals and ceramics has to be seriously taken into consideration, as different material surely has to be processed in its own unique methods. With that said, having a good understanding on the drill, the material and also its interactions will allow for a higher quality hole, thus avoiding defects from occurring (Feito et al., 2018).

2.2.2 Drill bit material for aircraft application

Material toughness, hardness, wear and also resistance to heat are some of the factors that will determine a drill bit's service life while at the same time deliver desired drilling results. An excellent drill bit must be able to drill without breaking, preventing wear from happening too fast, must not break or rupture during usage, and also able to withstand high machining temperature during machining process. This is due to most of the machining of CFRP are done without the presence of heat dissipating agent such as coolant. Dry cut is usually the preferred method of machining because CFRP is not suitable to be machined with the presence of any liquid. It is noted that hardness and toughness are some of the most important criteria in selecting tool bit material. Hardness is defined as the ability to prevent indenter penetration from occurring, while toughness is defined as the ability of a material to absorb energy without fracturing through plastic deformation. Materials with high toughness benefit from being able to withstand load shock, and able to prevent chipping and cracking during mishandling of drilling process. Usually, hardness and toughness are inversely proportional, but advancement of technology through research has pushed the boundary for development of materials that are both hard and tough. Generally, the drill bit must be manufactured using materials that are harder and tougher than the workpiece material because then only the drilling process could be executed smoothly. The tool should also be able to handle high temperature as the drilling may operate in temperature of up to 200°C. High-speed steel is able to withstand temperature of up to 600°C, and at the same time have good hardness and toughness, making it a desired material to be used as a drill bit.

2.2.3 Application of coating for tool life extension

Numerous methods have been explored to find out the best solution to allow for longer service life of drill bits. Utilizing drill bits with long service life is desired in the commercial aircraft industry, as it translates into higher productivity and lower operation cost. Tool coating is one of the solutions that is widely being used in this industry. Applying a layer of coating on the surface of the cutting tool does not only extend its service life, but at the same time also provide numerous benefits. Hari Nath Reddy et al., (2020) has found several importance of coating application for the extension of tool life. They reported that coated drill bits does result in higher tool life compared to uncoated drill bits. The machining performance of coated drill bits are also found to be superior compared to its uncoated counterparts. SEM imaging of the two types of drill bits after 50 drills have found that coated drill bit to have lower wear rate compared to uncoated drill bit. Hence, it is safe to say that application of coating onto drill bit surface have several advantages, and the positive impact surely is desired by the commercial aircraft industry as the increase of cost of the tool bit is justified.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter will further explain the overall methodology that were used for conducting this research. The experiment plan was presented in this chapter, together with the flow chart of the research is shown in Figure 3.1. The set of experiment used to conduct this research is also elaborated in this chapter. The materials used and the machining processes involved in the research including the specimen placement on the machines are explained in the next section of the chapter. Lastly, the methodology of quality performance analysis and tool wear analysis are also discussed in this chapter.

