OPTIMIZATION OF CUSTOMIZED TETRA-FLUTE DRILL REAMER FOR A BETTER HOLE QUALITY IN SINGLE SHOT DRILLING OF CFRP COMPOSITE LAMINATE

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DECLARATION

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

Signed ……………………………T.Xiang……………………….... (CHOO THEN XIANG)

Date ……………………17 July 2021………………………….

STATEMENT 1

This thesis is the result of my own investigations, except where otherwise stated.
Other sources are acknowledged by giving explicit references.
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ABSTRAK

Polimer bertetulang gentian karbon (CFRP) adalah bahan popular yang digunakan dalam industri aeroangkasa dan automotif belakangan ini. Proses penggerudian biasanya terlibat dalam pembuatan produk CFRP dan gerudi yang mempunyai reka bentuk yang baik dapat membantu industri pembuatan untuk mengurangkan pembaziran tanaga, bahan dan wang. Untuk mendapatkan pemacu gerudi yang baik, geometri gerudi seperti diameter gerudi, sudut heliks, sudut pelepasan dan ketebalan titik diuji selidik dengan mengumpulkan data berdasarkan lima tindak balas, iaitu daya tujah, ralat diameter, kekasaran permukaan, pemecahan panel dan keausan analisis. Berdasarkan analisis Regresi, daya tujah, kekasaran permukaan dan analisis keausan mempunyai kebolehubahan yang lebih tinggi untuk menjalani analisis yang lebih mendalam, iaitu plot interaksi yang digunakan untuk menganalisis hubungan antara empat faktor dalam ketiga-tiga tindak balas tersebut.

Terdapat sembilan pemacu gerudi khas yang dikategorikan dalam tiga kategori iaitu diameter gerudi 3.20 mm, 4.85 mm dan 6.35 mm digunakan dalam penyelidikan. Kesemua pemacu gerudi digunakan untuk menggerudi bahan kerja CFRP selepas itu. Melalui kajian ini, didapati bahawa empat faktor, iaitu diameter gerudi, sudut heliks, sudut pelepasan dan ketebalan titik akan memberi tahap kesan yang berbeza terhadap tindak balas tertentu. Selain itu, melalui penyelidikan, nilai tindak balas didapati akan berbeza dengan pelbagai kombinasi parameter. Pada peringkat akhir penyelidikan ini, parameter optimum untuk pemacu gerudi khas menggerudi CFRP dengan hanya satu tembakan untuk memperoleh kualiti lubang yang lebih baik ialah Run A1 (3.20 mm), Run B2 (4.85 mm) dan Run C1 (6.35 mm). Kombinasi parameter untuk Run A1 ialah sudut heliks (0°), sudut pelepasan (9°) dan ketebalan titik (15%). Sementara kombinasi parameter untuk Run B2 ialah sudut heliks (5°), sudut pelepasan (9°) dan ketebalan titik (20%) sedangkan Run C1 ialah sudut heliks (0°), sudut pelepasan (12°) dan ketebalan titik (20%).

ABSTRACT

Carbon fibre reinforced polymer (CFRP) is a popular material that used in the aerospace and automotive industries in recent years. The drilling process is typically involved in the manufacture of CFRP products and a drill with a good design can help the manufacturing industry to reduce waste of energy, material and money. To obtain a good drill reamer, drill geometry such as drill diameter, helix angle, clearance angle and point thickness were investigated by collecting data based on five responses, namely thrust force, diameter error, surface roughness, delamination and wear analysis. Based on Regression analysis, thrust force, surface roughness and wear analysis have higher variability to perform a deeper analysis, which is the interaction plot that used to analyse the relationship between the four factors in these three single responses.

Nine customized drill reamers that are separated into three categories, which are drill diameters of 3.20 mm, 4.85 mm and 6.35 mm, were used in the research. Those drill reamers were used to drill the CFRP workpiece afterwards. Through this research, it was found that the four factors, which are the drill diameter, helix angle, clearance angle and point thickness, would have different level of impact on certain response. The response values for the thrust force, diameter error, surface roughness, delamination and the wear analysis obtained through the research also differ with various parameters combinations of parameters. At the end of the research, the optimum parameters for customized tetra-flute drill reamer to perform one shot drilling of CFRP to obtain better hole quality was Run A1 (3.20 mm), Run B2 (4.85 mm) and Run C1 (6.35 mm). While the parameters combinations for Run A1 is helix angle (0°), clearance angle (9°) and point thickness (15%). While the parameters combination for Run B2 is helix angle (5°), clearance angle (9°) and point thickness (20%) whereas Run C1 are helix angle (0°), clearance angle (12°) and point thickness (20%).

CHAPTER 1 INTRODUCTION

1.1 Overview

In the recent years, the composite laminate material has become the concern in the manufacturing industries especially in the field of the aerospace and the automotive. In general, composite laminates are orthotropic, consisting of multiple layers of oriented or randomly oriented fibres bound together by a matrix in which each layers of fibres has a 2-D orientation (Jefferson, A. J., 2018). One of the examples of a composite laminate is carbon fibre reinforced polymers or we called CFRP. This composite material is rely on the carbon fibre to provide higher strength and stiffness while the cohesive matrix given by polymer is used to protect and hold the fibres together for providing certain toughness (J.R.Fekete, 2017). Thus, it becomes one of the popular materials that used to produce the body parts of the car, aeroplane, and other products.in most of the automotive and aerospace application. It is believed that the CFRP composite laminate will become the superior material in the coming generation that making body parts of car and aeroplane to become lighter, more efficient and safer (Nikhil Gupta, 2016).

We can’t deny that CFRP composite laminate is a good material; however, it has also brought certain problems in the manufacturing process in the industry. Usually, when the drilling process is carried out to drill a hole on the CFRP composite laminate; delamination will occur and the hole with poor quality will be obtained. Since we know that the delamination is a critical failure mechanism in laminated fibre-reinforced polymer matrix composites. It may lead directly to through-thickness failure owing to inter-laminar stresses (M.R.Wisnom, 2012).

Besides, the surface roughness of the drilled hole is also one of the concerning issues in the drilling process. The surface roughness is characterized as the shorter frequency of real surfaces relative to the troughs. The surfaces embody a complex and unpredictable shape made of a series of peaks and troughs of differing heights, depths, and spacing. It is enormously influenced by the microscopic asperity of the surface of each part (What is Surface Roughness, 2020). A hole with higher surface roughness may cause difficulties during the assembly because the fastener such as bolts, nails pins, screw, etc. cannot fit smoothly into the hole. These problems have caused the industries to loss the money since re-machining or scrap the defective parts will waste the materials, energy, time, etc.

To solve the following problems that have been faced by the industries, research has to be carried out and the field study of this research will be titled as material processing because it is an investigation of the drilling parameters that is correlated to the quality of the materials in the specific operation. The purpose of this research is to find out the optimum parameters of the drilling tool that used to be made a hole onto the CFRP composite laminate. The drilling tool involved in the experiment is drill reamer, which it is a rotary-type cutting tool that used in metalworking. Different combination of geometries will bring effect to the drilling responses.

