EXPERIMENTAL ANALYSIS ON DRILLING PROCESS OF CFRP COMPOSITE LAMINATES

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OF COMPOSITE LAMINATES

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A report submitted in partial fulfilment of the requirements
for the award of the degree of
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SUPERVISOR'S DECLARATION

We hereby declare that we have checked this project and in our opinion this project is satisfactory in terms of scope and quality for the award of the degree of Bachelor of Mechanical Engineering with Manufacturing Engineering.

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STUDENT'S DECLARATION

I hereby declare that the work in this thesis is my own except for quotations and summaries which have been duly acknowledged. The thesis has not been accepted for any degree and is not concurently submitted for award of other degree.

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ABSTRACT

This thesis deals with carbon fiber reinforced plastics (CFRP) composites, an advanced material which is widely used in manufacturing aircrafts because of their unique mechanical and physical properties. The research mainly involved drilling of CFRP. This study focused on analyzing the thrust force and delamination against drilling parameters namely feed rate, spindle speed and type of tool materials. Also, the optimal parameters were chosen using an optimization method called D optimal. It was observed that the higher the feed rate and spindle speed employed, the higher the thrust force and delamination that occurs. The optimal parameters obtained were 221.72mm/min for feed rate, 2000 rpm for spindle speed and the most suitable tool chosen was the SPF drill. A verification test was conducted and the percentage error obtained for delamination was 5.6% and for thrust force was only 2.3%. This shows, that the optimal parameters obtained is reliable as it could improve the process considerably.The results of this study could be used as a reference for further research and studies on drilling of CFRP.

ABSTRAK

Tesis ini membentangkan penyelidikan mengenai bahan komposit. Bahan komposit ini digunakan secara meluas di dalam industri kapal terbang, kapal angkasa dan sebagainya. Tesis ini memfokuskan kepada kerosakan yang terhasil pada permukaan komposit apabila proses menggerudi dilakukan. Berdasarkan kajian yang lepas, komposit menunjukkan kerosakan yang paling ketara apabila proses menggerudi dilakukan. Sejenis kerosakan yang paling ketara ialah pemisahan lapisan-lapisan komposit yang dicantumkan oleh resin atau lebih dikenali sebagai delaminasi. Penyelidikan yang lepas, menunjukkan bahawa delaminasi ini ada kaitan dengan daya tujah. Daya tujah merupakan daya yang dihasilkan semasa proses menggerudi dilakukan. Maka, objektif kajian ini adalah untuk membuat kajian mengenai daya tujah dan kesannya pada delaminasi. Berdasarkan kajian yang lepas, Beberapa nilai kelajuan pemotongan dan kadar pemotongan diuji untuk melihat kesannya ke atas komposit tersebut. Kemudiannya, satu kaedah untuk mencari parameter yang paling optimum dijalankan. Kaedah untuk mencari nilai optimum ini dinamakan D optimal. Sejenis kaedah baru yang melibatkan penggunaan program Design Expert 7.1. Hasil kajian ini menunjukkan keberkesanan kaedah ini kerana ia senang untuk dijalankan dan nilai optimum dapat diperoleh dengan begitu cepat dan tidak melibatkan pengiraan yang rumit. Nilai optimum diperoleh berdasarkan matlamat kajian iatu untuk mengurangkan daya tujah dan delaminasi. Hasil kajian ini sangat berguna di mana pada masa yang akan datang nilai optimum yang telah diperoleh ini boleh digunakan.

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LIST OF ABBREVIATIONS

CFRP	Carbon Fiber Reinforced Plastics
GFRP	Glass Fiber reinforced Plastic
RSM	Response Surface Methodology
DOE	Design of Experiment
CAD	Computer-aided drafting
EDM	Electrical Discharge Machining
HSS	High Speed Steel
SPF	Split Point Fibre
CVD	Chemical Vapor Deposition
PVD	Physical Vapor Deposition
CNC	Computer Numerical Control

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

Fiber reinforced plastics have been widely used for manufacturing aircraft and spacecraft structural parts because of their particular mechanical and physical properties such as high specific strength and high specific stiffness. There are two main categories of composites namely CFRP and GFRP (carbon fiber reinforced plastic and glass fiber reinforced plastic respectively). This study focuses on carbon fiber reinforced plastics. Carbon fibers are thin filaments made of elementary carbon with structures that vary from those of the amorphous carbon to those of the crystalline graphite. These fibers own very variable chemical and physical properties. Carbon fibers show excellent mechanical properties compared to other fibers: high specific stiffness, very high strength in both compression and tension and a high resistance to corrosion, creep and fatigue [1]. They are used as structural components and reinforcements in aerospace structures, for example airplanes' vertical fins, flaps, satellite platforms and in turbofan engines. Machining composite materials is a rather complex task owing to its heterogeneity, heat sensitivity, and to the fact that reinforcements are extremely abrasive. Drilling is a frequently practiced machining process in industry owing to the need for component assembly in mechanical pieces and structures. The drilling of laminate composite materials is significantly affected by the tendency of these materials to delaminate and the fibers to bond from the matrix under the action of machining forces (thrust force) [2]. This research presents a new comprehensive approach to select optimal cutting parameters for damage-free drilling in carbon fiber reinforced epoxy composite material (CFRP). The approach is based on an ideally new optimization method namely D optimal

method which is an extension of RSM. A set of drilling experiments, will be conducted based on the techniques of RSM, with cutting parameters prefixed on carbon fiber reinforced plastic (CFRP) laminate. The DOE is employed to find the optimal cutting characteristics of CFRPs using solid carbide and coated carbide drills. Finally, the optimal parameters namely cutting speed, feed rate and appropriate tool material will be chosen based on DOE performed and analysis done.

1.2 PROBLEM STATEMENT

Conventional machining of fiber-reinforced composites is difficult due to diverse fiber and matrix properties, fiber orientation, inhomogeneous nature of the material, and the presence of high-volume fraction (volume of fiber over total volume) of hard abrasive fibers in the matrix. A variety of machining operations are performed on these materials and drilling is one of the major methods used in industries. Even though this is so, drilling-induced delamination is among the major concerns of applying this material in various industries. To investigate the damage effects of drilling an optimization technique is employed. Appropriate control parameters are chosen to narrow the scope of study such as cutting speed, feed rate and three different type of carbide tools and the main outputs investigated are thrust force and delamination.

1.3 OBJECTIVE

The main aim of this research is to study and optimize the drilling process of CFRP using D-optimal method.

1.4 SCOPE OF RESEARCH

A study conducted to find the optimal parameters by using optimization method on drilling of CFRP using D optimal method (an extension of RSM). The parameters studied are also narrowed to focus on the effect of particular parameters on the composite. Here, the parameters studied are feed rate, cutting speed and tool material and types respectively.

1.5 ARRANGEMENT OF THESIS

1.5.1 Chapter 1

Chapter 1 gives a brief introduction about the study that will be conducted. It also outlines the problem statement, scope of study and so on. The methodology flow chart will be inserted here as well as the plan of work for the FYP.

1.5.2 Chapter 2

Chapter 2 gives a wholesome review about the previous researches that has been conducted on the area of study before. Journals of many authors have been included here to give an insight view of other authors regarding the same topic of study.

1.5.3 Chapter 3

Chapter 3 gives full details regarding on how the experiments were conducted, the machine and equipments, the DOE and so on.

1.5.4 Chapter 4

Chapter 4 discusses about the results and outcomes from this study.

1.5.5 Chapter 5

Chapter 5 summarizes or in other words concludes the study conducted based on the objective of the study and the results obtained.

