EFFECT OF TWIST DRILL GEOMETRY AND DRILLING PARAMETERS ON THRUST FORCE IN SINGLE-SHOT DRILLING OF STACK-UP MATERIAL

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ABSTRAK

Penggerudian secara berlapis merupakan amalan yang diguna secara meluas dalam industri aeroangkasa. Malah, keserasian gerudi untuk menggerudi kedua-dua bahan yang diperbuat daripada komposit dan logam masih muncul sebagai halangan yang besar kepada industry tersebut. Dalam kajian ini, berdasarkan kuasa teras yang dihasilkan semasa meggerudi CFRP/Al, kesan pengubahan geometri dan parameter gerudi twist dikaji secara mendalam. Hasil analysis ANOVA menunjukkan kadar suapan merupakan faktor yang paling mempengaruhi nilai kuasa teras untuk Aluminum dan CFRP.

Berdasarkan analysis kuasa teras, diameter lubang, kekasaran permukaan dan penghasilan chip, parameter alat yang paling optimum ialah combinasi 30° sudut helix, 6° pelepasan utama, 130° sudut titik, 30° sudut tepi pahat, 2600 rpm kelajuan and 0.05 mm/rev kadar suapan. Pada masa yang sama, parameter optimum yang disimpul dalam hasil kajian tersebut dibanding dengan parameter yang ditetapkan berdasarkan keperluan pelanggan, iaitu 2600 rpm dan kelajuan 0.1 mm/rev kadar suapan. Kajian mendapati parameter optimum menghasilkan kualiti yang lebih tinggi berbanding dengan keperluan pelanggan.

ABSTRACT

Stacked up drilling is being practiced widely in the aerospace industry, but the compatibility of the drill to compensate the widely differing properties of composite and metal is still a major challenge to the industry. In this study, the effect of the twist drill geometry and drilling parameters are being investigated based on the generation of thrust force signature during drilling of CFRP/Al. Based on ANOVA, it is found that the thrust force for both Aluminum and CFRP are highly dependent on feed rate.

Through the analysis of thrust force, supported by hole diameter, surface roughness and chip formation, it is concluded that the optimum tool parameters selection includes helix angle of 30°, primary clearance of 6°, point angle of 130°, chisel edge angle of 30°, speed of 2600 rpm and feed rate of 0.05 mm/rev. At the same time, the optimum parameters obtained in this study is verified of its capability to produce higher hole quality and efficiency compare to customer requirement, which set the parameters as 2600 rpm for speed and 0.1 mm/rev for feed rate.

Chapter 1 INTRODUCTION

1.1 Stacked up Material in Aerospace Industry in General

Aerospace is a high technology industry whereby they are involved in various field in designing, building, testing, selling and maintaining aircraft, aircraft parts, missiles, rockets or spacecraft. Since the early 1900's, Aluminum is opted as the primary material in aircraft construction and this material has contributed to 65 % to 75 % of the total weight of a passenger aircraft. Subsequently, due to the lightweight and strong properties of carbon fiber, it is adopted into the aircraft structure, which constitutes about 50 percent of the total material used [1].

For Aluminum alloy, the most common alloy used in aerospace is 7075. It possesses strong and high strength compare to many steels, has good fatigue strength, average machinability and has less corrosion resistance [2] as compare to other Aluminum alloys, making it possible to strengthen the aircraft structures. Aluminum alloy is a mixture of 1.6 % of copper, 2.5 % of magnesium and 5.6 % of zinc which contribute to the increase in ultimate strength, but the copper content makes it very difficult to weld [3].

The adoption of carbon fiber in aircraft is because of the drive to increase fuel efficiency and to improve the aerodynamic performance of aircraft [4]. Carbon fiber in aerospace composites comes in different forms, long and continuous or short and fragmented, and they can either be directionally or randomly oriented. But due to low material and fabrication cost, short fibers are preferred generally. With proper selection and placement of fibers, the prominent advantage is that the composite can be stronger and stiffer than steel parts with similar thickness, but 40 % to 70 % lighter [2]. Having less weigh is an add on advantage in aircraft industry as it will lead to much lower fuel consumption.

Drilling is a cutting operation which uses drill bit to cut a hole of circular cross section in solid materials. The most common type of drill type used in aircraft drilling is twist drill, which can be used both in portable and fixtured drilling. As drilling has a great impact on the aircraft structures, it is essential to have a good control over the characteristic angles of the cutting tool, operating and cutting conditions in order to fulfil the requirement of tight holes' tolerance in the aircraft industry.

1.2 Research Background

In aircraft industry, it involves more than 55,000 of holes' processes for each aircraft [5]. Hence, the drilling method, tools and parameter selected are essentially important to ensure that the tight tolerance of an aircraft is being fulfilled. Of late, single shot drilling technique is widely applied on the metal and composite materials, like Aluminum and carbon fiber-reinforced polymer (CFRP), where both materials are stacked up and drilled in a single shot [6]. The conventional drilling like polycrystalline diamond (PCD) drilling in the assembly of aircraft structures is seen to be replacing with one shot drilling mainly due to the reduction of drilling steps, which in return reduce the drilling cost, process time and the amount of cutting tools to be on stock [7]. In addition, one shot drilling technique is an avoidable process for stack up material which promises a more proper hole alignment and thus capable of producing holes with higher quality and accuracy [6].

With the development of one shot drilling technique, the industry still faces some challenges in producing optimum and consistent hole quality. Besides having a relatively small and tight holes' tolerance, the challenge imposed on the stacked-up materials is due to their vast difference in properties [8]. Carbon fiber is preferred in aircraft industry because of its high strength to weight ratio. However, at certain deflection limit, carbon fiber will shatter while Aluminum will bend. Besides, although carbon fiber has the ability to bounce back without leaving a scratch while Aluminum can be easily scratched, Aluminum has a much better resistance of heat than carbon fiber [9].

Due to the significant differences in properties of both metal and composite, the industry is still keen on identifying the best drilling parameter and drill geometry for the optimum holes' quality result. The fact in which the industry common practice to scrap the materials when the holes do not conform to specification, brings about huge loss to the company. There is also not much of research work being carried out on drilling of Aluminum / CFRP stack-up. Thus, further research on the hole quality of one shot drilling by varying the drilling parameters and drill geometry is worth and ought to be developed further.