Thus, the effect of the size and geometry of the drill reamer towards the drilling responses such as thrust force, hole's diameter, hole's surface roughness and spindle speed will be studied. The parameters such as feed rate and spindle speed will be set as constant in this project. When there is an optimal parameter that can be applied onto the drill reamer during the operation of the drilling, the waste of the materials, energy, time can be reduced since the problems of the delamination, and poor quality of hole can be minimized. Besides, the optimal parameter that obtains at the end of the research can also become a reference for the manufacturing industries which are doing the same manufacturing process.

1.2 Project Background

When a manufacturing company carry out the operation of the drilling process onto the CFRP composite laminate, it is usually caused the problems like uncut fibre and severe delamination. These problems lead to the waste of materials, time, energy, money and etc. Besides, use of the drill bit with inappropriate geometries in the drilling process will also cause the problem of delamination and resulting in the poor quality of the hole. The current method that implemented by the company to solve these problems is that they apply the drilling process followed by the reaming process to reduce the delamination and to obtain better hole's surface roughness. But, this method has increased the number of manufacturing processes.

Thus, it is believed that there should be a method that can be used to obtain a better quality of hole in one shot of the drilling process. Based on this, there must be optimal geometries that can be applied onto the drill reamer to improve the performance of the drilling process so the problems of the delamination can be minimized and resulting in better surface roughness of the hole. In this project, the effect of nine customized drill reamer with different size of 3.20 mm, 4.85 mm and 6.35 mm and their geometries towards the thrust force together with the quality of the hole such as hole diameter, hole's surface roughness, delamination and wear analysis will be investigated by using an experimental design approach. The size of the drill reamer will be fixed as those three values since the company in the manufacturing operation to manufacture certain parts of specified models commonly uses these manufacturing tools with different diameters.

The outcome of this project is that the optimal geometries of the drill bit that used to drill a hole onto the CFRP composite laminate by one shot can be obtained at the end of the research. It can help the company that fabricate the automotive or aeroplane parts (by using CFRP composite laminate) to reduce material wastage and also shorten the lead time of the manufacturing process. With that, the manufacturing cost can be reduced and the company can produce a better quality product at a cheaper price.

1.3 Problem Statement

Due to the limited literature on this topic, the research regarding the optimization of customized drill reamer in single-shot drilling of CFRP composite laminate has large potential to be carried out. It targets a better understanding of the optimal geometries of the specific tool to obtain a satisfying hole's quality in the drilling operation. Since we know that, the drilling operation of CFRP will bring various damage such as fibre pull-out, fibre-matrix de-bonding, fibre fragmentation and delamination which will affect the hole's quality (Wang, 2020). The delamination issue during insert or exit of the holes in the drilling operation has always become as unwanted issue in majority of CFRP (Suresh, 2020). Besides, delamination is considered as the major damage among all the defects in the drilling process, in which it can caused 60% of part rejection in aircraft industry (Tao, 2016). Thus, the outcome of this research is to provide a reference for the manufacturing industry. This is because in the current industrial field, there is still insufficient information about the suitable application of the optimal geometries of this customized drill bit to obtain better hole's quality by minimizing the delamination and other damages such as diameter error, surface roughness, etc. through one-shot drilling on CFRP materials during the fabrication process.

1.4 Project Objectives

1. To investigate the drill geometries of customized tetra-flute drill reamer on drilling a CFRP panel in a single shot drilling process.
2. To evaluate the thrust force, diameter error, holes' surface roughness, delamination and wear condition of the customized tetra-flute drill reamer
3. To optimize the drill geometries of the customized tetra-flute drill reamer for improving the hole's quality effect and wear

1.5 Scope of Work

In this project, the main point in the early stage is to study the theory of the related topic to improve the understanding of the basic knowledge in the specific field such as the properties of the CFRP composite laminate, the customized drill reamer, and the condition of the hole's surface roughness, etc. After that, the real experiment will be carried out to collect the data of the condition of the hole that has been drilled on the CFRP composite laminate in one shot by using the tetra-flute drill reamer with various geometries but constant feed rate and spindle speed. Initially, the combination of the geometries for nine of the customized tetra-flute drill bit is generated based on the design of experiments (DOE). Besides, Minitab will also be used to carry out the data analysis and then the interpretation will be proceeding based on the analysed result. The area of the research will be focused on the finding of the optimal drill geometry based on the result of the various factors towards the experimental responses.

CHAPTER 2 LITERATURE REVIEW

2.1 Drilling of CFRP

Based on the result of modelling, the fibre orientation of CFRP has a strong effect on the quality of the hole surface. CFRP with well-arranged fibre orientation can make better hole quality for the inner wall. The modelling result also mentioned that a suitable feed rate with a suitable feed force can help the CFRP laminate to avoid delamination (Bonnet, 2015).

It has been proven that the thrust force, torque and delamination damage will increase significantly when the feed rate is increased, however, this side-effect will decrease gradually with an increased cutting speed. Thus, a low feed rate that less than 150 mm/min and a high cutting speed that is larger than 600 rpm should be chosen for the ideal drilling of CFRP (Vaibhav A. Phadnis, 2010). Besides, when the number of holes increased, the peak thrust force is increased. With the higher number of peak thrust force, the hole diameter decrease with the rising number of holes due to tool wear. Higher thrust force results in severe tool wear, and this also caused the poor delamination to be occurred easily (A. D' Orazio, 2017).

In addition, chip breakability is correlated to the feed rate and the drill diameter since an increase in the cross-sectional area of chips will make the surface contact to be enlarged. However, spindle speed has a smaller effect on it. Thus, a smaller feed rate with a constant spindle speed can be used in the drilling process to obtain better hole integrity (Zitoune, 2016). Increasing spindle speed will increase drilling temperature whereas increasing feed rate will get the reverse result. However, higher spindle speed can minimize the diameter error, thus the value of the spindle speed has to be considered clearly in the drilling operation (Wang, 2015).

By using the multi-objective Taguchi technique, the parameter that affects most of the drilling process is the feed rate, followed by cutting speed and type of drill bit. Based on the research carried out by K. Shunmugesh with the team, it was found out that a good combination of drilling process parameters can minimize the surface roughness, thrust force, torque and vibration (K. Shunmugesh, 2017). There is an analysis through ANOVA indicated that higher feed rates result in higher thrust force and caused delamination easily. However, a higher spindle speed can reduce the occurrence of delamination on the workpiece (Krishnamoorthy, 2015).

As thrust force significantly affects the delamination damage of CFRP composite, similar changes of delamination factor and the thrust force concerning changes of cutting parameters can be observed. The size effect of the micro-drilling process will bring an effect towards the cutting forces and hole quality parameters A lower feed rate wouldn’t result in minimum cutting forces and hole quality error but it is caused by feed rate value that is nearly equal to the tool edge radius (Anand, 2018).

2.2 Drill Reamer

Tool geometry plays a significant role in the drilling of CFRP. Smaller thrust force and lower wear quantity are generated from a tool with a higher flute. It has been proved that the hole quality is affected by the drill geometry and the drilled holes are smoother when a three-flute drill is used to drill the holes. It can be deduced that drill tools with higher flutes can perform better in the drilling process (Alonso, 2019). An experiment showed that the use of a novel drill bit can minimize the damage on the CFRP workpiece by reducing the burrs and delamination through the drilling process. With a novel drill bit, better hole quality can be obtained, however, the control of the feed rate is important in the drilling process to avoid avulsion defects (Su, 2018).