1.6 PLAN OF WORK

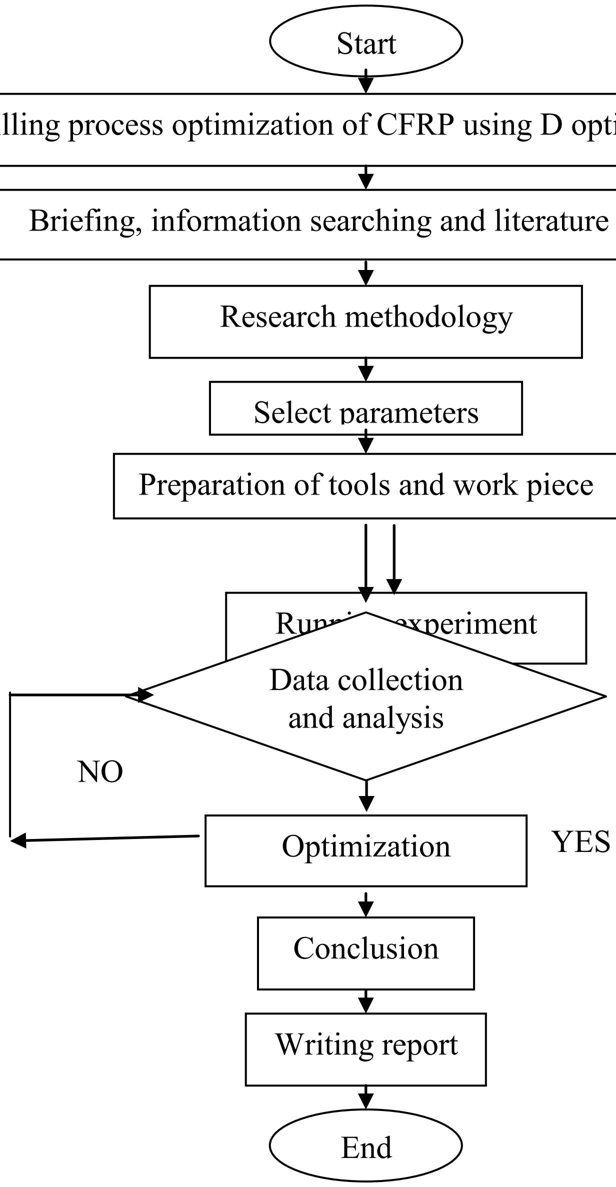

Figure 1.1: Flow of chart for methodology

Table 1.1: Plan of work for FYP

Work Progress/ Month	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Title Confirmation												
Set objective and scope												
Problem Statement												
Literature Review												
Research Methodology												
PSM 1 Report												
PSM 1 Presentation												
Tools Preparation												
Experiment Process												
Data collection												
Data analysis												
PSM 2 Report												
PSM 2 Presentation												

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

Composites are different from metals whereby it comprises a combination of materials differing in composition or form. The constituents retain their identities in the composition and do not dissolve or otherwise merge completely into each other although they act together. Composites consist of high strength fibers and it is embedded in an epoxy resin matrix. [1] Normally, the components can be physically identified and exhibit an interface between one another. Composite materials provide major weight savings in airplane structure as they have high strength to weight ratios. Advanced composites contain strong, stiff, engineering fibers embedded in a high performance matrix. Examples of fibers are fiberglass, carbon fiber, Kevlar, Spectra and different ceramic fibers. The matrix is polymer (plastic) such as epoxy, polyamide, phenolic or bisma lamides. Applications on airplane includes fairings, flight control surfaces, landing gear doors, wing stabilizer leading and trailing edge panels, interior components and other primary structures(777) [4].

2.2 AEROSPACE MATERIALS (HISTORY OF COMPOSITES)

The first century aircraft in 1908, used Duralumin, an aluminium alloy introduced by Alfred Wilm. This sets the stage for aluminiums' critical role in aircraft industry. In 1910 the alloy 2017-T4, was used in the construction of propellers and dirigibles, including the USS Shenandoah. During the 1940's alloy 7075-T651 was used on the B-29. It was not until the late 1960s' that the application of composite was used widespread in the aircraft industry. During the 1940s' composite was used mainly in military aircrafts but due to their poor relative specific stiffness has prevented them from extending foothold they have found on fairings, doors, etc to the primary structural applications of wings, stabilizers and major fuselage sections. Aramid fibers introduced in 1960s found parallel applications with glass fibers, but their lack of specific stiffness and poor compressive strength limited their use, despite their tolerance to damage that composites utilizing these fibers can afford. The adoption of composite materials as a major contribution to aircraft structures followed on from the discovery of carbon fiber at The Royal Aircraft Establishment at Farnborough, UK in 1964.

2.3 MACHINING OF COMPOSITES

Conventional machining of fiber-reinforced composites is difficult due to diverse fiber and matrix properties, fiber orientation, inhomogeneous nature of the material, and the presence of high-volume fraction (volume of fiber over total volume) of hard abrasive fibers in the matrix. Since cemented carbide tools wear rapidly, diamond-impregnated tools may have to be used. Several advances have been made in the development of tool materials, including polycrystalline diamond tools, diamond-plated tools, and diamond-impregnated tools in various forms, such as core drills, milling cutters, drills, and grinding wheels. To overcome the rapid tool wear experienced in conventional machining of some composites containing hard, abrasive, or refractive constituents, unconventional machining operations have been adopted. Laser machining, electrical discharge machining, water jet cutting and abrasive water jet cutting, are basically non-contact machining operations involving no cutting tools and, consequently, no cutting forces. Laser machining is based on the interaction of the work material with an intense highly directional and coherent monochromatic beam of light. Material is removed predominantly by melting and/or vaporization. In the case of resin matrix material it is also removed by chemical degradation. The physical processes involved in laser machining are basically thermal in origin. High-pressure water jet cutting in unison with fine abrasives is a possible process for machining inhomogeneous materials that are hard and abrasive, such as most polymer-matrix composite materials. Water cools the work piece and hence minimizes the thermal deformation problems commonly experienced in conventional machining of composites. A narrow kerr, minimum amount of dust and toxic fumes, and practically no delamination effects are some of the salient features of this system. The rapid tool wear commonly experienced in conventional machining of composites is not an issue in water jet cutting or abrasive water jet cutting [4].

2.4 DRILLING OF COMPOSITES

2.4.1 Cutting Tools

Various studies have been conducted to investigate the effects of conventional drilling on composites. Researches mainly have evaluated the effect of tool material and geometry used on composites. Pedro Reis et al. [5] conducted a study of delamination in drilling carbon fiber reinforced plastics using different type of drill material. Their studies showed that carbide drills exhibit an almost null wear land compared to HSS drills which presented a significant wear value. Piquet et al. [6] carried out a study on drilling thin carbon/epoxy laminates with two types of drills: a twist drill (4.8mm diameter, twist angle of 25◦, rake and clearance angles of 6◦) and a drill with special geometry (4.8mm diameter, three cutting edges, twist and rake angles of 0◦ and clearance angle of 6◦). Both drills presented a major cutting edge angle of 59◦, but the special drill had a minor cutting edge angle varying from 59◦ to 0◦. The results indicated a superior performance of the special geometry drill confirming that the principal cutting edge significantly affects the hole quality. According to the authors, the smaller contact length between the special geometry drill and the hole resulted in less delamination. Mathew [9] studied the influence of using a trepanning tool on thrust force and torque when drilling GFRP. The investigation showed that the performance of the trepanning tool was superior to the conventional twist drill, resulting in 50 and 10% of thrust force and torque, respectively. Bhatnagar Singh et al. [8] carried out a comparative study aiming to evaluate the influence of the drill geometry on unidirectional laminate glass reinforced plastics. The results showed that 8 facet and Jo-drills presented lower thrust force and torque, thus becoming a suitable choice for drilling composite materials. A.M Abrao et al. [1] summarized a survey with regards to the tool materials and geometries used to drill polymeric composites. It can be seen that high-speed steel (HSS) and tungsten carbide (ISO grades K10 and K20) are equally used as tool materials, while polycrystalline diamond (PCD) is seldom tested. As far as the tool geometry is concerned, it can be seen that the use of drill with special geometry (such as core drills, multi-facet drills, candle stick, parabolic drills) together with drills with modified geometry (various chisel lengths and rake, clearance, point and helix angles) are preferred when drilling with tungsten carbide tools. On the other hand, when using high-speed steel drills the use of standard twist drill and drills with special geometry are similar.

N.Ramakrishnan et al. [9] investigated the effects on trepanning tool on composite laminates. It was concluded that the overall quality of the holes produced by trepanning tools is superior to those produced by the twist drills under identical cutting conditions. In another study, a tubular cutting tool with one end of the tube coated with diamond particles for drilling CFRP was tested by Chambers and Bishop [16]. It shows a smooth variation in thrust during operation, but the diamond grit wheel had to be frequently dressed. Chen [15] investigated the variations of cutting forces with or without onset damage during drilling and concluded that a damage-free drilling process may be obtained by the proper selections of tool geometry and cutting parameters. In order to investigate the effect of the drill diameter on the thrust force and torque, El-Sonbaty [19] employed conventional high speed twist drills with different diameters to machine a glass fiber reinforced plastic using a constant rotational speed of 875 and feed rates of 0.1–0.23 and 0.5 mm/rev. The results indicated that thrust force and torque increased with drill diameter and feed rate, due to the increase in the shear area. The influence of the roundness of the drill on delamination was studied by Tsao and Hocheng [15]. Their work took into account the theories of mechanics of fracture and energy conservation. Their findings indicated that the drill run-out causes the thrust force to increase, consequently resulting in more severe delamination of the work piece. In a study by Tsao and Hocheng [13], they found out that feed rate and drill diameter were the parameters which most affected the delamination factor. In addition to that, the damage caused by the twist drill was superior to those caused by the candle stick and saw drills, probably due to the differences in the cutting edges of the drills. Davim and Reis [5] investigated the effect of cutting parameters on delamination when drilling a carbon fiber reinforced plastic with a thickness of 4 mm. The findings suggested that the delamination increased with feed rate and cutting speed and that the cemented tungsten carbide drill outperformed the high-speed steel material when machining under the same cutting conditions. When comparing the cemented tungsten carbide drills, the twist drill presented lower delamination factor compared to the four flute drill.