1.3 Problem Statement

Single-shot drilling of stack-up materials are widely used in aircraft structure. However, the industry faced huge obstacles due to rapid tool failure and poor hole quality when the single-shot drilling is carried out on two different materials with very contrast properties. This leads to about 60 % of the rejection are due to the defects in the holes. On top of that, current practice in the industry, the drilling process is carried out by trial and error method or dependent on the experience of the operators. Consequently, the inconsistency in holes' tolerance and quality have resulted in high scraps, which lead to high production cost. Since the performance of single-shot drilling is mainly contributed by the variation in setting the drilling geometry and parameters, continuous research on the optimum drilling parameters and drill geometry will not only provide a guide to the operators on how to conduct a proper drilling operation but also will leave a significant impact to the industry.

1.4 Objectives

1. To discover the effect of the drill geometry and drilling parameters on the thrust force produced.
2. To relate the force signature to hole quality in relation with hole diameter, surface roughness and chip formation.
3. To identify the optimum drill geometry and drilling parameters to conduct the single shot drilling on stack-up materials.
4. To compare the result of optimum drilling parameters in this study with parameters set by customer requirement.

1.5 Scope of Work

In my research, the primary goal is to utilize the force characteristics produced during drilling as an indicator for the occurrence of tool wear besides monitoring the hole quality. Thus, the area of study will be on finding the optimum drill geometry and drilling parameters for one shot drilling of Aluminum and CFRP. In order to achieve that, the properties of Aluminum and carbon fiber will be studied individually to discover the optimum operating range for both materials. As a method of measurement of the holes' quality, two methods will be used to evaluate the holes' quality, which is by monitoring the force signature generated from dynamometer during the drilling process and offline measurement on properties like surface roughness and hole diameter.

Chapter 2 LITERATURE REVIEW

2.1 Drilling on CFRP

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 make up 50 % of the structural weight of aircraft. In order to facilitate component assembly, drilling is a common machining process. However due to the property of alternately matrix and reinforcement materials of CFRP, the tool selection and parameters will largely correspond to the machining process quality. In the research conducted by **Vaibhav A. Phadnis, Farrukh Makhdum, Anish Roy, Vadim V. Silberschmidt** [10], thrust force, torque and delamination damage increase significantly with feed rate, but decrease gradually with increasing cutting speeds. Therefore, for proper drilling of CFRP, low feed rate (< 150 mm/min) and high cutting speed (>600 rpm) should be selected for an ideal result of CFRP drilling. The research was supported by **Biren Desai, Jaypalsinh Rana and Hiren Gajera** [11], who concluded the relationship of drilling torque with cutting speed and feed rate. Besides, circularity was emphasized in the paper as a parameter to evaluate the hole quality. With the aid of MINITAB, it indicates that cutting speed is closely related to circularity while the feed corresponds to the hole size. **Marta Fernandesa***, **Chris Coo** [12] presented their study of drilling of CFRP on varying thickness. They have related the chip formation during drilling operation to high tool wear rates. Tool wear is closely related to delamination because the force required to cut the material increases with tool wear. In their study, two workpiece of thickness 2mm and 5.2mm was selected and based on their research, thinner workpiece will result in higher thrust force due to wear. However, in research supported by **Z. Qi, K. Zhang, H. Cheng & S. Liu** [13]**,** delamination-free holes can be obtained if he thrust force maintains lower than the critical thrust force. In term of the effect of varying point angles on the effect of drilling, in **Uwe Heisela , Tobias Pfeifroth's** [14] paper, they proposed that a lower point angles will result in the smallest feed force and vice versa. Table 2.1 summarize the parameters used for the study of CFRP.

Table 2.1: Comparison of Parameters used for Drilling of CFRP

Research	1 [10]	2 [14]	3 [11]
Machine	Harrison M-300 lathe machine	Test machine Ex-cell-O XHC 241	Vertical machining center made of Haas Inc.
Variable	Cutting speed, feed rate	Cutting speed	Cutting speed and feed rate
Spindle power (kW)	2.24	40	22.4
Cutting speed (rpm)	40, 150, 600, 1300, 2500, 5000 (Optimum: >600)	21, 43, 64, 85, 128, 171, 214, 256, 299, 342, 385, 427, 470, 513	1500, 2500, 3500, 4500, 6000 (Optimum for circularity: 1500 Optimum for hole size: 6000)
Feed rate (mm/rev)	0.06, 0.12, 0.20 (Optimum: <0.06)	0.10, 0.15,0.2	Federate: 0.01mm 0.01, 0.03, 0.07, 0.1, 0.15 mm/rev
Thickness (mm)	2	9	2
Type of drill bit	TiN-coated twist drill (elastic stiffness 500-700GPa)	Cemented carbide (elastic stiffness 1600N/mm2)	Cemented carbide (grade K20) twist drill
Diameter of drill bit (mm)	3	6.8	5

2.2 Drilling on Aluminum

Aluminum 7075 is an Aluminum alloy, with zinc as the primary alloying element. It is vastly used in aircraft construction due to its strong and high strength advantage compare to many steels, possesses good fatigue strength and average machinability. Research has been done to study the effect of feed rate and drill diameter on burr height and surface roughness of drilling holes in order to produce the desired drilling quality which conforms to specification. In the research conducted by **Ugur Köklü** [15], it proposed that drilling process produces burrs on both the entrance and exit surface of the workpiece, but most problem associated to burr are caused by the exit burr as the burr is larger at the exit than the entrance. Severe burr formation will lead to deterioration of the surface quality, dimensional distortion on the part edge, assembly and handling error. Based on analysis of experimental result using S/N ratio and ANOVA, the feed rate plays the most significant role in affecting the burr height, followed by cutting speed. Generally, drill diameter does not have impact on the burr height. On top of that,

K. Anand Babu#1, Dr. G. Vijaya Kumar* [16] have applied a different approach which is Taguchi Fuzzy approach to study the optimum cutting parameters. The controllable parameters are speed, feed rate, tool material, point angle and cutting environment. As a result, the most desirable cutting parameters is 500 rpm, 0.2 mm/rev feed rate, TiAlN-HSS tool material, 118°-point angle and under diesel cutting environment. Furthermore, **Redouane Zitoune *, Vijayan Krishnaraj, Francis Collombetthe** [17] mentioned in their paper that most common drilling condition arises in Aluminum is the built-up-edge (BUE) and burr at the exit side of the hole. However, BUE can be eliminated by increasing spindle speed and the exit burr can be reduced if the feed rate is increased.