Furthermore, a modified shot drill can drill burr-free holes 6 times more than an ordinary one-shot drill since the drill geometry of the previous drill is a combination of different parameters (Jia, 2016). For the performance analysis of a optimization techniques in the drilling process, the chosen optimum drilling parameter is spindle speed of 800 rpm and feed rate of 0.11 mm/rev. It is because it gave minimum delamination effect, while the tool with a helix angle of 35 ° gave minimum delamination effect as compared to the tools with a helix angle of 27 °(Bhushi, 2019).

A smaller helix angle can result in smaller thrust force and torque in which can produce better hole quality (Wei, 2016). When a higher feed rate is applied in the process, the drill with a higher helix angle will suffer from chipping of primary cutting edges. While lower helix angle may have a stronger cutting edge since there is less contact of the drilling surface towards the workpiece in the drilling, but higher thrust force is generated when a lower helix angle drill is used (Liu, 2018).

In an experiment conducted by Feito, N with researchers, it is found out that stepped drill has lower values of delamination factor and thrust force compared to the twist drill. The design for the stepped drill has a diameter section of 4 mm to 6 mm from the tip and the step length is 6.6 mm, while the twist drill consists of the point angle of 118 °. In addition, a supporting back plate is suggested to use in the drilling operation since it has proved that the damage onto the drilled holes can be minimized (Feito Sánchez, 2018). Besides, researcher D. Samuel Raj and L. Karunamoorthy has carry out a research regarding the effect of tool wear based on three types of drill bit, which are twist drill, brad & spur drill and double margin drill. The result showed that brad & spur drill bit produced the least thrust force while double margin drill contributed most consistent thrust force and the least tool wear. In term of surface roughness value, twist drill produced largest surface roughness on drilled holes while that of the double margin drill is the least. For the holes' dimension accuracy, brad and spur drill bit performed the best, which it has produced the holes that closed to nominal diameter of 6.35 mm. Double margin drill also has the best performance for the circularity error since it has the least error compared to others (Raj, 2016). Based on the result, it can be concluded that a combination of drill reamer that owed the characteristics and drill geometry of brad & spur drill and double margin drill may able to perform the best result in the drilling process.

CHAPTER 3 RESEARCH METHODOLOGY

3.1 Overview of Methodology

This chapter presents the overall methods used to study the effect of the customized tetra-flute drill reamer geometry towards the thrust force, holes' diameter, holes' surface roughness, delamination and wear analysis. Nine runs of experiment has been generated based on the orthogonal array of Design of experiment (DOE) and the dominant factors are the diameter of the drill reamer, helix angle, clearance angle and the point thickness. Figure 3.1 showed the approaches that applied in this research, which is the usage of the specific equipment that used to collect the data for the related five responses. Afterwards, those data are analysed through Taguchi analysis, Regression analysis and ANOVA Interaction analysis by using the Minitab software. Figure 3.2 showed the detailed methodological framework of the research.