2.4.2 Effect of Quality, Thrust force and Delamination

Researchers have conducted many studies regarding the quality of the composites and factors affecting it such as thrust force, delamination and so on. Davim et. al. [18] studied the behavior of two cemented tungsten carbide drills with distinct geometries ("Stub Length" and "Brad & Spur") when machining a glass fiber reinforced plastic. The results indicated that the thrust force increased with feed rate; however, lower values were recorded when using the Brad & Spur drill. Similar work was carried out by El-Sonbaty, [19] who tested the same work material using five cutting speeds ranging from 5.5 to 46.5 m/min and three feed rates (0.05–0.1 and 0.23 mm/rev). The author found that there is a delay between the response for thrust force and torque, after which the former reaches a maximum value.

From this point the thrust force value is reduced (probably due to the softening of the matrix caused by friction) and the torque increases due to the fact that the last fibers are not sheared, but entangled in the drill. They also noticed that the effect of cutting speed on thrust force is negligible, whereas torque increases with cutting speed. Surface roughness was not significantly affected by both cutting speed and feed rate. Lachaud et. al. [10] investigated the distribution of the thrust force along the cutting edge of the drill while machining a carbon reinforced epoxy composite. The analytical and experimental results suggest that an accurate model must consider the thrust force uniformly distributed on the chisel and principal cutting edges. Lachaud classified the damages of drilling polymeric composite materials into four categories: delamination at drill entry, geometric defects, temperature-related damages and delamination at drill exit. The delamination at drill entry is not always present. The tool geometry related damages are associated to the angle between fibers orientation and the cutting edge. This occurs due to the fact that before shearing takes place, the fibers are subject to alternate torsion and compression, resulting on an elliptical hole, in which the smaller axis of the ellipse is in the same direction of the fibers and is inferior to the drill diameter. In general, temperature related damages appear as a result of friction between the dill and the wall of the hole. Delamination at the drill exit probably happens owing to the fact that under this circumstance not all fibers are cut, thus resulting in a normal stress which opens the matrix/fiber interface. Finally, the author concluded that metal cutting drills are not suitable for machining polymeric composite materials and the damages caused by this grade (HSS) of tools are frequently observed in aircraft structures. Khashaba [17] adds that due to the fact that drilling is typically a final operation (reaming is rarely employed for polymeric composites), delamination is responsible for the rejection of approximately 60% of the components produced in the aircraft industry. Among the damages observed during the machining of polymeric composites, such as fiber pull out and thermal damages, Capello [12] regards delamination as the most critical owing to the fact that it can severely impair the performance of the machined component. Davim and Reis [5] carried out an experimental work with two distinct geometries of cemented tungsten carbide drills (5mm diameter) on CFRP laminates. The authors concluded that delamination at the drill entry and exit are affected by distinct parameters, i.e., at drill entry feed rate was the most significant factor affecting delamination whereas at the tool exit, delamination was most affected by cutting speed. Chambers and Bishop [16] investigated tool wear after drilling polymeric composites and asserted that it is rather difficult to obtain the surface quality required for an accurate assembly of structural components. Lin and Chen [15] also investigated tool wear, however, when high speed drilling is used in fiber reinforced plastics they found out that an increase in cutting speed leads to an increase in tool wear, which in turn provokes an elevation in the thrust force, which may impair the quality of the machined component. According to Inoue, [14] when a small number of holes must be produced with high quality, low feed rates should be employed, whereas higher feed rates should be used for large scale production with fair quality. For Ogawa [14] feed rate is the most significant factor affecting the surface roughness of holes. Moreover, an increase in thrust force results in inferior surface finish on the hole wall. Caprino and Tagliaferri [24] assert that the damages observed after drilling glass fiber reinforced plastics with a high speed steel drill are strongly affected mainly by feed rate. As feed rate is increased from 0.057 to 2.63 mm/rev, the damage pattern, initially represented by delamination at the intersection between the principal and secondary cutting edges, changes to step-like delamination, interlaminar cracks and high-density micro failure areas are observed. Hocheng and Tsao [13] assert that using especially designed drills a higher threshold feed rate on the onset delamination can be achieved.

2.5 OPTIMIZATION METHODS

2.5.1 Response Surface Methodology

The response surface methodology (RSM) is an empirical modeling approach for determining the relationship between various processing parameters and responses. The RSM is a collection of mathematical and statistical procedures, used for the analysis of problems in which the desired response is affected by several factors. In order to develop the mathematical model based on experimental data, a proper planning of experiments is necessary. The traditional method of experimentation, varying one parameter at a time and studying its effect is considered costly and time consuming. Hence, the design of experiments (DOE) technique has been selected that requires minimum number of experiments to be conducted. [2]

2.5.2 Taguchi

Through sophisticated analysis of the results, the experimenter is able to learn the relative impact of each variable, including how important it is to the overall output of the experiment. It performs better than other algorithms in noisy environments (those with lots of uncontrollable variables.) Taguchi is also a good choice because it gives insight with relatively smaller sample sizes. [23]

2.5.3 Genetic Algorithm

Genetic algorithm (GA) is a search technique used in computing to find exact or approximate solutions to optimization and search problems. Genetic algorithms are categorized as global search heuristics. Genetic algorithms are a particular class of evolutionary algorithms (also known as evolutionary computation) that use techniques inspired by evolutionary biology such as inheritance, mutation, selection, and crossover (also called recombination). [22]

2.6 NEW TREND IN MACHINING OF COMPOSITES

2.6.1 Ultrasonic Assisted Machining

Ultrasonic-assisted drilling involves the use of a rotary tool to which is superimposed an axial vibratory motion at high frequency. A special adapter is required to transmit the vibration from a piezoelectric transducer to the tool. Ultrasonic vibration can reduce friction, break chips, and reduce tool wear. It is a particularly useful technique when the matrix or reinforcing fibers are hard brittle materials. Use of a core drill permits cutting fluids to pass through its center. Ultrasonic machining, though slow, can result in high finish and accuracy of intricate parts. Hence, it is recommended for applications in which intricate shapes of high accuracy and finish are required.

Composites contain fibers that, when machined, can release finer fractions of the fibers into the atmosphere. Also, in the case of polymer-based composites, some of the chemicals released due to heat and thermal damage during machining can be harmful. It is well known that fibrous materials such as asbestos can cause cancer, and that other fibers such as glass are suspected agents. Simultaneous exposure to both inorganic fibers and organic compounds released during machining of polymer-based composites can bring about respiratory and other medical problems. Adequate ventilation and appropriate safety procedures to prevent exposure of personnel to these gases in the laser cutting facility is recommended. [4]

2.6.2 Ductile Regime Machining

Emerging technologies, such as ductile regime machining, succeed in converting these nominally brittle (non metallic) materials to behave in a ductile fashion allowing them to be machined similar to metals, avoiding catastrophic brittle fracture, resulting in smooth-damage free surfaces. [4]

2.6.3 Edm Drilling

EDM can make complex shapes with high precision. It is a slow process, but automation can bring the cost of manufacturing down. The prerequisite for EDM is that the work material be electrically conductive. Organic matrix composites are, therefore, not possible materials for this method of machining. They can be made conductive by being impregnated with metallic fillers (Cu, Al, or Ag powder), but that can defeat the purpose of composites for high-strength and lightweight applications. Metal-matrix composites are ideal candidates for EDM, especially where complicated shapes and high accuracy are required. Only a few ceramic-matrix composites that are electrically conductive can be shaped by EDM. However, recent improvements in the mechanical properties of ceramic-matrix composites-especially the fracture toughness and strength of whisker-reinforced ceramics through better processing technology and starting materials--make them ideally suited for high-temperature and fatigue-resistant applications. For example, the fracture toughness of silicon carbide whisker-reinforced alumina is nearly double that of the material without the fibers. The same is true with silicon nitride-based composites, which are very hard but extremely difficult and costly to machine or grind. If, however, these materials can be made electrically conductive by adding conductive refractory materials such as TiC or TiN without compromising other properties, processing these components by EDM can become an economic possibility. The particle size and percentage of TiC or TiN to be added to the matrix can be adjusted to make it electrically conductive enough to carry out the EDM process without significantly compromising the ultimate properties and performance requirements of the material. [25]

CHAPTER 3

METHODOLOGY

3.1 INTRODUCTION

In this study, the CFRP that is used is named unidirectional and woven graphite and glass cloth faced aramid honeycomb core floor panel stock, BMS 4-20L, an aircraft material. This fiber is made of medium-density core, with faces approximately 0.39 inch thick, for use in aisles and entries particularly in BOEING aircrafts. The approximate dimension of this sample is 0.3110m x 0.1011m. The material has an areal weight of 0.46 lb/sq ft max. A long beam load of 230 lb, and a deflection of 0.575 inch. Panel shear is recorded to be 585 lb, insert shear of 840 lb, impact strength of 6 lb and a stabilized core compression of 600 lb/sq in. The sole manufacturer for this material is BOEING.