2.3 One Shot Drilling of Stacked up Material (CFRP/AL)

When drilling stacked up materials like CFRP and Aluminum, the selection of process parameters is important due to the difference of material properties. In most of the research, the study of critical thrust force is used as a benchmark to evaluate the drilling quality of stacked up materials. In the research paper by **Redouane Zitoune *, Vijayan Krishnaraj, Francis Collombet** [17]**,** similarly to single material drilling, the thrust force and torque will increase with the feed rate but decrease with spindle speed. According to the result, the thrust force and torque is double at low feed rate (0.05 mm/rev) but tripled at higher feed rate (0.1 mm/rev and 0.15 mm/rev). This is because of the higher impact of the fiber and reduced effective clearance angles of the drill, thereby creating frictions between the CFRP/Al stack. Even so, **Benezech et al [18]** paper explains that when drilling stacked up materials, machining demands higher feed rates in order to break up the chips and avoid the creation of burrs or BUE-BUL (Built-Up Edge-Built-Up Layer). But for spindle speed wise, thrust force reduces with high spindle speed because the cutting resistance of epoxy was lower with higher cutting edges temperature. Table 2.2 is a list of properties of Aluminum and carbon fiber. It is observed that the properties differ extensively and there is no overlapping of range, where possible best compromise of property is found.

Table 2.2: Comparison table of Aluminum and Carbon Fiber Properties

Mechanical Properties	Aluminum	Carbon Fiber
Density (kg/m^3)	2710	1110-1400
Stiffness against weight (x 10^6 m^{2}s^{-2})	26	113
Resistance to damage (kN.m/kg)	214	785
Young's modulus (GPa)	69	181

Ultimate Tensile Strength (kN.m/kg)	500	1600
Heat Expansion (inch/ °F)	13	2
Heat Conduction (W/m)	210	5-7

2.4 Drill Bits

2.4.1 Twist Drill Geometric Design

The kinematics of drilling is a process of using a rotating drill bit to create or enlarge existing round holes in a workpiece [19] and drill bits are cutting tools used to create cylindrical holes, mostly for circular cross-section [20]. With the aid of one or more cutting lips and flutes, the spiral (or rate of twist) in the drill bit serve as a function of controlling the rate of chip removal and access of a cutting fluid [19]. The type of drill commonly used in the industry is twist drill [20]. The varying parameters which will contribute to the twist drill geometric design includes helix angle, primary clearance, point angle and chisel edge angle.

2.4.2 Drill Bits Material Selection

The life of a drill is dependent on its hardness, toughness, wear and thermal resistance [19]. When opting for a suitable drilling tool material, it is essential for the hardness value of the tool to be higher than the material of the workpiece so that the tool can drill and remove the unwanted area of the workpiece without causing wear and torn to the drilling tool. The table below shows the hardness value of different types of drilling tools and stacked up material.

Table 2.3: Hardness of Drill Bits and Stacked-up Material [21-24]

Type of Material		Hardness (HRC) 150kgf	Hardness (HRB) 100kgf	Vickers Hardness (HV) (converted from HRC or HRB)
Drilling tool	High Speed Steel (HSS)	63-65	-	775-834
	Tungsten Carbide	89-108	-	2371- 5612
	Polycrystalline Diamond (PCD)	673	-	22821641
Stacked-up	Carbon Fiber Reinforced Plastic	-9	75	136
	Aluminum 2 series (Al 2024)	-9	75	136
	Aluminum 7 series (Al 7075)	5	87	171

From Figures 2.1 and 2.2, PCD which is the hardest tooling material among HSS and cemented carbides, possess the least toughest property as it undergoes a sharp deformation at temperature of 600°C. On the other hand, HSS and cemented carbides are capable of performing better at high cutting speed [19]. **Christopher Tate** [25] states that the selection of tool material is also dependent on the number of hole to be drilled and number of hole size. High performance carbide drill has the advantages of having the highest penetration rate and shortest cycle time, but it is costly. Therefore, if the number of holes to be drilled is low, it is appropriate to select alternative like HSS drill due to its cost-effective advantage. In terms of hole size, it is advisable to select HSS drill if the hole size is between 12 mm to 24 mm as it is expensive to fabricate carbide drills above 12 mm. In **Davim and Reis [**26**]** research, it proves that helical flute carbide drill is better because of the hot hardness when compare to HSS drill. In addition, in aerospace industry, the high hole number and hardness of the drilling workpiece lead to the selection of tungsten carbide as the drilling tool.

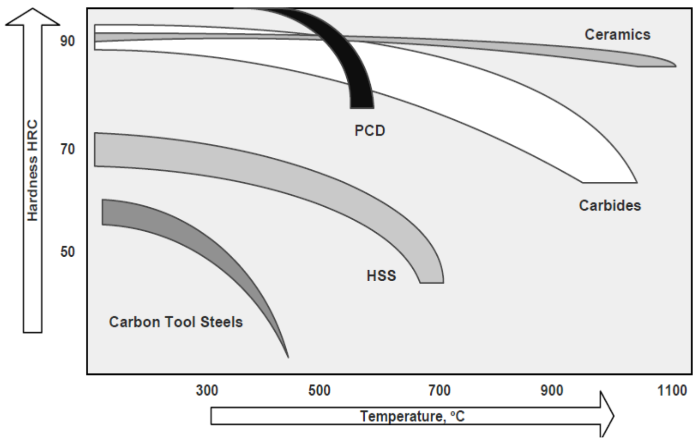


Figure 2.1: Relationship between Hardness of Drill Material and Temperature

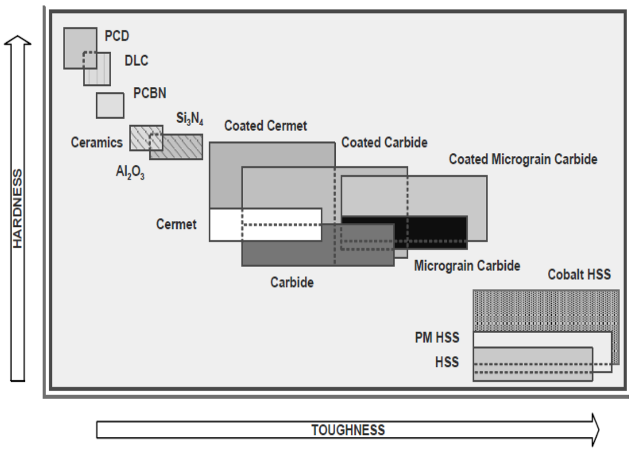


Figure 2.2: Relationship between Hardness and Toughness of Drill Material [19]

2.5 Effect of Drilling Parameters and Tool Geometry on Thrust Force, Surface Roughness and Chip Breakability on Stacked-up CFRP and Aluminum

Thrust force is the signature generated from dynamometer at real time to monitor the drilling operation of the stacked-up materials. Based on the tabulation of data in table 2.4, the thrust force recorded during drilling of Aluminum was found to be two to three times higher than those recorded during drilling of the composite material. The thrust force generated while drilling CFRP is within the range of 40 N to 300 N, while a range of 180 N to 658 N are recorded for drilling of Aluminum. Besides the mechanical properties of the stacked-up material, the thrust force is influenced by the parameters and tool geometry set.