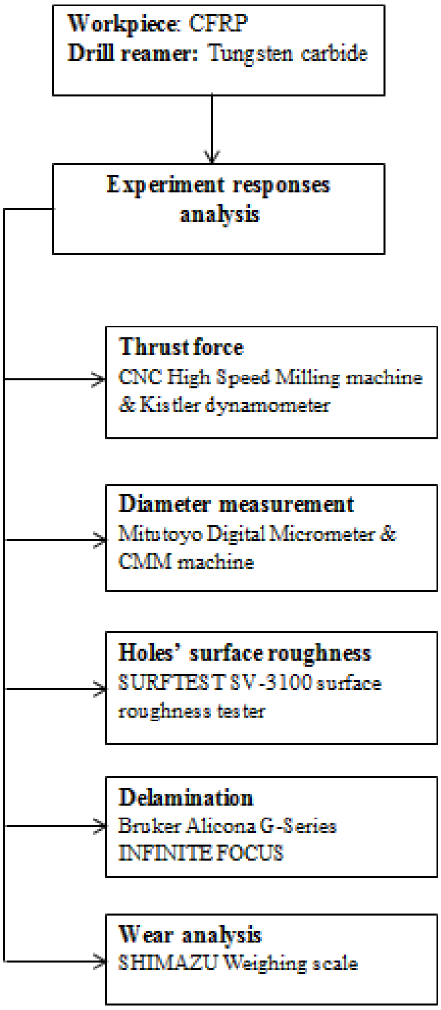


Figure 3.1: Testing approaches of the research

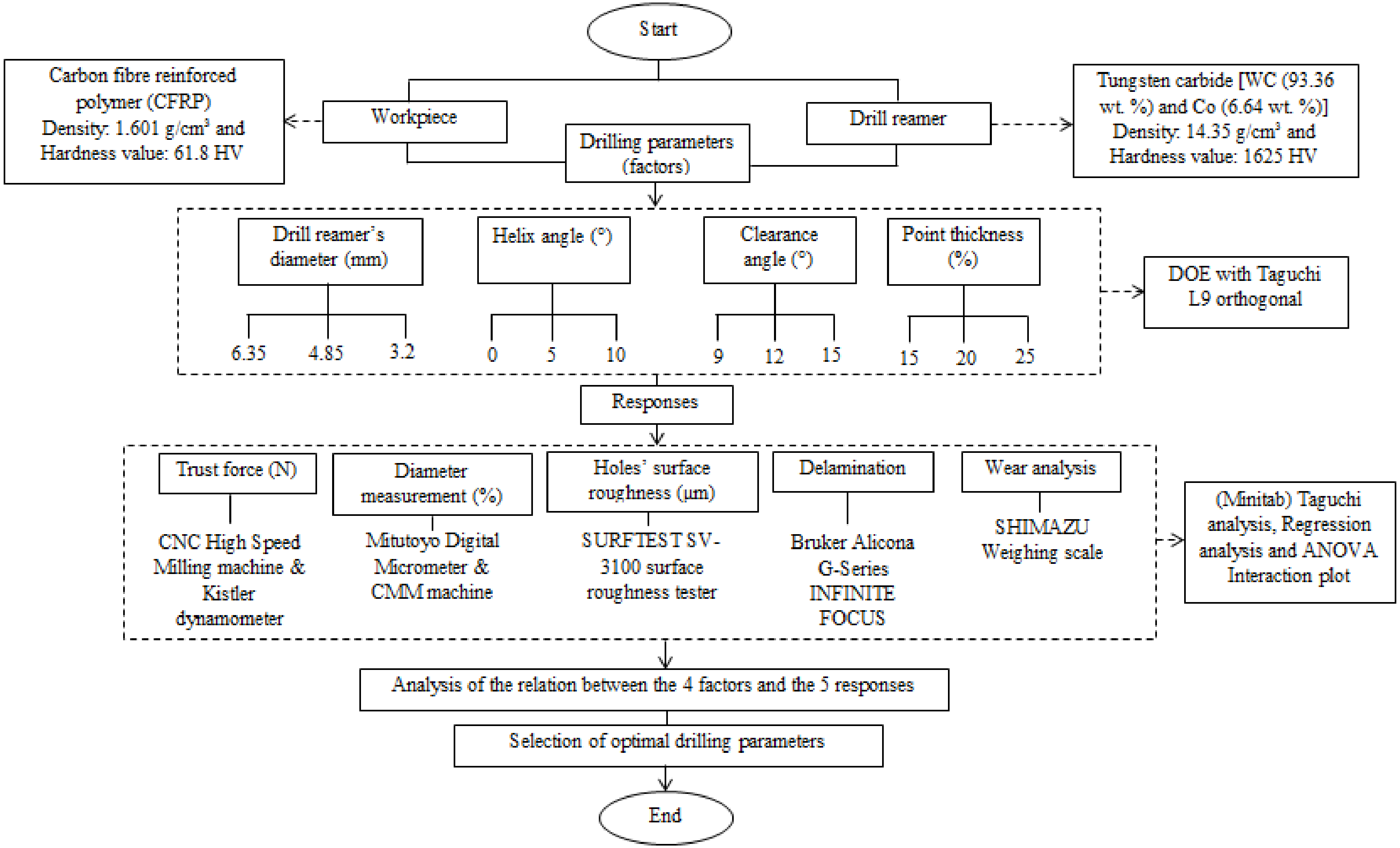


Figure 3.2: Methodological framework of the research

3.2 Materials

3.2.1 Workpiece

The panel as shown in Figure 3.3 is carbon fibre reinforced polymer (CFRP). It is used in the experiment as the workpiece to undergo the drilling process. It has a density of 1.601 g/cm^3 and a hardness value of 61.8 HV. The thickness of the workpiece is 3.58 mm and its inner structure is made up of 26 layers of 0.125 mm thin carbon composite with 2 layers of 0.08 mm thin glass composite. They are joined together by carbon and epoxy prepregs in a unidirectional way (Chim, 2017).

Figure 3.3: The CFRP workpiece used in the research

3.2.2 Cutting tools

Figure 3.4 showed the customized drill reamer that used to drill through the surface of the workpiece in the experiment. The material of the drill reamer is tungsten carbide with the composition of WC (93.36 wt. %) and Co (6.64 wt. %) while the density of the drill reamer is 14.35 g/cm^3 and hardness value of 1625 HV (Chim, 2017). It is obvious that its density and hardness value is higher than that of their workpiece. Figure 3.5 showed the images of the drill reamer that has been designed by using software. The particular parts such as the point angle, helix angle, web thickness, primary clearance angle, etc. have been pointed out in the figure. There is a total of four parameters with three levels are being studied to find out the optimum drilling parameters that used to drill through the CFRP panel with one shot. These parameters are drill reamer’s diameter, helix angle, clearance angle and point thickness while the spindle speed and feed rate is remained constant in this experiment. Table 3.1 tabulated the parameters set for the contributing factor in this experiment and these parameters set is formed by various combination based on L9 Taguchi method.

Figure 3.4: The customized tetra-flute drill reamer

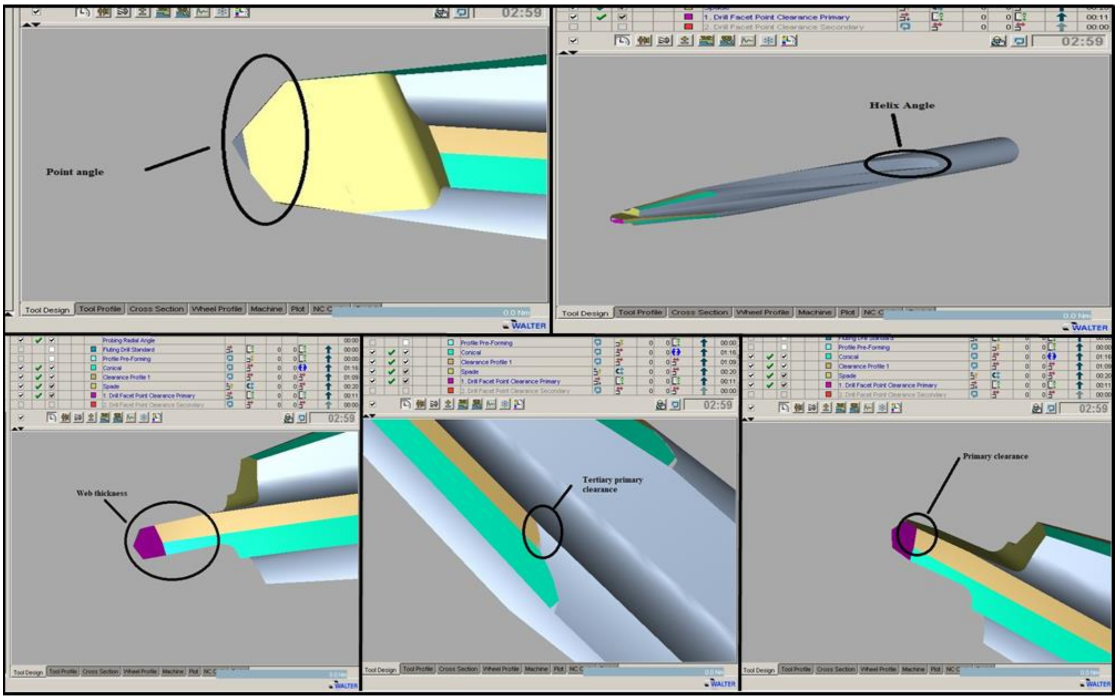
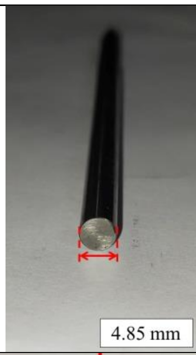
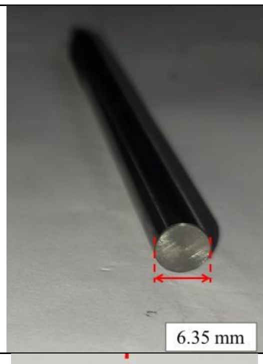
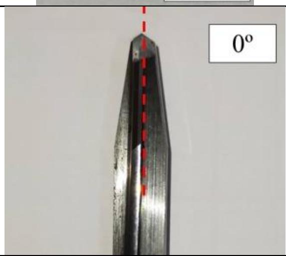
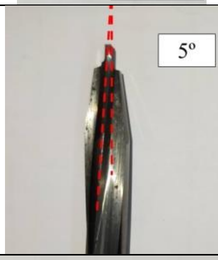
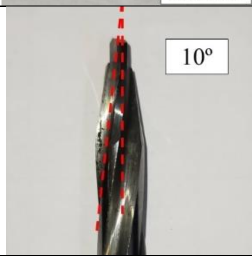
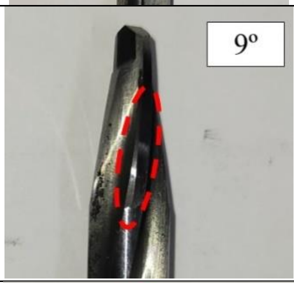
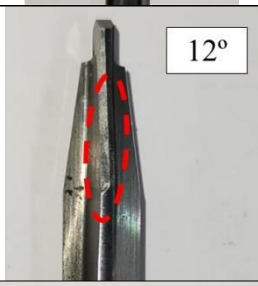
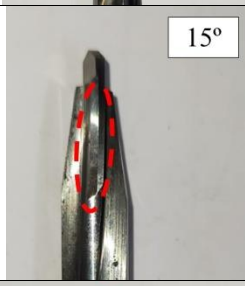
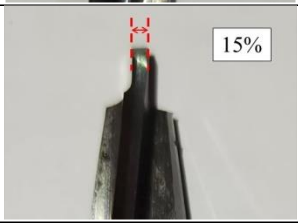
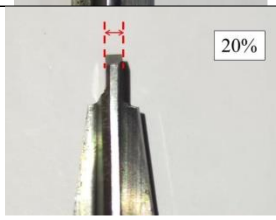