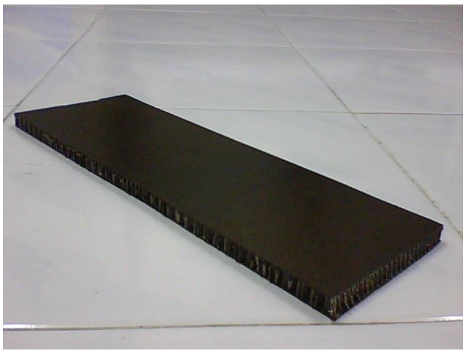

Figure 3.2: The CFRP that is used in this study

3.1.1 Table of properties

Table 3.2: Table of properties for the CFRP.

Properties	Areal weight (Lb/sq ft max)	Thickness (Inch, range)	Long beam bending [load] (lb)	Long beam bending [deflection] (lb)	Panel shear (lb/inch)	Impact strength (in – lbs)	Stabilized core compression (lb/sq in)
Values	0.46	0.39-0.41	230	0.550	585	6	600

Source: BOEING Material specifications (2007)

3.1.2 Fabrication of Material

One method of producing graphite-epoxy parts is by layering sheets of carbon fiber cloth into a mold in the shape of the final product. The alignment and weave of the cloth fibers is chosen to optimize the strength and stiffness properties of the resulting material. The mold is then filled with epoxy and is heated or air cured. The resulting part is very corrosion-resistant, stiff, and strong for its weight. Parts used in less critical areas manufactured by draping cloth over a mold, with epoxy either pre impregnated into the fibers (also known as prepreg), or "painted" over it. High performance parts using single molds are often vacuum bagged and/or autoclave cured, because even small air bubbles in the material will reduce strength. The process in which most carbon fiber reinforced plastic is made varies, depending on the piece being created, the finish (outside gloss) required, and how many of this particular piece are going to be produced. For simple pieces of which relatively few copies are needed, (1–2 per day) a vacuum bag can be used. A fiberglass or aluminum mold is polished, waxed, and has a release agent applied before the fabric and resin are applied and the vacuum is pulled and set aside to allow the piece to cure (harden). There are two ways to apply the resin to the fabric in a vacuum mold. One is called a wet lay-up, where the two-part resin is mixed and applied before being laid in the mold and placed in the bag. The other is a resin induction system, where a tube with holes or something similar is used to evenly spread the resin throughout the fabric. A third method of constructing composite materials is known as a dry lay-up. Here, the carbon fiber material is already impregnated with resin (prepreg) and is applied to the mold in a similar fashion to adhesive film. The assembly is then placed in a vacuum to cure. The dry layup method has the least amount of resin waste and can achieve lighter constructions than wet lay-up. A quicker method uses a compression mold. This is a two-piece (male and female) mold usually made out of fiberglass or aluminum that is bolted together with the fabric and resin between the two. However, the molds require a lot of material to hold together through many uses under that pressure. Many carbon fiber reinforced plastic parts are created with a single layer of carbon fabric, and filled with fiberglass

3.2 MACHINE

Figure 3.3: The CNC Milling machine that is used in this study.

The abbreviation **CNC** stands for **computer numerical control**, and refers specifically to a computer "controller" that reads G-code instructions and drives a machine tool, a powered mechanical device typically used to fabricate components by the selective removal of material. The machine that will be used in this study is a 3 axis machine which means it could move in 3 axes namely X, Y and Z. The machine name is CNC MILLING (FANUC). The model is FANUC ROBODRILL (T14 iFEe). Maximum spindle speed that could be accepted by this machine is 10 000 rpm. The acceptable range of feed rate is 1 to 30,000mm/min. This CNC milling machine could accommodate up to 14 tools with a maximum tool diameter of 80mm and maximum tool length of 250mm. The work piece table could withstand a maximum load of 250kg. Lastly, this machine is manufactured in Japan.

3.3 EXPERIMENTAL SETUP

3.3.1 Experimental Planning (DOE)

To design the experiments, the following steps are to be implemented: the selection of the appropriate optimization method for drilling process of fiber reinforced plastics composite (CFRP), select parameters to study and preparation of tools and work piece. Size of the cutting tools in this drilling process will be fixed for all sets of experiment which is 6mm for all three types of carbide tools, which is SPF solid carbide drill (without coolant), multi layered PVD coated carbide drill, and solid carbide jobber drill K20. The control parameters are spindle speed, feed rate and type of cutting tool. The responses or the effect studied here is the delamination and the thrust force exerted on the CFRP. The range of the input parameters will be fixed as given in Table2.

Table 3.3: Machining Parameters and Their Levels for Each Type of Different Types Of Carbide Tools

Symbol	Machining parameter	Level 1	Level 2	Level 3
S	Spindle Speed	2000	5000	8000
F	Feed Rate (mm/min)	200	400	600

The number of experiments or DOE has been decided using full factorial design. This means, since there are three different ranges for cutting speed and feed rate and three different types of tool material therefore the number of experiments that has been conducted were 3^3 = 27sets. Therefore for each different three values, different types of combination have been obtained amounting to a maximum number of 27 tests.

Later on, the optimization method has been conducted using the D optimal method. The D-optimal method is relatively a new technique, related to response surface methodology, used for carrying out the design of experiments, the analysis of variance, and the empirical modeling. The D-optimal criterion was developed to select design points in a way that minimizes the variance associated with the estimates of specified model coefficients. In a sense this method is more useful than central composite design (a conventional response surface method) that it demands smaller number of experiments to be conducted and also it can tackle categorical factors included in the design of experiments. In this study, the optimization process has been done by a statistical software named Design Expert 7.1. This software requires the users to enter the values obtained after conducting the experiment and further deduction together with the ANOVA table will be generated automatically in this software. ANOVA is used to study the significance of each parameter on the outputs. The optimal parameters have been obtained by observing the contour plot. After, the optimal parameters are chosen; a last set of experiment has been conducted to verify the results.

3.3.2 Experimental Procedures and Test Analysis

The experimental procedures involve a detailed planning before implementation as various factors should be taken under consideration before moving on with the study. As mentioned, this study involves the optimization of drilling process on fiber-reinforced composites. In this case, carbon fiber reinforced composite is used or CFRP shortly. To narrow the study, only two main output parameters are chosen which is thrust force and delamination of the composite. The control parameters were set to be the feed rate, spindle speed and cutting tools or the type of drill material. Based on a detailed study of other researchers it has been found out that there are mainly two types of drills used on composites namely high speed steel (HSS) and carbide drills. A comprehensive analysis was made and it was known that using carbide tools will improve the quality of the holes drilled and exhibit almost null wear after repeated usage on composites. Therefore, it has been decided that carbide tools will be chosen to drill holes on the CFRP. To study the variation of hole quality on the drilled specimen, three different types of carbide tools will be used with two main categories which is solid carbide and coated carbide tools mainly. The three main types of carbide tools chosen for this study were solid carbide SPF drills (without coolant), multi layered PVD coated carbide drill and solid carbide jobber drill K20. The work piece namely the unidirectional and woven graphite and glass cloth faced aramid honeycomb core floor panel stock with a dimension of 311mm x 101mm has been mounted on the Kistler multi channel charge amplifier with piezoelectric dynamometer fixed with the CNC milling machine. The work piece mounting has been designed precisely so as to avoid chatter and vibration during the hole drilling process which will cause inaccurate results. This would eventually lead to the failure of the research. The work piece has been clamped using dot clamping with a clamping tool. The position of the CFRP was adjusted to stabilize it. Proper clamping should be done before starting the drilling process. Also, the position of the work piece was placed in line with the holes on the platform of the dynamometer to obtain the force readings needed. To start a drilling process on the CNC milling machine, an adequate knowledge of the G code system is compulsory. The necessary control parameters were in the simulator so as to run the machine without hassle. The values of RPM and feed rate ranges from 2000 – 8000 and 200 - 600mm/min respectively. Table 3 shows the respective values that will be used to conduct the experiment.