In **M. Montoya & M. Calamaz & D. Gehin & F. Girot [27]** research, it is concluded that abrasion was the strongest wear mechanism observed in CFRP/AL drilling, which is due to highly abrasive properties of carbon fiber. The CFRP damage at the hole entry is directly related to the Aluminum chip evacuation. **Redouane Zitounea et al** [28] found that the increase feed rate will lead to a significant increase in the value of the roughness, regardless of the type of drill used. In addition, **Benezech et al** [18] concluded that the machining parameter selected has more influence on the surface roughness of CFRP than Aluminum. This could be due to the isotropy property of the material [17].

Chip breakability is another factor which influenced the quality of holes produced. **R. Zitounea, V. Krishnarajb, F. Collombeta, S. Le Roux [**29] mentioned that the feed rate and the drill diameter have an effect on chip breakability because of the increase in cross sectional area of chip whereas effect of spindle speed on chip breakability seems to be smaller. Generally, discontinuous chips or small well broken chips are more desirable for Aluminum because when the chips are smaller in size, they can move through the flutes more easily, decreasing the torque requirement and temperature and eventually reducing the risk of drill breakage. Meanwhile **R. Zitoune, N. Cadorin et al** [30] found that the presence of continuous chips in Aluminum at low feed rate impact the hole quality of the composite by the presence of the peel up delamination at the top of the hole. On top of that, **R.Zitoune et al** deduced that the efficiency of vacuum system is reduced with the presence of continuous chips as the dust quantity in the air increases[29]. Hence, in order to compensate both the Aluminum and CFRP hole quality, the most optimum parameter is with the use of higher feed rate (0.1 mm/rev). Both surface roughness and chip breakability are found to be highly dependent on feed rate but not spindle rate.

On the topic where the hole diameter of metal hole is consistently larger than the composite, recent article by **Ginger Gardiner** [6] explains that this is due to the fact that the fibers flex back into the hole after a few days. Furthermore, during the evacuation of Aluminum chips, it affects the hole quality of CFRP directly, at both the hole entry and the wall of the hole. [17] **Lin Zhang et al** explained that the defects which are found in the CFRP holes is erosion, flash, tearing whereas Aluminum appear to have adhesive material and large burr on the hole surface [31].

Tool geometry design also has a significant influence on the thrust force generated during the drilling process of stacked-up material. There are four factors which are considered in tool geometry, which are the point angle, helix angle, chisel edge angle and primary clearance. Studies by **W Chen** suggested that an increase in point angle will led to an increase in thrust force and a reduction in torque, while an increase in helix angle and chisel edge result in a decrease in thrust force and torque [32]. For helix angle, **Krystian k et al** found out that drill with higher helix angle suffered from chipping of primary cutting edges when higher feed rate is applied. On the other side, drill with lower helix angles has stronger cutting edge and is less prone to chipping, but it results in higher cutting forces and temperature [33]. Lastly, primary clearance is important to keep the drill flank from rubbing against the workpiece. A large clearance angle will improve the tool life as friction is reduced but as the clearance angle increases, the strength of the tool decreases [34].

In this study, initial deduction made is that thrust force has a direct relationship with surface roughness and hole diameter. Hence by monitoring the thrust force, the hole quality of the stacked-up material can be predicted.

Table 2.4: Tabulation of Thrust Force for One Shot Drilling on Stacked-up CFRP and Aluminum [17, 27-30, 35-37]

No	Stacked-up Sequence	Tool Diameter (mm)	Thickness and Type of Material		Maximum Thrust Force (N)		Type of Tool Geometry	Parameters				
			CFRP (mm)	**Al (mm)**	**CFRP**	**Al**		**Feed rate (mm/rev)**	**Spindle speed (rpm)**	**Point angle**	**Helix angle (°)**	**Chisel edge angle(°)**
1	CFRP < Al	6.35	4.2 (uni)	3 (Al2024)	1. 80 2. 100 3. 122	1. 180 2. 330 3. 486	1. Twist drill double cone drill	1. 0.05 2. 0.10 3. 0.15	2020	90 132	-	-
2	CFRP < Al	6	4.35(uni)	3 (Al2024)	1. 108 2. 142 3. 180	1. 285 2. 486 3. 658	1.Coated drill 2.Uncoated drill	1. 0.05 2. 0.10 3. 0.15	2750	136	-	-
3	CFRP < Al	8	4.2 (uni)	3 (Al2024)	100	250	1.Plain carbide	0.1	1050	118	-	-
4	CFRP < Al	6	7 (woven)	14 (Al7010)	1. 40 2. 100 3. 60 4. 70	1. 120 2. 180 3. 140 4. 140	1. coated twist drill 2.diamond uncoated 3.TIALCrN uncoated 4.AlTiSiN-G uncoated	0.04	3000	124	30	-
5	CFRP < Al	6.35	4.2 (uni)	- (Al2024)	50	300	1.Twist drill (tungsten carbide)	0.05	2020	90 132	-	-
6	CFRP < Al	6.8	16.8	10 (Al2024)	300	450	1.Solid carbide standard drill	0.06	3500	-	-	-
7	CFRP < Al	6.8	16.8	10 (Al2024)	250	300	1.Solid carbide drill coated with TiCN	0.06	3050			
8	CFRP < Al	9.53	8.74 (uni)	6 (7075-T651 Al)	1. 100 2. 175	1. 200 2. 325	Diamond coated drill bit with double tip point angles	1. 0.02 2. 0.08	2000	1st - 130 2nd - 60	30	-

Chapter 3 METHODOLOGY

3.1 Overview of Methodology

This chapter presents the overall approaches used in this research to study the effect of twist drill geometry and drilling parameters on thrust force in single-shot drilling of stack-up material. Design of experiment (DOE) using orthogonal array is used to select eight runs of experiment to evaluate the significance of tool geometry and parameters on thrust force during the drilling operation. Figure 3.1 shows the approaches involved in investigating the properties of materials, conducting the drilling operation and analysis of hole quality characteristics after drilling. Understanding of the properties of material is necessary to ensure the compatibility of workpiece and drill bits. Hence, density and hardness of material for both workpiece and drill bit are evaluated and presented in this section. In this paper, thrust force signature is the main measurement method of output characteristics of a hole quality. The setting and method used in operating dynamometer to measure the thrust force during drilling operation of stacked-up material are also briefed. Meanwhile, roughness, hole diameter and chip formation of drill bit are selected as hole quality assessments for the purpose of supporting the accuracy of results from thrust force generation. Subsequently, analysis of variance (ANOVA) is opted as a tool to reflect the significance of parameter and tool geometry on thrust force of stacked up material. The detailed methodological framework of the study is presented in Figure 3.2.