Figure 3.5: Design of customized drill reamer in software

Table 3.1: Contributing parameters with different levels

Parameters	Level 1	Level 2	Level 3
Diameter			
Helix angle			
Clearance angle			
Point thickness			
Spindle speed		2500 rpm	
Feed rate		0.05 mm/rev	

3.3 Design of Experiment (DOE)

In this experiment, the effect of drill geometry of the drill reamer is the only focusing point. With this, there are 4 influencing factors of drill geometry which are drill reamer’s diameter, helix angle, clearance angle and point thickness has been selected in this experiment. By applying DOE’s method, a combination of parameters are generated based on Taguchi orthogonal array L9 (3^4) and the outcome is shown in Table 3.2. In addition, Figure 3.6 showed the nine drill reamers that have been arranged according to the sequence of the run (from Run A1 to Run C3). They are categorized into 3 groups based on their diameter which is 3.20 mm (blue colour dashed-box), 4.85 mm (yellow colour dashed-box) and 6.35 mm (red colour dashed-box).

Table 3.2: Nine runs with combination of parameters by Taguchi design

Run	**Diameter (mm)**	**Helix angle (°)**	**Clearance angle (°)**	**Point thickness (%)**
A1	3.20	0	9	15
A2	3.20	5	12	25
A3	3.20	10	15	20
B1	4.85	0	15	25
B2	4.85	5	9	20
B3	4.85	10	12	15
C1	6.35	0	12	20
C2	6.35	5	15	15
C3	6.35	10	9	25

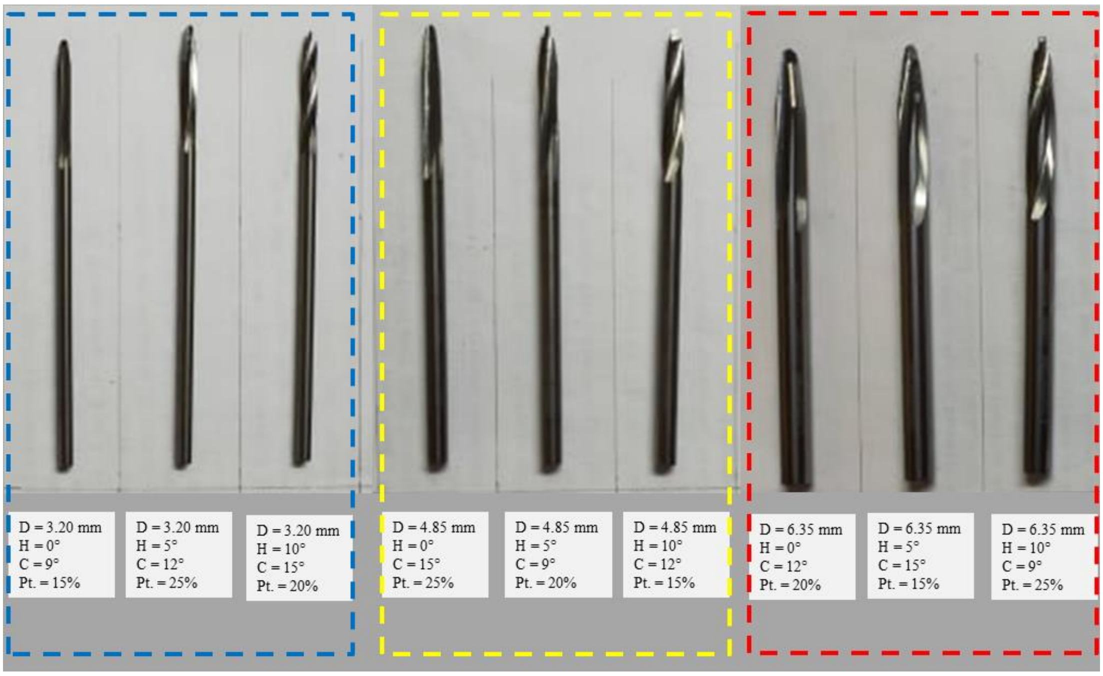


Figure 3.6: Run A1 to Run C3 with specific combined parameters

3.4 Thrust Force Measurement

The data of the thrust force are obtained in the drilling operation which has been carried out in CNC Laboratory. An Alpha T21iFB model CNC High Speed Milling machine as shown in Figure 3.7 is used to execute the drilling process. In the same figure, the workpiece is clamped into a specific jig and then the position of the jig is fixed to make sure the drilling process can be carried out smoothly. At the same time, there is a dynamometer with the model type of “Kistler 4 component dynamometer type 9272” as shown in Figure 3.8 has been placed beneath the jig. The data of the thrust force obtained in the drilling operation is transmitted in form of the signal to the data acquisition system as shown in Figure 3.8 and the amplifier is used to amplify the signal. The result is displayed on the screen of the computer in term of thrust force versus the drilling time.

Left side of Figure 3.9 showed the calibration steps for the CNC milling machine which is carried out to minimize the uncertainty and increase the consistency and accuracy of the drilling process especially the drilling point, drilling depth, etc. In the right side of Figure 3.9, it is showed that the drilling process is in progress and the grey dust around the drilling point is the drilling cuttings or chips produced in the drilling operation. In the end of process, a CFRP panel with 45 drilled holes is obtained and the drilled workpiece is shown as Figure 3.10.

Figure 3.7: CNC High Speed Milling machine (Left) and the workpiece that clamped inside a jig with fix position (Right)

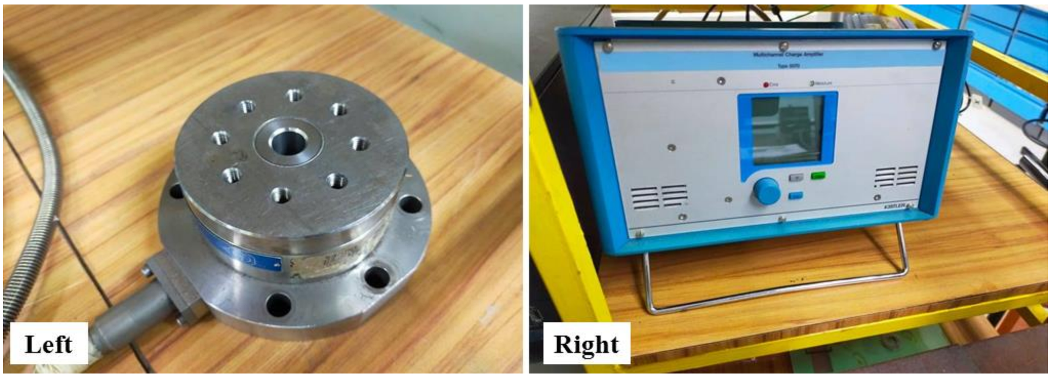


Figure 3.8: Kistler dynamometer (Left) and Data Acquisition System (Right)