Table 3.4: DOE of the experiment layout.

Tool	Expt#	Control parameter	
		Spindle Speed	Feed rate
SPF Drill Solid Carbide Drill	1	2000	200
	2	2000	400
	3	2000	600
	4	5000	200
	5	5000	400
	6	5000	600
	7	8000	200
	8	8000	400
	9	8000	600
PVD Multi Layered Coated Carbide	10	2000	200
	11	2000	400
	12	2000	600
	13	5000	200
	14	5000	400
	15	5000	600
	16	8000	200
	17	8000	400
	18	8000	600
Jobber Drill Solid Carbide K20	19	2000	200
	20	2000	400
	21	2000	600
	22	5000	200
	23	5000	400
	24	5000	600
	25	8000	200
	26	8000	400
	27	8000	600

Each experiment was conducted thrice with prior respect to the three types of tools used. In total 27 holes were drilled on the composite irrespective of cutting speed, feed rate and tool material. At the same time, thrust force readings will be generated on the special software equipped with the piezoelectric dynamometer. The general schematic diagram of the work piece mounted on the dynamometer is shown in Figure 3.

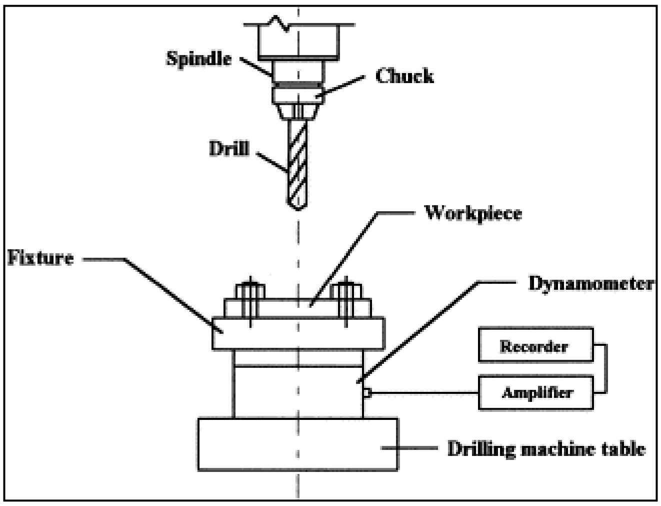

Figure 3.4: Schematic Diagram of the Mounted Work Piece

After completing the drilling process and the measurement of the thrust force, the work piece was inspected for the effects of delamination. A metallurgical microscope was used for this purpose. SEM is not used in this study due to the fact that the damage caused by the drilling process could be seen and evaluated by using a microscope with normal magnification and the damage investigated will not be invincible as to require a machine with micro units. The work piece was clipped onto the metallurgical microscope whereby the focus should be on the holes drilled. Analysis was done to see the damage caused by the different cutting speed, feed rate and tool material. Also, analysis was done to see the other damages caused by the drilling process such as fiber/resin pullout and so on.

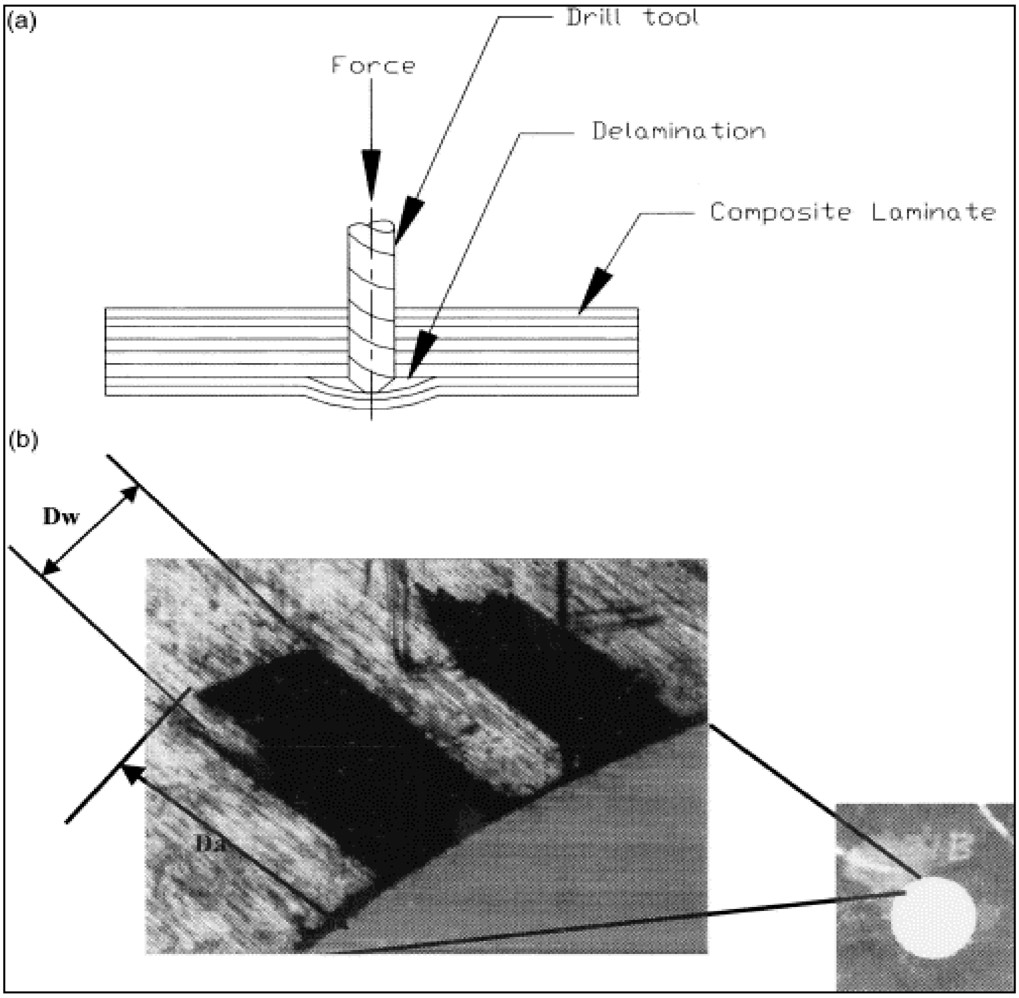

Figure 3.5: Schematic of drill exit delamination. (b) Damage caused by abusive drilling in carbon fiber reinforced plastic (CFRP).

Figure 3.5 shows an example of delamination on a drilled hole of CFRP. In this study it is expected to observe damages such like this.

As mentioned above, this experiment involves the study of two outputs namely thrust force and delamination. Therefore, each output requires its own procedure so that accurate results could be obtained. A CNC milling machine was used here to drill the holes required. The CFRP was held in a rigid fixture attached to a force-torque Kistler piezoelectric dynamometer. The force signals were sent to Kistler 5070A charge amplifiers and lastly the results were interpreted using a special software of Kistler called DynoWare 2825A. Piezoelectric sensors convert mechanical quantities such as pressure, force and acceleration directly into an electric charge.The charge produced is proportional to the force acting on the quartz crystal contained in the sensor. The sensitivity of the sensor is stated in pC/ M.U. The mains-operated multi-channel charge amplifier receives the charge from the piezoelectric sensor and converts it into a proportional voltage. The electronic system ensures simple and clear operation of the instrument, within wide limits. The nominal power line voltage is 100V ~ 240V ~ (50 – 60 Hz). The typical measuring chain consists of a piezoelectric dynamometer with charge output, the connecting cable and the multi channel charge amplifier as well as a data acquisition and analysis system namely DynoWare 2825A. The piezoelectric dynamometer mentioned above is shown in Figure 5.