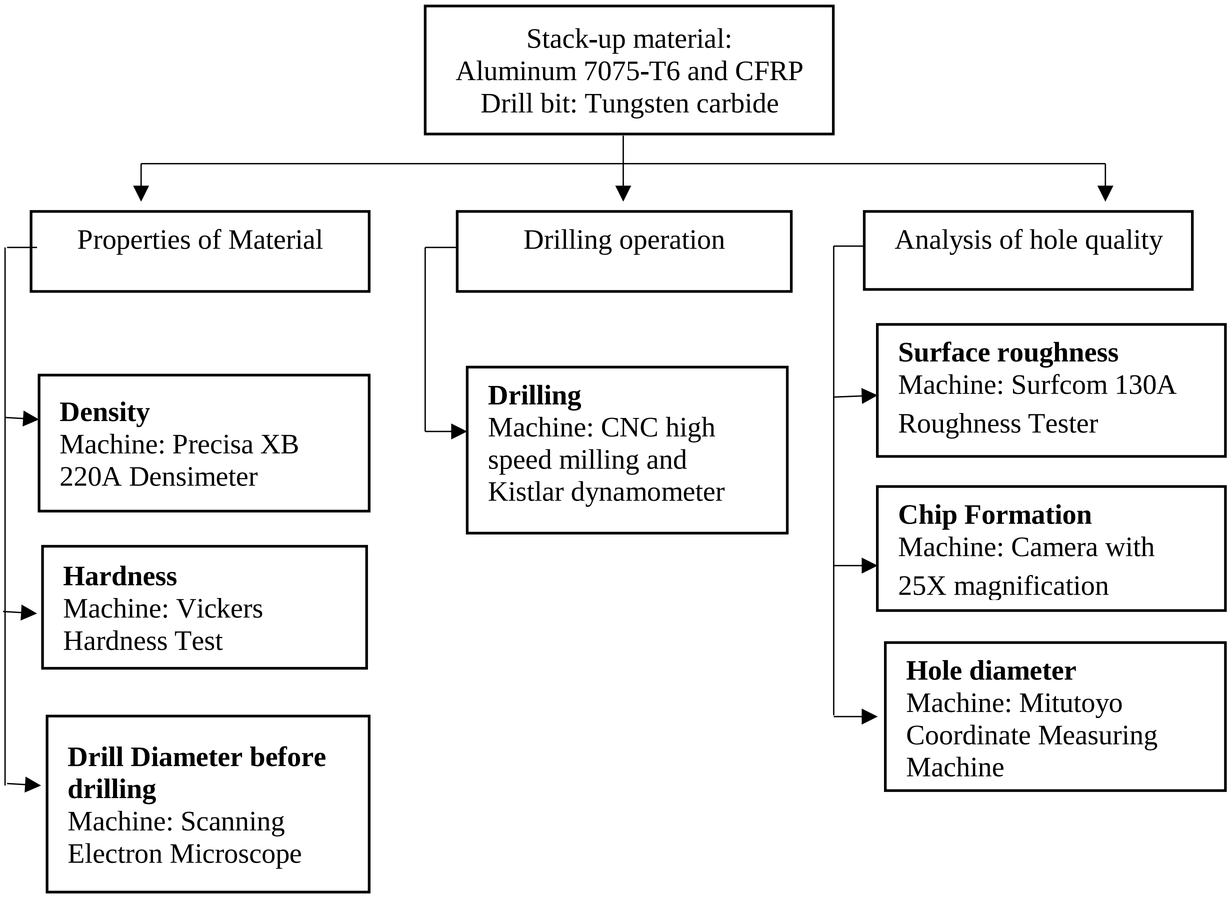


Figure 3.1: Approaches and Test Conducted for the Research

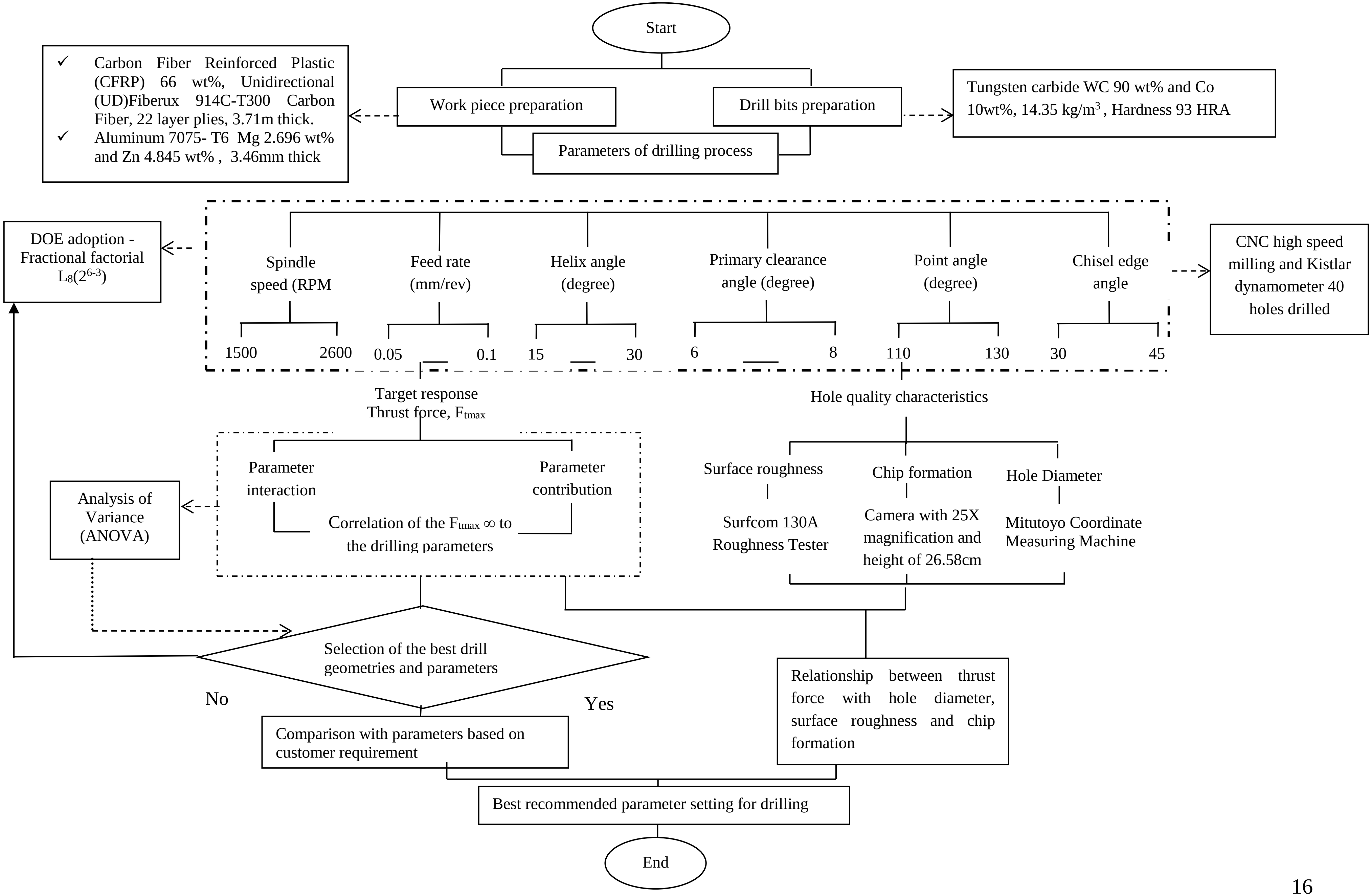


Figure 3.2: Methodological Framework of the Study

3.2 Materials

3.2.1 Workpiece Materials

The stacked-up materials used in this study is CFRP and Aluminum 7075-T6. The density of CFRP and Aluminum is 1.601 g/cm^3 and 2.597 g/cm^3 respectively and the hardness value of the former is 61.8 HV while the latter is 68.4 HV. The composite specimen is of thickness 3.6 mm, whereby it is made up of 26 ply of unidirectional carbon composite and 2 ply of glass composite, joint together by carbon/epoxy prepregs. The thickness of carbon and glass composite are 0.125 mm and 0.08 mm each respectively. The layer stacking is symmetric, with the sequence of $[45/135/90_2$ $/0/90/0/90/0/135/45\ 2\ /135]_{s.}$ Meanwhile, the metal panel used is Al7075 T6 with the percentage of alloying elements as follows: Al 92.459 wt%, Mg 2.696 wt% and Zn 4.845 wt%.

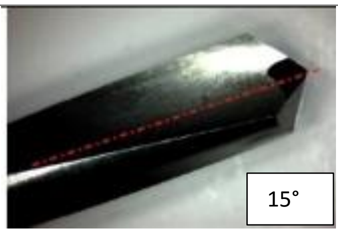
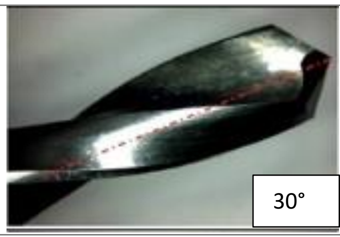
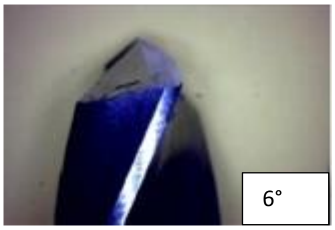
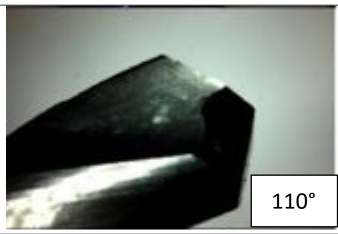
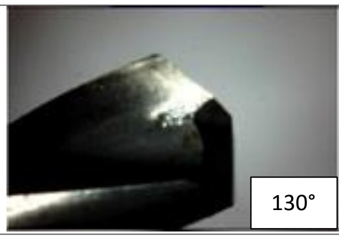
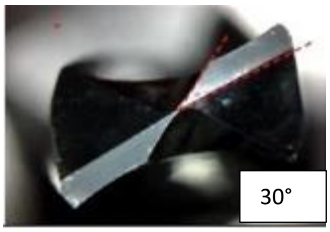
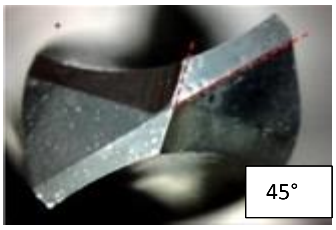
3.2.2 Cutting tools Materials

In this work, the twist drill bit is made of tungsten carbide (Figure 3.3) with composition of WC~ 93.36 wt% and Co~6.64 wt%. It has a density of 14.35 g/cm^3 and hardness value of 1625 HV, both of which are significantly higher than the workpiece material. The drilling tools can easily shear the surface of workpiece material without causing breakage.

Figure 3.3: Twist drill bit of one shot drilling

Six parameters with two levels are being studied in order to identify the optimum drilling parameters for stacked up CFRP/Al that comply to the specifications. The parameters selected to be experimented are feed rate, spindle speed, helix angle, primary clearance, point angle and chisel edge angle. The parameters set for