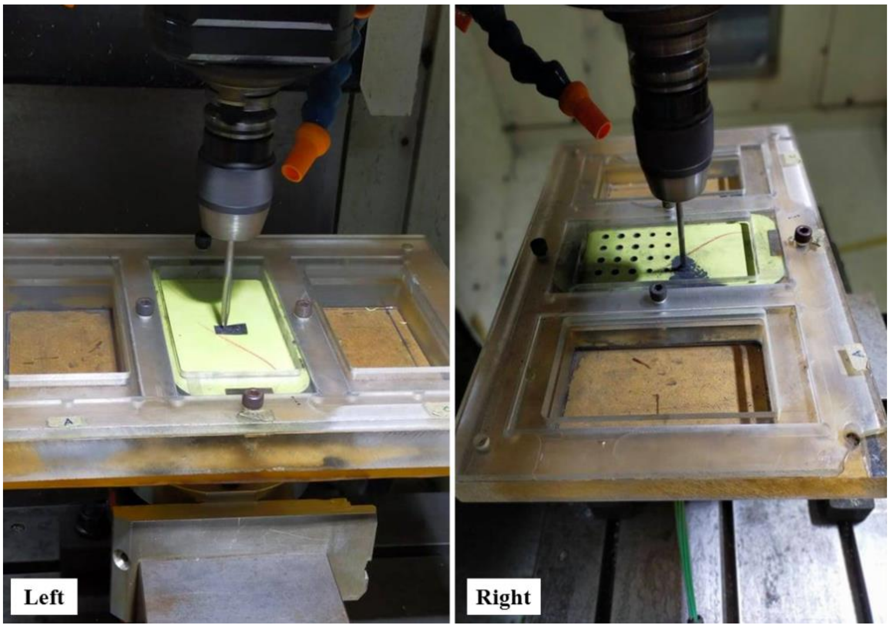


Figure 3.9: Calibration process of CNC Milling machine (Left) and the drilling process of the CFRP workpiece (Right)

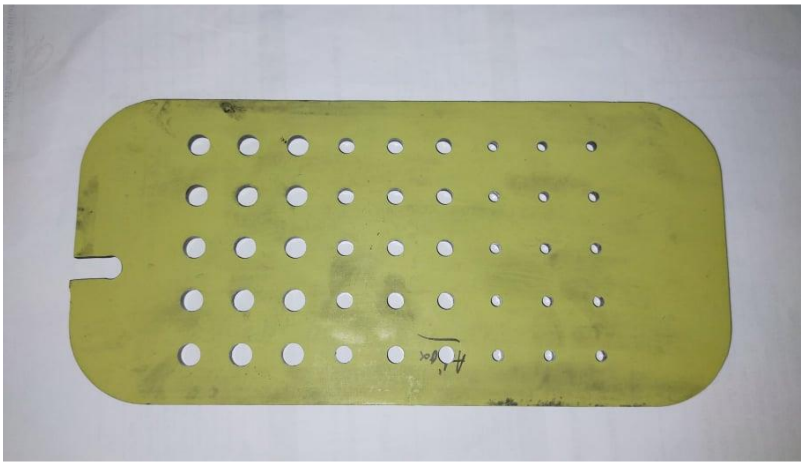


Figure 3.10: The drilled CFRP workpiece

3.5 Diameter Measurement

3.5.1 Drill reamers' Diameter Measurement

Mitutoyo Digital Micrometer is used to measure the diameter of the drill reamer. The calibration process has been carried out by resetting the reading value to zero in the beginning. The body of the drill reamer is placed between the anvil and spindle of the digital micrometer and the measurement is carried out by turning the ratchet to tighten the spindle faces towards the drill reamer to obtain its diameter. There is a total of nine drill reamers' diameter has to be measured and each of them has undergone this measuring process for 5 times to increase the consistency and accuracy of the results. The measuring process of the drill reamers' diameter is shown in Figure 3.11.

Figure 3.11: Measurement of the drill reamers' diameter by using Mitutoyo digital micrometer

3.5.2 Holes' Diameter Measurement

Mitutoyo Coordinate Measuring Machine (CMM) as shown in Figure 3.12 is used for the measurement of the holes' diameter. The workpiece is placed on the table and its position is made sure to be located within the reachable range in X, Y and Z orthogonal axes for the movement of the CMM touch probe. Before the measuring process, the probe characterizing sphere as shown on the left side of Figure 3.13 is used for the calibration of the CMM touch probe to reduce the measurement error.

To increase the consistency and accuracy of the data, the number of points to be collected from each drilled hole is selected as 12 reference points and thus the touch probe of the machine is controlled manually to contact the inner surface of the holes to obtain those data. The touch probe is moved to the center of the hole and downwards into half of depth of the hole to obtain those reference points. The measuring process is shown in right side of Figure 3.13. Since there are 45 holes on the panel, the total number of data points to be collected is 540 values. MCOSMOS software is used to receive and analyse those discrete points. A circle is appeared on the screen and the diameter of the circle is showed. The steps are repeated until all holes' diameter are obtained and recorded as shown in Figure 3.14.

Figure 3.12: Mitutoyo Coordinate Measuring Machine

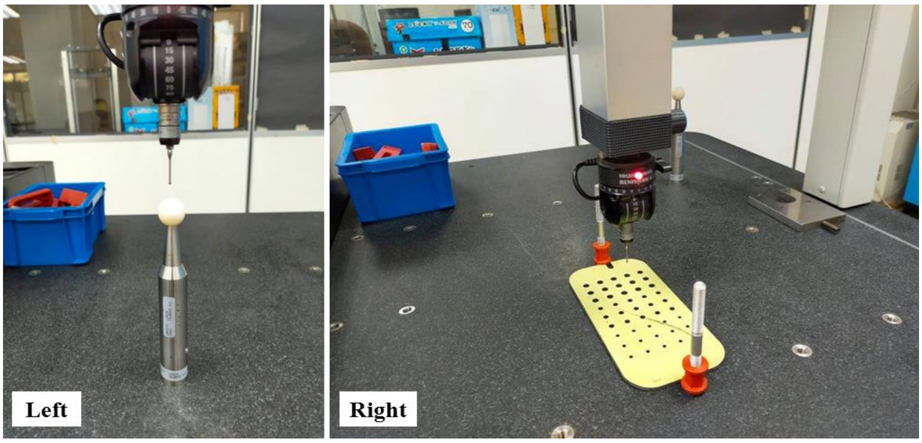


Figure 3.13: CMM probe calibration process (Left) and holes' diameter measuring process (Right)