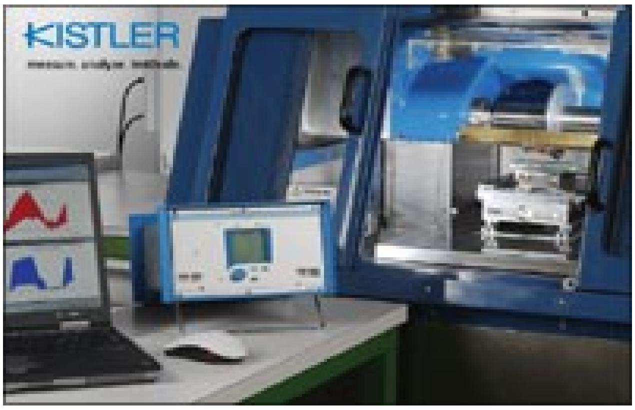

Figure 3.6: The Kistler Piezoelectric Dynamometer with Charge Amplifiers 5070A

To study the delamination of the composite, as mentioned above a metallurgical microscope was used. In this case, the metallurgical microscope used is Meiji Techno IM7000 inverted metallograph series. The IM7000 delivers an excellent performance-to-cost ratio because it has the features and versatility that one would expect to find in more expensive instruments. The IM7000 has an integrated front mounted camera port with adapters available for 35mm, CCD, CMOS and other cameras.The IM7000 metallurgical microscope is equipped with a JENOPTIK CT3 PROGRES digital camera. This will enable the caption of the sample work piece for further study. The digital microscope camera ProgRes® CT3 allows for quick and precise setting of specimen and microscope, and hence provides comfortable operation. The integrated CMOS sensor is absolutely resistant against blooming and shows superior performance in imaging highlights. The camera is configured with standard interfaces such as C-Mount and IEEE 1394 Firewire. The figure of the microscope and the digital camera is shown below.

Figure 3.7: The microscope equipped with the digital camera

3.4 TOOLS

3.4.1 SPF Drill (Split Point Fiber) Solid Carbide Drill

The tools used in this study are basically three different types of carbide drills. HSS was eliminated from this study after referring to previous studies whereby it was recorded that the usage of HSS drill will cause inferior damage to the composites. Carbide drills have been proven to give better performance Therefore, this study focuses on the effect of three different types of carbide drills. The first tool used in this study is the SPF drill or the Split Point Fiber drill whereby this drill is a new discovery and is especially used in the aviation industry. SPF drill has a multilayer diamond coating enclosed with CVD (Chemical Vapor Deposition). This tool is used as an alternative to PCD (Polycrystalline Diamond) which is the best tool to drill composites as it is much cheaper. Studies show that the cost is reduced to almost 50% by using SPF. SPF has been designed especially to drill CFRP mainly and it has added advantages such as that it does not wear easily as it has a longer tool life. Therefore, SPF drill was used in this study to test the effectiveness on the CFRP used for this research.

3.4.2 PVD Multi Layered Carbide Drill

PVD multilayered carbide drill is a drill which is coated with gold thin like coatings at the tip of it. PVD or physical vapor deposition is a thin film coating which is coated to improve the tool's reliability and improve the machine's performance. Basically, this PVD tool has multi layers of PVD on it and this causes it to possess a long tool life as it has excellent resistance to wear.

3.4.3 Jobber Drill K20

Jobber drill K20 is a type of solid carbide drill. It is used to drill heat resistance steel such as titanium, manganese, and bronze and so on. This drill has a long tool life as it could be used on materials that are hard and requires tough machining.

CHAPTER 4

RESULTS

4.1 INTRODUCTION

This chapter shows all the results obtained from this study. Tables of results, graphs, and figures are included. Detailed explanation of graphs and figures are also provided. The optimization method usage and interpretation of its results are obtained based on detailed study of the usage of the software involved. In this case the Design Expert 7.1, statistical software which is user friendly and reliable was used in the experiment. Lastly, the results obtained will be compared to the previous studies and the similarities and discrepancies are observed.

4.2 RESULTS

Table 4.5 shows the results obtained for the two responses studied namely thrust force and delamination against three different types of controlled parameters namely spindle speed, feed rate and type of tool material.

Table 4.5: Design experiment layout and the responses

Number of runs	Parameter 1: Spindle Speed (rpm)	Parameter 2: Feed rate (mm/min)	Parameter 3: Tools	Response 1: Thrust Force (N)	Response 2: Delamination (mm)
1	2000	200	SPF Solid Carbide Drill	239.52	0.9641
2	2000	400		242.81	0.4485
3	2000	600		240.25	1.1304
4	5000	200		243.94	1.1743
5	5000	400		244.12	0.5903
6	5000	600		245.06	1.012
7	8000	200		246.40	1.176
8	8000	400		246.49	1.1687
9	8000	600		246.88	0.5981
10	2000	200	PVD Multi Layered Coated Carbide Drill	245.02	1.5343
11	2000	400		248.29	0.9032
12	2000	600		247.06	0.8717
13	5000	200		248.15	0.6120
14	5000	400		247.29	0.8681
15	5000	600		247	0.9803
16	8000	200		247.64	0.5840
17	8000	400		247.5	1.002
18	8000	600		247.8	0.6450
19	2000	200	Jobber Drill K20	249.54	0.7474
20	2000	400		251.35	0.9540
21	2000	600		248.19	0.7089
22	5000	200		248.92	0.625
23	5000	400		247.69	0.6740
24	5000	600		248.88	0.7566
25	8000	200		248.62	1.3100
26	8000	400		248.8	1.133
27	8000	600		248.6	0.9191

4.3 ANALYSIS OF GRAPHS

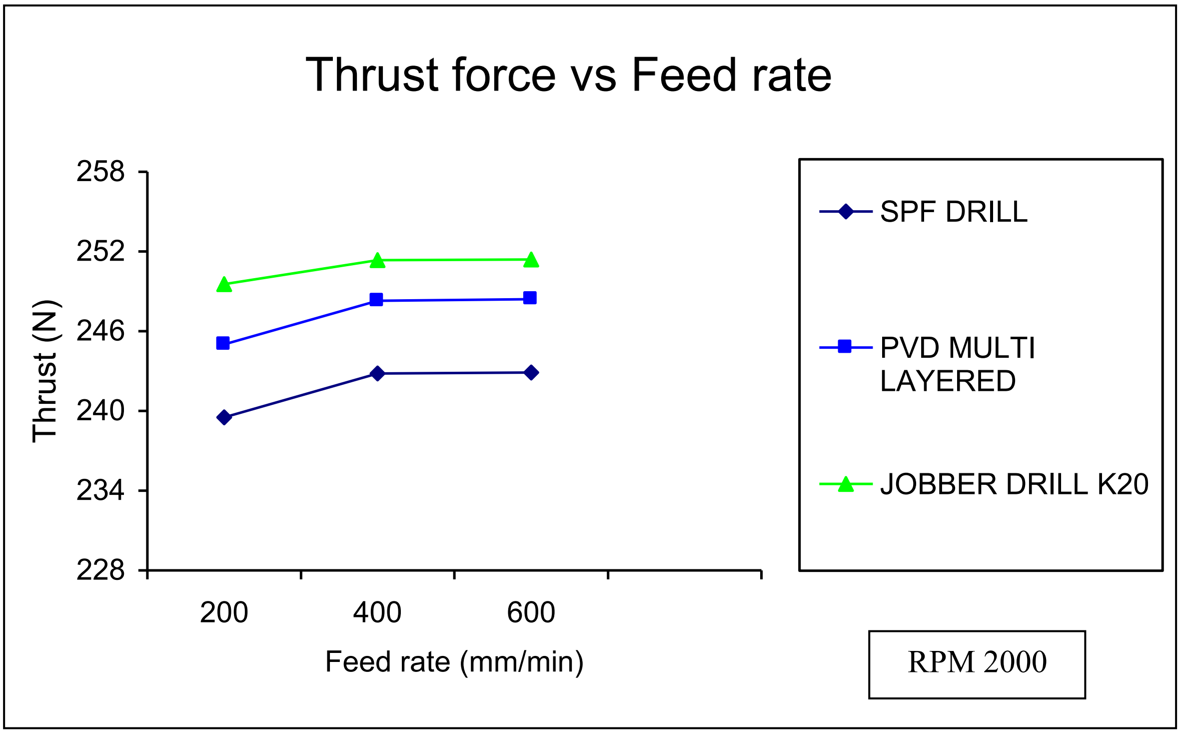

Figure 4.8: Thrust Force versus Feed rate for 2000 RPM

Figure 4.8 shows the thrust force versus feed rate for all three different types of tools namely SPF drill, PVD multi layered, and Jobber drill K20 under the RPM of 2000. This figure is created to obtain a clearer view of the variation of the thrust force under the same RPM which in this case is 2000. It could be clearly observed that the SPF drill produces the least thrust force among the other two drills namely PVD and K20. The thrust force values recorded for SPF drill here were 239.52N, 242.81N, and 240.25N for the feed rate of 200, 400 and 600 mm/min respectively. For the PVD drill, the thrust force recorded are 245.02N, 248.29N, and 247.06N for the feed rate of 200, 400 and 600 mm/min respectively and lastly for K20, the thrust force values recorded are 249.54N, 251.35N, and 248.19N for the feed rate of 200, 400 and 600mm/min respectively. Although, the thrust force was supposed to increase linearly with the feed rate regardless of the tool, this discrepancy could be due to certain experimental errors. Basically, there were other thrust force versus feed rate figure drawn for different RPM which is 5000 and 8000. The figures obtained were similar to the one above whereby, the SPF Drill exhibits the least value of thrust force compared to the other tools and the thrust force increases with feed rate for all the tools. This results is totally in accordance with the previous studies obtained whereby, it was proved that the thrust force increases with an increase of the feed rate.[18] The SPF drill is recorded to have the lowest thrust force under these three cases due to the fact that this drill is specially made to drill composite materials mainly CFRP due to its unique properties whereby the CVD and diamond layered surface increases the strength of the tool bit and therefore it does not require a high force to penetrate the composite surface.