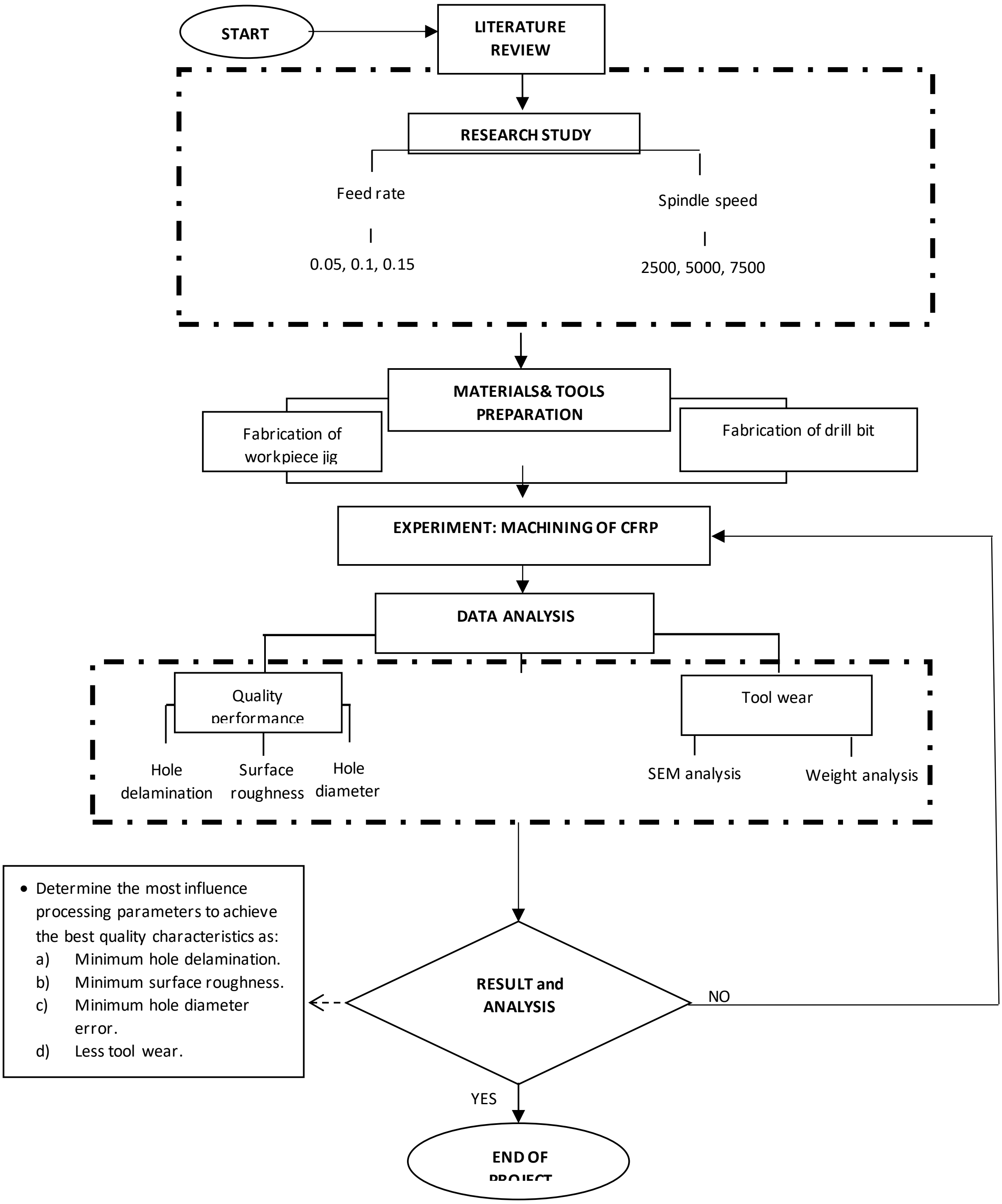

Figure 3.1: General flow chart of the research.

3.2 Set of experiment

This research is conducted on experiment basis, whereby most of the data are collected and obtained through laboratory works. To achieve desired results, the procedure of experiments, including the parameters were systematically designed to fit the nature of the research based on the experiment objectives that were set earlier. Previous works were referred as guidance on setting up the experiment flow for maximum efficiency of available resources. Two parameters of machining were then decided to be used as manipulated variables of the experiment, which is the spindle speed and feed rate. Three levels of input were chosen for each parameter, consisting of lower input level, middle input level and higher input level. The set of parameter combinations are shown in Table 3.1. The same feed rates are used across all the three machining processes, while rotational speed varies between the 4.85mm drilling, 6.35mm drilling and facing & trimming process. As a preparation, all tool bits were cleaned in ultrasonic bath for three minutes, then removed from the bath and dried using heated blower. The weight of all tool bits was recorded before the start of the experiment.

Table 3.1: Combination of parameter and its levels.

	4.85mm Drilling		**6.35mm Drilling**		**Facing & Trimming**	
Bit	Feed rate (mm/rev)	Rotational speed (rpm)	Feed rate (mm/rev)	Rotational speed (rpm)	Feed rate (mm/rev)	Rotational speed (rpm)
1 & 4	0.05	2500	0.05	2000	0.05	7000
2	0.1	5000	0.1	4000	0.1	8500
3	0.15	7500	0.15	6000	0.15	10000

The machining process will then be executed using a Computer Numerical Control (CNC) milling machine. All tools were loaded into the tool magazine of the CNC machine before the start of the machining process. A fixture was fabricated to support the workpiece during machining process. The fixture, made using aluminium block, was machined with through holes along the tool path to allow for better chip evacuation during the workpiece machining process, preventing chip build-up that will block the tool path and subsequently impact the experiment results. The workpiece was placed on top of an aluminium fixture that was already machined to accommodate the tool path of the machining process. Then, the workpiece and aluminium fixture was secured on a jig that is locked into place using four unit of Allen key screws. To verify the positioning of the workpiece in terms of flatness, a spirit level was placed on top of the workpiece. The machine will then execute the machining process using the tool path that was set beforehand. Same tool path was used across all CFRP panels in the experiment. The machining sequence started with machining of five 4.85mm holes, followed by five 6.35mm holes, followed by facing process and lastly trimming process. After completing each part of the machining, the CNC machine was stopped to allow for collection of machine chip for analysis purposes. Excess chips were then cleared from the workpiece using a vacuum cleaner to allow next process to resume. This process is to allow for a more accurate experiment results as factors that may hinder data accuracy was removed. The machine was then resumed for the next machining process, and the steps were repeated until all the machining processes were completed on the workpiece.