each contributing factor are tabulated in table 3.2. Experiments are conducted based on L8 fraction factorial design where 8 experiments with varying parameters are considered. Each experimental condition is repeated five times to reflect the quality of holes more accurately by taking the average readings besides monitoring the thrust force. For this experiment, 8 drill bits with bit diameter of 4.826 mm each are required.

Table 3.1 Set of Contributing Parameters and Levels.

<table>
<tr><th>Parameters</th><th>Level 1</th><th>Level 2</th></tr>
<tr><td>Helix Angle</td><td></td><td></td></tr>
<tr><td>Primary Clearance</td><td></td><td></td></tr>
<tr><td>Point Angle</td><td></td><td></td></tr>
<tr><td>Chisel Edge Angle</td><td></td><td></td></tr>
<tr><td>Speed (RPM)</td><td>1500</td><td>2600</td></tr>
<tr><td>Feed Rate (mm/rev)</td><td>0.05</td><td>0.1</td></tr>
</table>

3.3 Design of Experiment (DOE)

The adoption of design of experiment (DOE) in this research is crucial to select the optimum number of required experiment, taking into account of numerous factors affecting the experimental results. DOE focuses on a few designated experiments and at the same time, combination of experiment which are not significant are eliminated. Orthogonal arrays which consist of a set of tables is used to design the number of experiments, given the number of factors. It allows the execution of fractional factorial experiments rather than the full factorial experiments.

In this research, six input factors of drill geometry and drilling parameters are being considered. With the application of DOE method, the combination of parameters for each run (Table 3.1) is generated based on L_8 (2^6) fractional design using Minitab 16. In a total of six factors, the two factors selected to be studied for drilling parameters are feed rate and spindle speed, meanwhile helix angle, point angle, clearance angle and chisel edge angle are factors affecting the tool geometry. All of which are investigated in two levels (low and high).