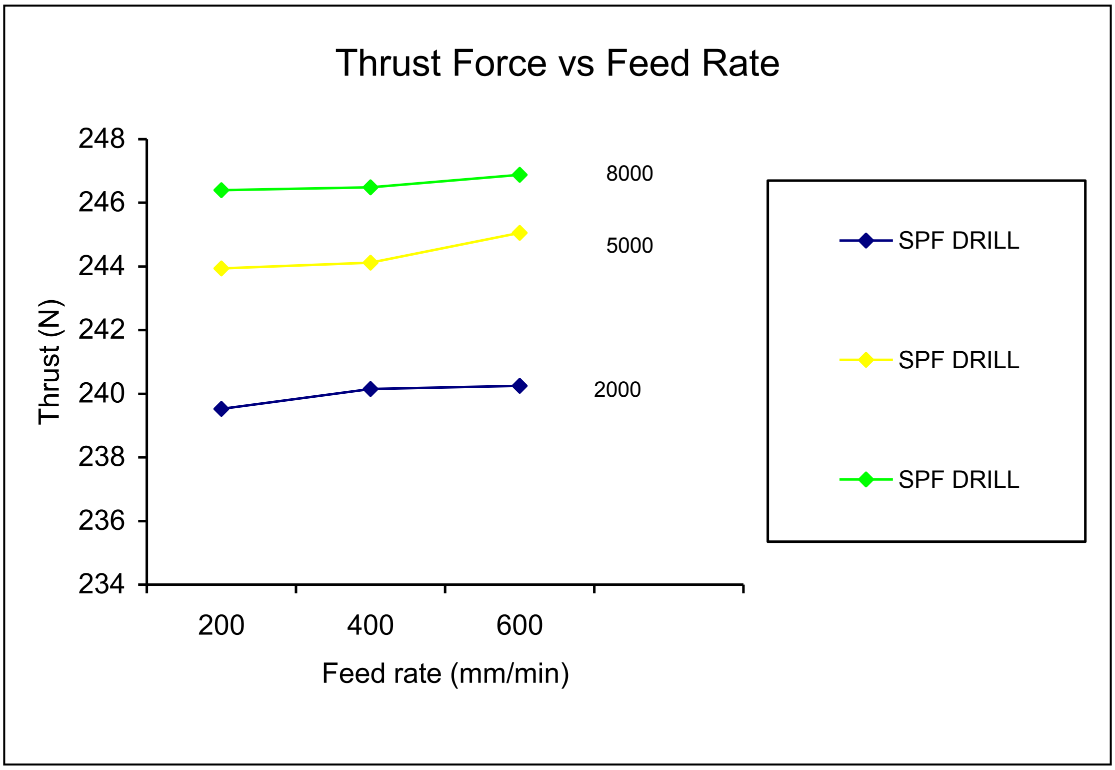

Figure 4.9: Thrust Force versus Feed rate for SPF Drill

Data for the SPF drill is collected, analyzed separately and presented as a graph as shown above. Based on the experimental results obtained, from the very start it could be seen that SPF drill has been proven to give better results compared to the other two tools in terms of thrust force. This graph compares, thrust force generated by SPF in three different RPM. As mentioned earlier, based on literature review the thrust force generated will definitely increase linearly with the feed rate [2]. The graph obtained through this experiment shows a noticeable increase but not in a linear manner, maybe due to certain unavoidable errors. Generally, the thrust force generated during 5000 RPM and 8000 RPM shows a clear increase but only the thrust force generated during the 2000 RPM shows a marginal error where the thrust force is at its highest peak at a feed rate 400mm/min compared to 600mm/min.The value recorded at this peak was 242.81 N.

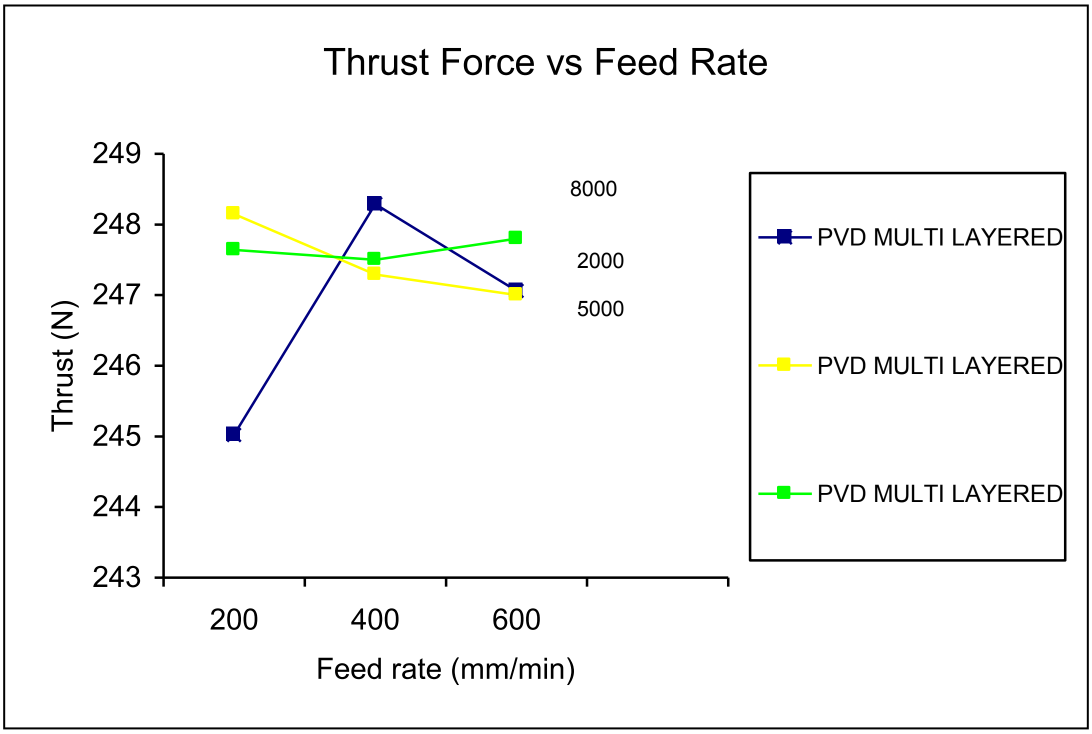

Figure 4.10: Thrust Force versus Feed rate for PVD multilayered

Data generated by the PVD multi layered drill is taken out separately, analyzed and presented as a graph as shown above. Here, only the thrust force generated during the 8000 RPM is noticed to follow the rule stated which is that the thrust force increases with feed rate. As for the spindle speed of 5000 RPM a slight error is detected whereby the thrust force generated at a feed rate of 200mm/min which is 248.15 N is higher compared to the thrust force generated at a feed rate of 400mm/min and 600mm/min which is 247.29 N and 247 N respectively. Lastly, the major discrepancy is observed at a spindle speed of 2000RPM whereby the highest peak recorded is at a feed rate of 400 mm/min which is 248.29 N. This value recorded even out beats the highest peak of the other forces generated at a higher spindle speed. This maybe due to the fact that the PVD multi layered drill is not quite suitable to drill high strength materials like CFRP even though this tool bit is classified as a carbide drill.