(a) (b)

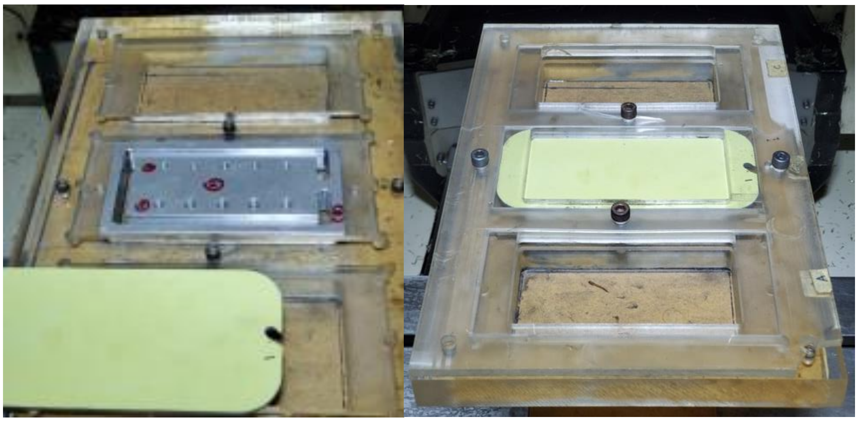

Figure 3.2: Placement of aluminium fixture into the jig (a) in the CNC machine which are then secured using a jig (b) with four Allen screws.

Figure 3.3: Spirit level verification on the workpiece placement.

The workpiece was then unclamped and removed from the CNC machine after the machining process has been completed. The next workpiece was then clamped, and the machining processes were repeated with the set parameters until all panels were machined. All the panels were cleaned from machine chip using air gun. The tool bits were removed from the machine tool magazine and were also cleaned from excess particles. The tool bits were placed in ultrasonic bath for three minutes to remove debris from the tool bit. The tool bits were then dried using a heated blower. Then, all tool bits were weighted using a high accuracy weighing machine to observe the weight difference before and after the machining process.

3.3 Materials

The material used for this research is Carbon Fiber Reinforced Plastic (CFRP) with a dimension of 85mm x 185mm. The CFRP panel is made up from 26 layers of pre-impregnated and pre-cured carbon fiber sheets that are sandwiched together into shape with the use of heat and pressure. Each layer of the carbon fiber ply is 0.125mm thick, which equals to 3.25mm of carbon fiber thickness. On the outer layer of both sides of the carbon fiber, a layer of epoxy woven fabrics was also glued together. The purpose of the epoxy layer is to secure the panel from both entry and entry delamination from forming. With the paint applied, the average thickness of the CFRP panel used in this experiment is 3.5mm. The carbon fiber layout is unidirectional. The sequence of carbon fiber layer stacking is $[45/135/90_2/0/90/0/90/0/135/45_2/135]_s$. The layering direction is mirrored from the outer layers to the inner layers of the CFRP panel. The CFRP panel has a density of 1.601 g/cm^3.

Figure 3.4: 185mm x 85mm CFRP panel used in this research.

Other than the CFRP panel, the tool bits used in this research are made from tungsten carbide. The material is selected for its characteristics of having a high melting temperature at 2747°C. This means that tool bits made of tungsten carbide is highly heat resistant, which is a desired property considering that the machining process in this experiment were done without the presence of coolant to help lower the temperature. Other than that, tungsten carbide have a high hardness of 9 in Mohs hardness scale, which is just below the hardest material which is diamond. Tool bit 4, which was coated with diamond-like carbon (DLC) coating on the outer surface was introduced at a later stage of the experiment. The best set of machining parameter out the first three tool bits was determined, then the parameters were used for tool bit 4 for comparison of machining quality between uncoated and coated tool bit. DLC has several favoured properties that may be useful for machining of CFRP, including high hardness, low machining friction and high wear resistance. It may help to produce higher quality machining of CFRP panel and also result in longer tool life.