Table 3.2: Parameters for each run based on fraction factorial design

Run	**Helix angle**	**Primary clearance**	**Point angle**	**C/edge angle**	**Speed**	**Feed rate**
	Degree	Degree	Degree	Degree	RPM	mm/rev
1	15	6	110	45	2600	0.1
2	30	6	110	30	1500	0.1
3	15	8	110	30	2600	0.05
4	30	8	110	45	1500	0.05
5	15	6	130	45	1500	0.05
6	30	6	130	30	2600	0.05
7	15	8	130	30	1500	0.1
8	30	8	130	45	2600	0.1

3.4 Hardness Measurement

Hardness is the property of a material that enables it to resist plastic deformation. In the context of drilling, hardness of drill bit must be higher than the workpiece material so that the unwanted area of the workpiece could be removed, without causing breakage to the drill bits. The hardness of the respective materials is determined by using Vickers hardness test (Figure 3.4).

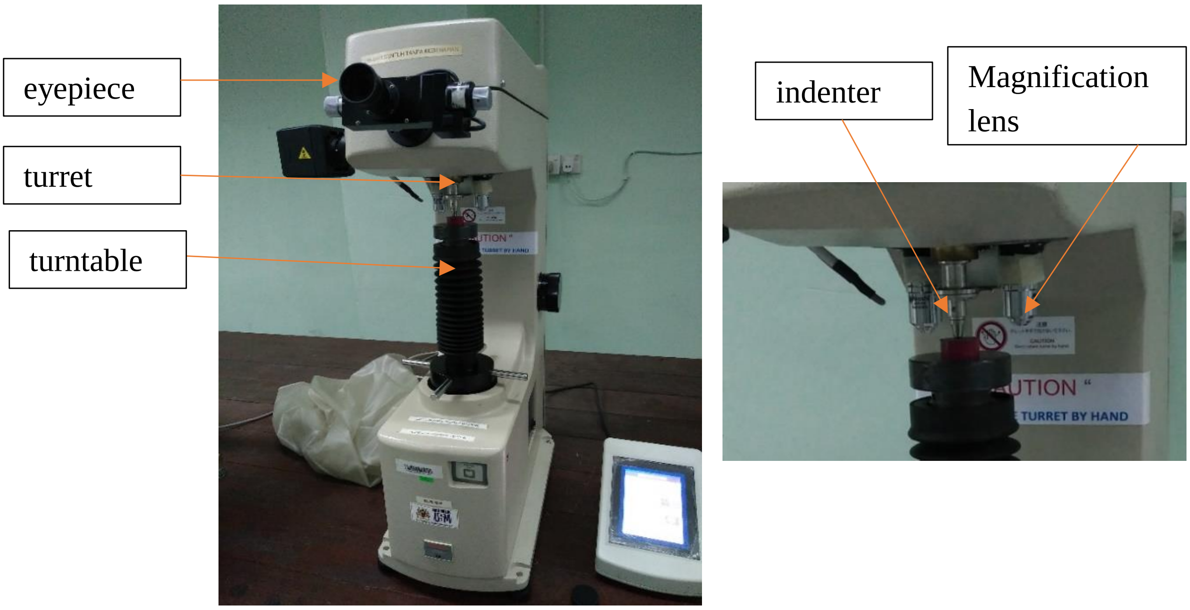


Figure 3.4: Vickers Hardness Tester

The specimen is placed on the turntable and a load of 20 kgf is set. The magnification lens is focused on the specimen and the height of the turntable is adjusted until a clear image of the specimen microstructure is obtained. Then, the turret is rotated to the indenter and the load is applied on the specimen by the indenter. Through the eyepiece, D1 is obtained by aligning both the reference lines to the end of the indentation diamond. The eyepiece is rotated 90° and the same process is repeated to obtain D2. The hardness value will then be calculated and displayed on the instrument.

3.4.1 Working Principle of Vickers Hardness Tester:

The Vickers hardness test method consists of indenting the test material with a diamond indenter, in the form of a right pyramid with a square base and an angle of 136° between opposite faces subjected to a load of 1 to 100 kgf as shown as Figure 3.5. The full load is normally applied for 10 to 15 seconds. The two diagonals of the indentation (Figure 3.6) left in the surface of the material after removal of the load are measured using a microscope and their average is calculated. The larger the indentation, the softer the material. The area of the sloping surface of the indentation is calculated. The Vickers hardness is the quotient obtained by dividing the kgf load by the square mm area of indentation.

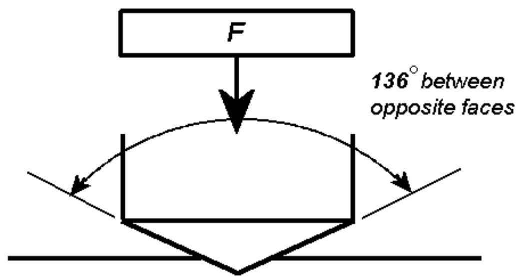


Figure 3.5: Load applied with 136° Indentation angle

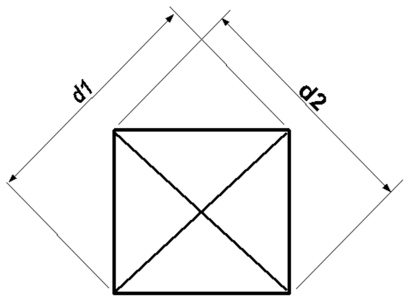


Figure 3.6: Diagonals of Indentation

Given:

F= Load in kgf

d = Arithmetic mean of the two diagonals (*d1* and *d2*in mm)

HV = Vickers hardness

$$HV = \frac{2F\sin\frac{136}{2}}{d^2}$$

$$= 1.854\frac{F}{d^2}$$

3.5 Density Measurement

The density of tungsten carbide, Aluminum and CFRP are determined using a densimeter (Precisa XB 220A). Three specimens with dimension of 1 cm x 1 cm for each material are prepared. The average density of each material is obtained in order to improve the accuracy of the readings.

To determine the density of non-floating solids, the setup is shown in Figure 3.7, using a beaker and a universal basket. The beaker is filled with distilled water and the universal bracket is suspended by the universal holder in such a way that one of the bracket is suspended in the air, and the other is immersed in the water. Density measurement involved two steps, weighing in air and weighing in liquid.