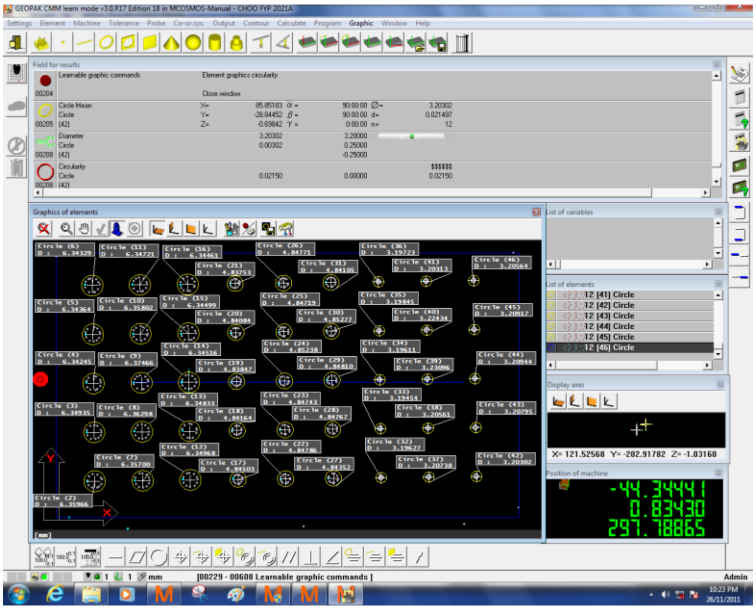


Figure 3.14: Result of the holes' diameter for drilled CFRP workpiece

3.5.3 Diameter Error Measurement

The element involved in the calculation is the average diameter of the drilled holes and the average diameter of the drill reamer. The diameter error is calculated based on the formula as shown below:

$$\text{Diameter error} = \frac{\textit{Diameter of the drilled hole} - \textit{Diameter of the drill reamer}}{\textit{Diameter of the drill reamer}} \times 100\%$$

3.6 Holes' Surface Roughness Measurement

SURFTEST SV-3100 surface roughness tester as shown in Figure 3.15 is used to measure the hole's surface roughness. It consisted of a contact typed stylus that can measure the surface roughness by touching the surface of the drilled holes. The workpiece is placed perpendicularly to the stylus and two heavier blocks are used to fix the workpiece's position. In this experiment, FORMTRACEPAK software is used as the support system to evaluate and analyse the surface roughness of the holes. After both equipment and software are initiated and connected, the evaluation length is set as 2.0 mm together with other measurement conditions based on the setting in Figure 3.17 and the controller is used to move the stylus towards the drilled holes. Following that, the stylus is moved along the surface of the drilled holes in the X-axis to measure the surface roughness as shown in Figure 3.16. The result of average surface roughness, R_a value is then displayed on the screen and the profile of the drilled holes' surface can be seen through the result as shown in Figure 3.18. To increase the consistency and accuracy of the results, there are 4 reference pathways have been measured for each of the holes which are top, bottom, left and right position of the drilled hole, this resulted in 180 data to be collected.