3.4 Machining process

Several machines were used to conduct this experiment, including to extract and analyze data. Starting from the preparation process of the experiment to the machining process, and all the way to the data collection process, machines were utilized to assist the research. In the initial stage of the research, three machines were used to assist the preparation of the machining process. All the three machines were used by the tool bits for cleaning and weighing process. The first machine used is the ultrasonic bath machine. Tool bits were cleaned before the start of the experiment using this ultrasonic bath. There are two reasons for cleaning the tool bit before the start of the experiment. The first reason is to ensure that no particles are present within the tool bit that may cause interference to the machining process, thus reducing the data accuracy, and the second reason is to prepare the tool bit to be weighed before the start of the experiment. The second machine used for this experiment is the Buehler Metaserv Specimen Dryer. This machine is used to dry the tool bits after being immersed and cleaned in the ultrasonic bath. The machine has two functions, which are to only blow the specimen and to blow the specimen with the presence of heat using the built-in heater. Tool bits that were cleaned in the ultrasonic bath were dried using this specimen dryer machine using the blow and heater function for two minutes to allow for complete drying of all the tool bits. Then, the tool bits were weighed using the third machine used in this research, which is Shimadzu AUW220D high precision weighing machine. The weighing machine is able to weigh up to 220g of specimen, and the high sensitivity machine can detect minute increments of 0.01g, hence able to deliver high accuracy reading of the tool bit weight.

Figure 3.5: Tool bit immersed in ultrasonic bath.

Figure 3.6: Buehler Metaserv specimen dryer machine.

Figure 3.7: Shimadzu AUW220D high precision weighing machine.

The experiment was continued to the next stage, which is the machining process. CNC machine was utilized for the machining process of the experiment. In this research, Fanuc Robodrill Alpha T21iFB High Speed CNC Milling was used. All the four tool bits were clamped into the tool magazine that is built into the machine before the start of the machining process.

(a) **(b)**

Figure 3.8: (a) Fanuc Robodrill Alpha T21iFB high speed CNC machine with (b) tool magazine of the CNC machine for holding the tool bits used in the experiment.

3.5 Quality performance measurement

Completing the machining process will then resume to the next step of the research, which is the data collection for quality measurement purposes. This step is crucial as the success of this experiment will be determined using the data obtained in this step. For this step, four machines were utilized to extract the data for analysis. The machines used, specimen positioning in the machine and supporting setup data such as the result sample are also presented in this section. For each of the machine used in this research, specimen would be placed into the machine to obtain the desired results. Having the correct placement of specimen into the machines will yield results that are more accurate, reliable, and error-free.

3.5.1 Delamination measurement

Measuring delamination of the drilled holes in this experiment is done using the Alicona IFM Infinite Focus Optical 3D Surface Metrology machine. This machine is a digital imaging machine that is used to analyze delamination of machined holes. Other functions that are available to be used in the Alicona IFM Infinite Focus Optical 3D Surface Metrology machine is surface roughness analysis, gap and distance analysis and depth analysis. Both entry delamination and exit delamination were analyzed for all machined holes. The delamination factor was calculated using the following formula:

$$\text{Delamination factor}, F_D = \frac{D_{max}}{D_0}$$

The maximum diameter of delamination, D_{max} that occurs on the workpiece was divided with the diameter of the hole, D_0 formed by the drilling process to obtain the delamination factor, F_D of the drilled hole. According to AITM 06-4022 2016 standard shown in Figure 3.9, the delamination formed on the panel with thickness of less than 5mm should be less than 2mm of each side, which means the maximum delamination diameter, D_{max} should not exceed 4mm from D_0 value.

Hole Nominal diameter D (mm)	Flaking Depth Dimension H (mm)	Defect Dimension A (mm)		Remarks
		Thin Part t < 5mm	Thick Part t > 5mm	
<3,2	↑	2	2	
3,6		2	2	
4		2	2,5	
4,8		2	2,5	
5,6		2	2,5	
6,4		2,5	2,5	
8		3	3	
9,5	Refer to Table 2	3	3	
11,1		4	4	
12,7		4	4	
14,3		4	4	
15,9		4	4	
19		4,75	4,75	
22,2		5,5	5,5	(NOTE 1)
>25,4	↓	6,5	6,5	

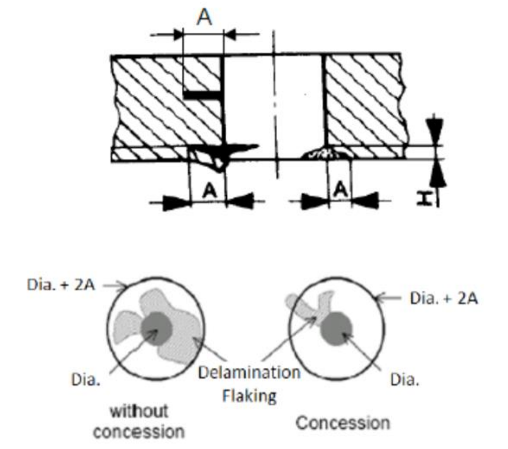

Figure 3.9: AITM 06-4022 (2016) standard on acceptable delamination formed on drilled panel.