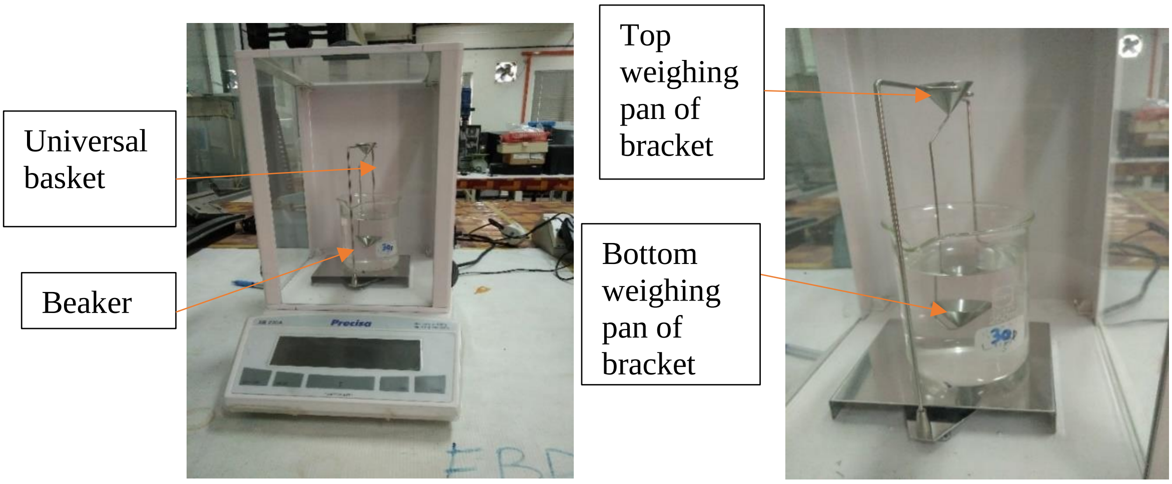


Figure 3.7: Densimeter

3.6.1 Working Principle of Densimeter

Densimeter applied Archimedes' principle for the purpose of density determinations. The principle states that every solid body immersed in a fluid losses weight by an amount equal to that of the fluid it displaces.

The density of a solid material is determined with the aid of a liquid with density p_0 (water or ethanol are usually used as auxiliary liquids). The weight of the material in air and liquid is denoted by A and B respectively. The density can be calculated by using the following formula.

$$Density, p = \frac{A}{A-B}(p_o - p_L) + p_L$$

Where p = density of the sample

A= weight of the sample in air

B= weight of the sample in the auxiliary liquid

V= volume of the sample

p_o = Density of the auxiliary liquid

p_L= Density of air (0.0012g/cm^3)

3.6 Drilling Process

The drilling operation is carried out on CNC High Speed Milling machine, model Alpha T21iFB as shown in Figure 3.8 and 3.9. For acquiring the thrust force signature, a dynamometer (Figure 3.10) is attached to the worktable of the CNC machine. When the force is detected during the drilling operation, the test data will be transmitted to the data acquisition system (Figure 3.11). Then, the detected signal will be amplified and the output will be displayed in the computer in the form of thrust force signature versus cutting time.

Figure 3.8: CNC High Speed Milling Machine

Figure 3.9: Worktable of CNC High Speed Milling Machine

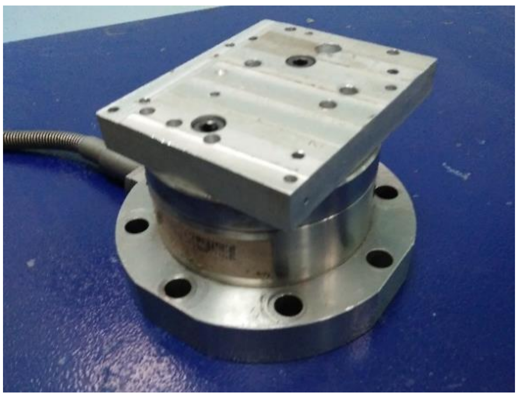


Figure 3.10: Dynamometer

Figure 3.11: Data Acquisition and Amplifier

A dynamometer (Kistler 4 component dynamometer type 9272) as shown in Figure 3.12 was used to monitor the thrust force and torque during the drilling process of stacked-up material. The workpiece which was clamped by the jig, was mounted on the dynamometer on the table of the four axes milling machine. The data acquisition system which was connected to the dynamometer, consist of a multichannel charge amplifier (type 5070) and Kistler DynoWare software (imc Measurement and Control Version 3.2 Rev 2). The thrust force signature was generated when the dynamometer consisting of a four components sensor transfers the charge signal to the multichannel charge amplifier. The multichannel charge amplifier converts the resulting charge signal, which were proportional to the applied force, to voltage. The resulting signals were converted to force and torque by the calibrated data and were displayed in the software. Figures below show the 2D drawing and the actual dynamometer respectively.

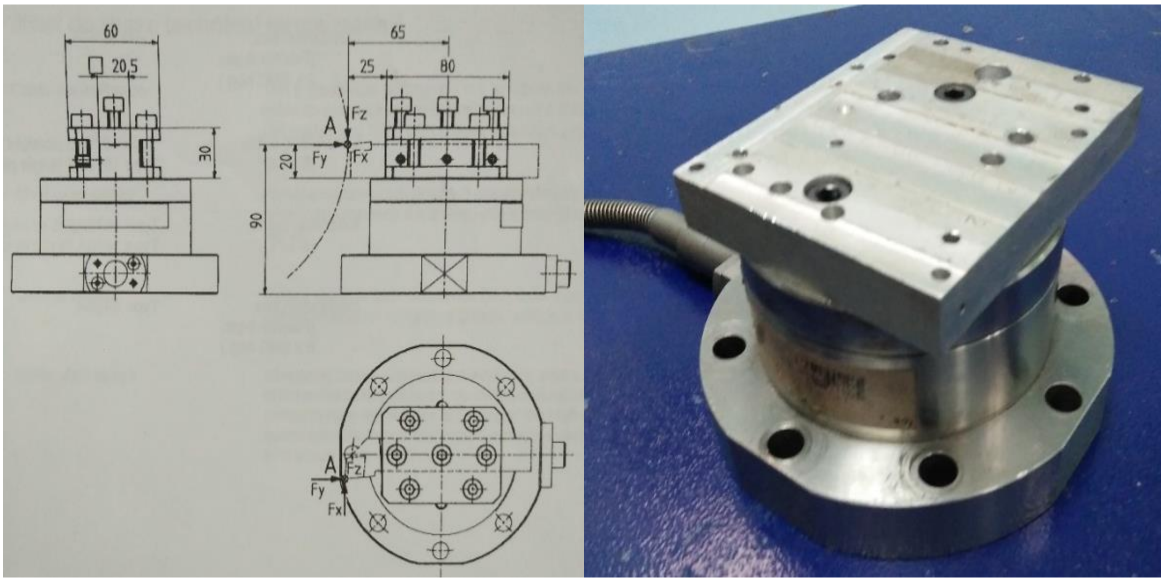


Figure 3.12: Comparison of 2D Drawing and Actual Dynamometer