Figure 3.15: SURFTEST SV-3100 Surface roughness tester

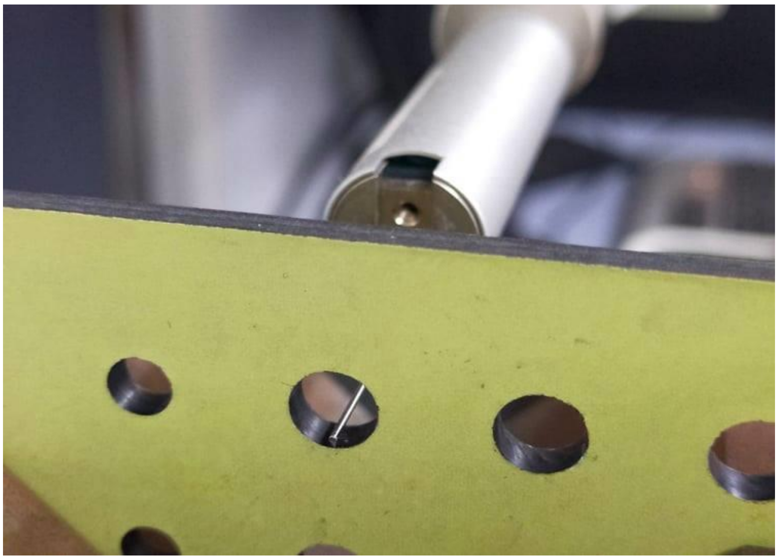


Figure 3.16: The stylus is moved along the drilled hole

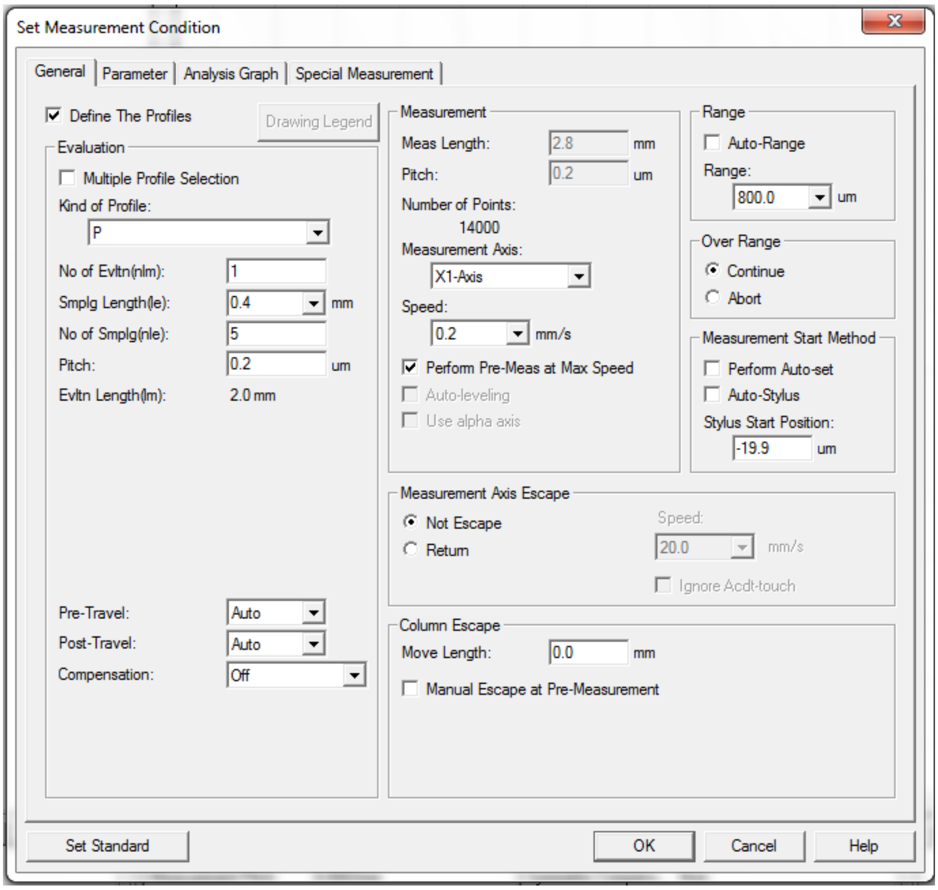


Figure 3.17: Setting of surface roughness measuring system

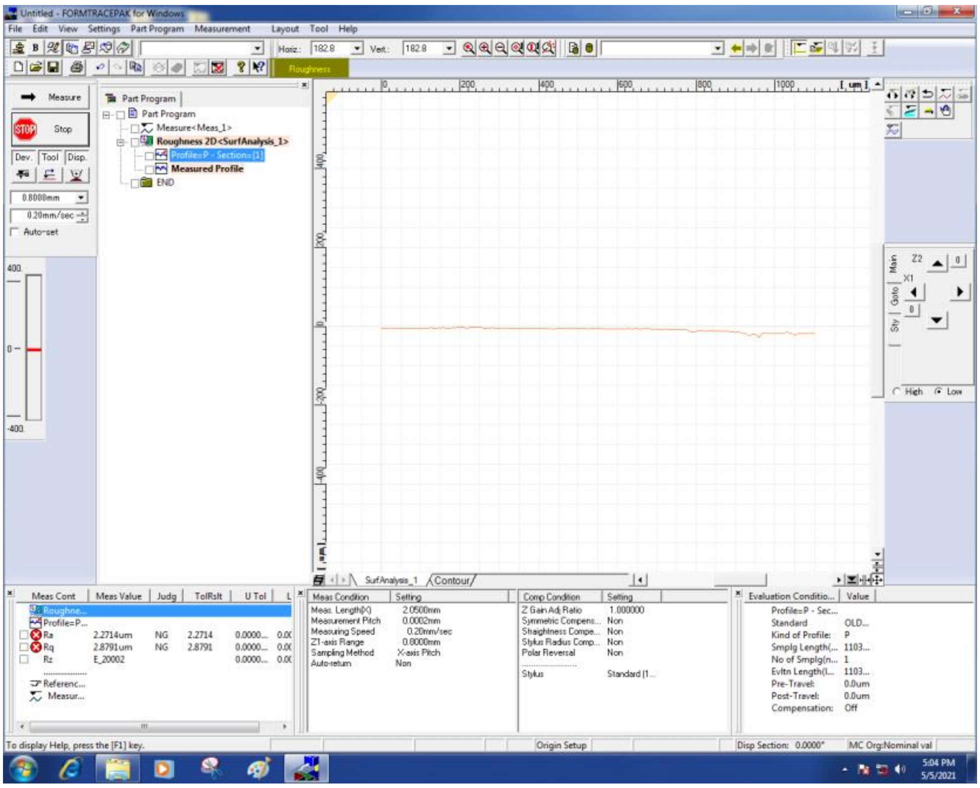


Figure 3.18: Result of the hole's surface roughness

3.7 Delamination Measurement

3.7.1 Measurement of delamination area

Bruker Alicona G-Series INFINITE FOCUS as shown on the left side of Figure 3.19 has been used to capture the images of the drilled holes of the panel. In this part, the entrance of the 3rd drilled holes for Run A1 to Run C3 has been observed through Alicona optical machine and the possibly affected region called delamination is determined. The software named ImageJ is used to analyse the enlarged hole' images to calculate the delamination area. The image of the hole that surrounded by the fine yellow line as shown in the right side of Figure 3.19 is the delamination area. With the result obtained, the delamination factor is calculated based on the delamination's area and the original drill reamer's area.

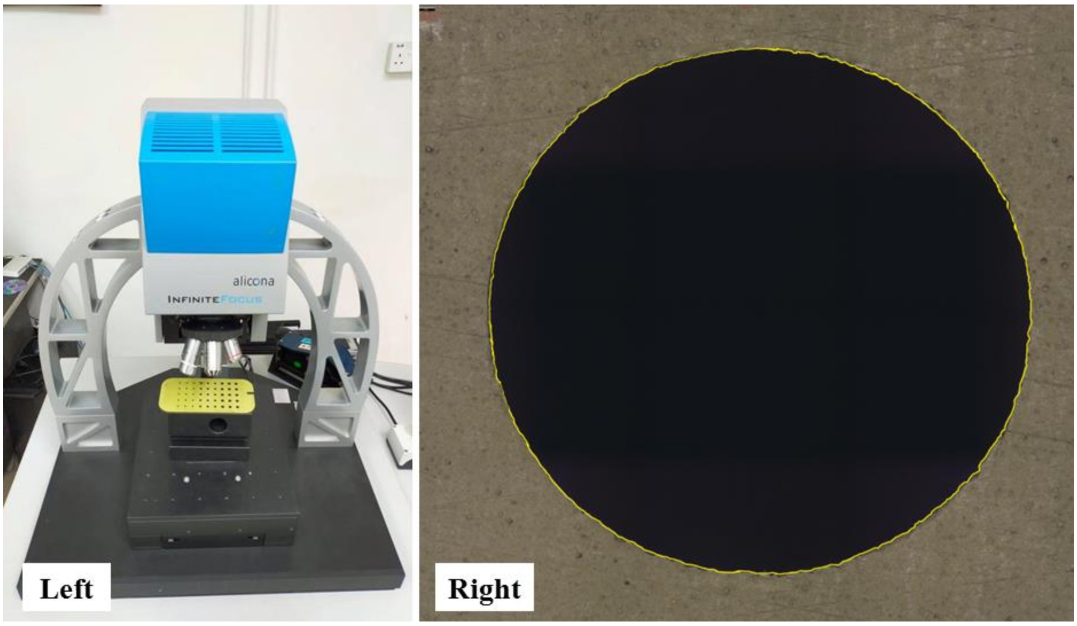


Figure 3.19: Bruker Alicona G-Series INFINITE FOCUS (Left) and the delamination image (Right)

3.7.2 Measurement of delamination factor

To obtain the delamination factor, the element involved in the calculation is the area of the delamination that occurred around the drilled holes and the area of nominal hole. The formula for the delamination factor has been shown as:

$$\text{Delamination factor} = \frac{Area\ of\ delamination\ that\ occurred\ around\ the\ drilled\ hole}{Area\ of\ the\ nominal\ hole}$$

3.8 Mass Measurement of Drill Reamer

3.8.1 Mass measurement before and after drilling process

SHIMAZU Weighing scale as shown on the left side of Figure 3.20 is used to weigh the mass of the drill reamers before the drilling process and after the drilling process. Based on the right side of Figure 3.20, the level bubble is made sure to be located within the red circle so the accuracy and stability of the weighing result are achieved in the best condition. For both the mass measurement before and after the drilling process, there is total of 9 drill reamers have been weighed and each of them is weighed for 5 times to obtain higher consistent and accurate result.

Figure 3.20: SHIMAZU Weighing scale (Left) and the level bubble of the weighing scale (Right)

3.8.2 Wear analysis

Wear analysis is carried out by calculating the wear amount and wear rate of the drill reamer based on the difference between the mass before and after the drilling process. With the use of specific formula, the wear coefficient of the drill reamer from Run A1 to Run C3 is then obtained and the comparison between nine different combined parameters drill reamer is carried out. There are some formula used to calculate the wear coefficient for the drill reamer and they are as shown as:

$$\text{Wear rate} = \frac{Wear\ amount}{Number\ of\ holes \times depth\ of\ drilling}$$

$$\text{Wear coefficient} = \frac{Wear\ rate}{Thrust\ force\ of\ the\ drilling}$$