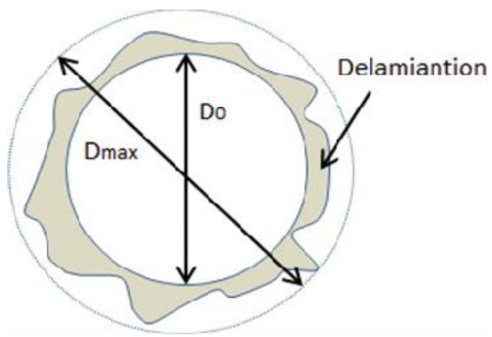

Figure 3.10: Method of measuring D_{max} and D_0 to determine delamination factor, F_D in this experiment.

The depth of facing profile on the workpiece were also analyzed using this machine. Other analysis that was done using this machine is the trimming gap analysis, whereby the distance between the trimmed workpiece were measured. The gap analysis was also conducted under this section of the study, as the gap produced in the trimming process are related to the delamination produced. Figure 3.12 shows the position marked on the workpiece for gap measurement.

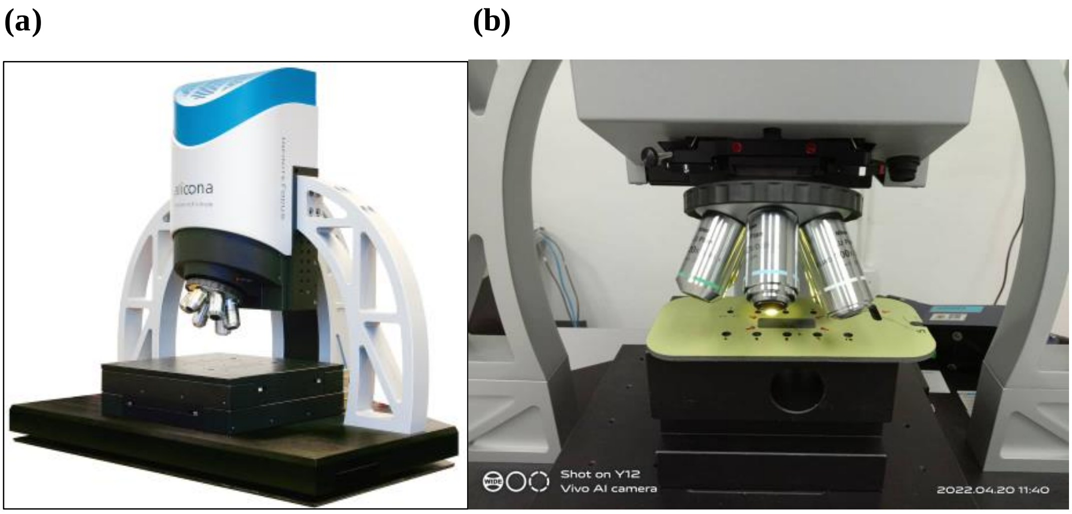

Figure 3.11: (a) Alicona Infinite Focus digital imaging machine and (b) specimen placement on the machine.

Figure 3.11: Locations of gap reading for each CFRP panels.

3.5.2 Roughness measurement

The first machine is the surface roughness measurement machine. The surface roughness machine that was used for this experiment is the Mitutoyo Surftest SV-3100, as shown in Figure 3.13. This machine is used to analyze the surface roughness of machined holes and trimming roughness. Analyzing the roughness is crucial as it is a method to verify whether the roughness obtained in this experiment meets the industry standard or not. All the seven CFRP panel workpieces were subjected to this roughness test.

(a) (b)

Figure 3.12: Mitutoyo Surftest SV-3100 with (a) specimen mounted perpendicular to the stylus probe and (b) side view of the machine with aligned holes and stylus probe.

3.5.3 Hole diameter error measurement

Lastly, the final machine that was used in this research is the Coordinate Measuring Machine (CMM). The CMM machine that was used in this research is the Mitutoyo Crysta-Plus M443 CMM machine. This machine was used to analyze the size of machined holes. The first five holes of both 4.85mm and 6.35mm hole for each tool bit were measured using this machine. For each hole that was measured, four points were probed, starting from 12 o-clock position and moving clockwise, as shown in Figure 3.15 (a).