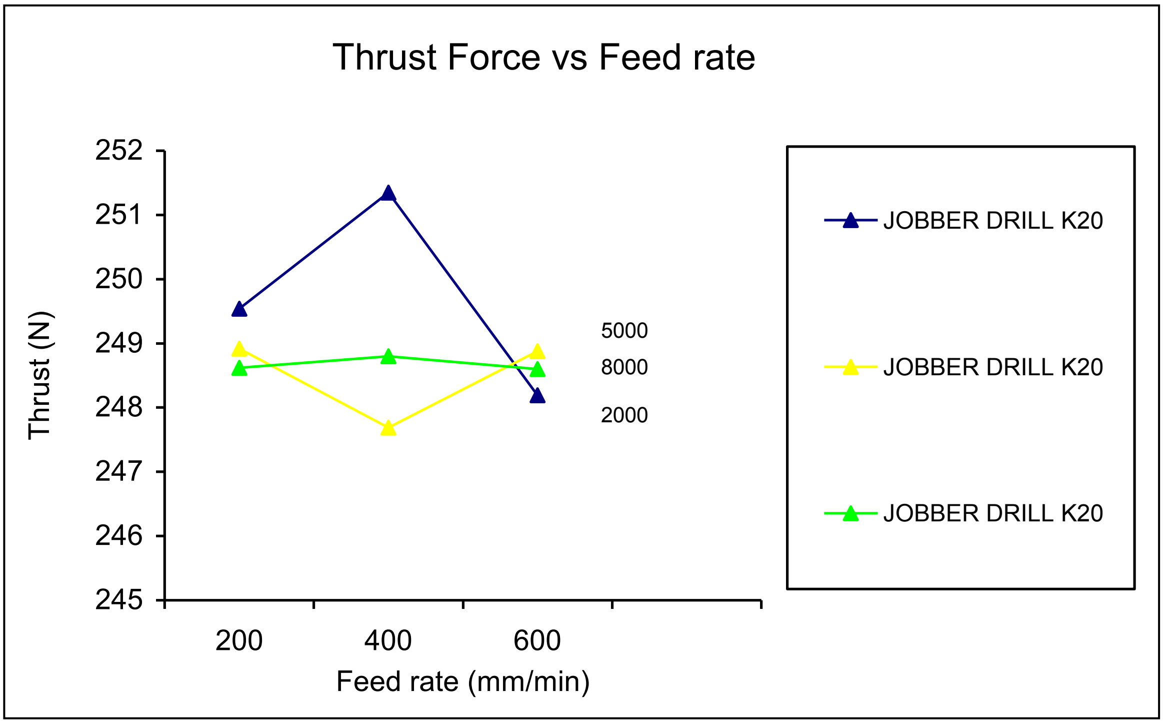

Figure 4.11: Thrust Force versus Feed rate for Jobber Drill K20

The thrust force generated by the Jobber drill K20 is taken out separately, analyzed and presented as a graph shown above. Here, it is observed that the rule of thrust force increases with feed rate is only applied at the spindle speed of 5000RPM. Meanwhile, the other two graphs obtained is slightly askew especially the data for the spindle speed of 2000RPM ,whereby the feed rate 400 mm/min shows the highest peak where the thrust force value recorded here was 251.35 N. As for the 8000 RPM nothing unusual could be observed except that the feed rate 600mm/min generates a slightly lower thrust force of 248.6 N compared to 248.8 N for the feed rate of 400 mm/min. This marginal error may due to certain unavoidable circumstances. As known, jobber drill is used for heat resistance steel like chromium, brass and so on; therefore discrepancies in the figure obtained may be due to the fact that the tool bit used is not suitable for composites due to the fact that fiber layers of composites is not highly heat resistant.

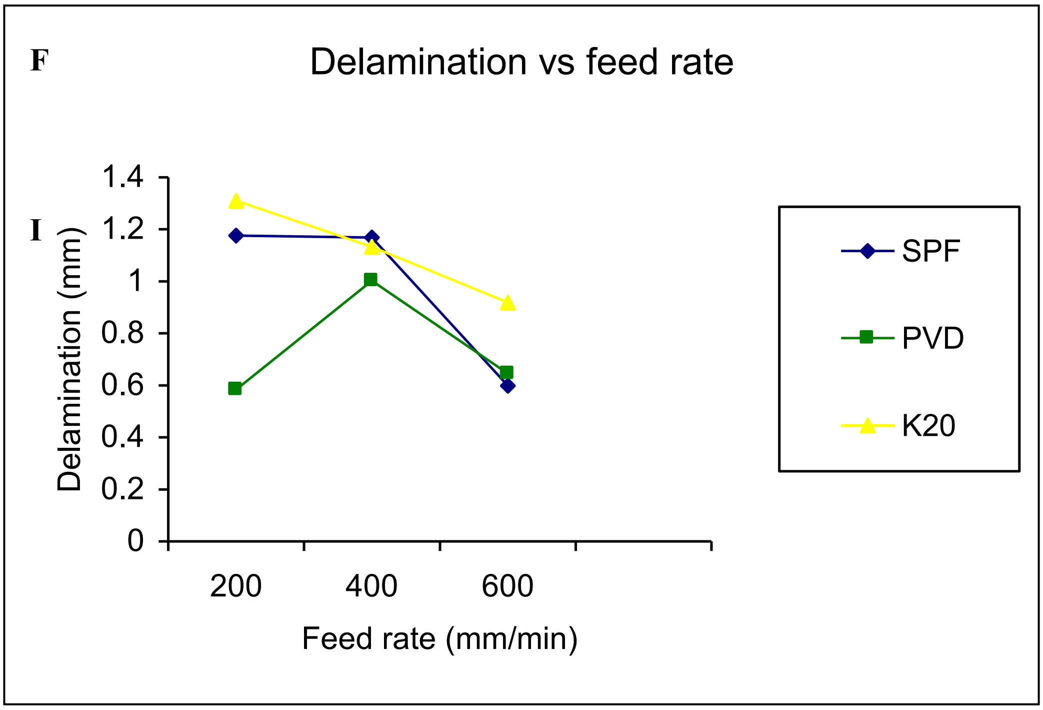

Figure 4.12: Delamination versus Feed rate for 8000 RPM

This is an example of a delamination graph obtained versus feed rate at a spindle speed of 8000 rpm. According to previous studies, the delamination decreases with an increase in cutting speed and a lower feed rate. But based on this graph it could be observed that the delamination obtained is totally opposite from the previous studies. This may due to certain unavoidable circumstances or unavoidable experimental errors. Basically, after doing a comparison individually, it is observed that the SPF drill gives the lowest thrust force values at all spindle speed.

4.4 OPTIMIZATION METHOD

The RSM D-optimal criterion, one of several “alphabetic” optimalities, was developed to select design points in a way that minimizes the variance associated with the estimates of specified model coefficients. The basic rules to set up a D-optimal design in Design Expert would be firstly to select the number of factors and their high and low levels (add constraints if needed). Secondly, select the model that you want to fit with Edit Model button (Quadratic is default). Lastly, enter the name of the responses. The software will automatically creates an overall candidate point set which is many possible runs depending on the model chosen. This software will also be able to choose specific design points including replicates. It does this step several times based on the number of replicates specified and then compares the d-optimality value of the designs created. It outputs the best of the designs created. The steps done before obtaining the optimal parameters will be described in detail. [26]

Table 4.6: Number of Factors Added and Type of Factors

Numeric Factors	2
Categoric Factors	1

Table 4.7: Name of Parameters and the Minimum and Maximum Values

Name	Units	-1 Level	+1 Level
Feed rate	mm/min	200	600
Spindle Speed	Rpm	2000	8000

Table 4.6 and 4.7 shows the initial layout to compute the parameters obtained D optimally. First and foremost, a user should be able to identify the amount of numeric factors and categoric factors needed or available in the experiment conducted. For this case, the numeric factors are two namely feed rate and spindle speed respectively. The categoric factor as stated above is one. Based on the experiment conducted, the categoric factor is the tools and the tool material used. Therefore, since we have only one non numerical factor therefore it should be stated on as above. Later on, the minimum and maximum or the -1 level and the +1 level are filled in the table given for the numeric factors. In this experiment, the minimum value for the feed rate or 'A' value is 200mm/min and the maximum value is 600mm/min. As for spindle speed or 'B' the minimum value is 2000 rpm and the maximum value is 8000 rpm. By specifying these values, users will be able to complete the first step of the D optimal criterion.

Table 4.8: Entering the Categoric Factors General Specification

Factor C	Name: Tools
	Units: Material
	Levels: 3

Table 4.9: Naming the Categoric Factors Nominally

Treatments
SPF
PVD
K20

Table 4.8 and 4.9 shows the second step of completing the D optimal criterion. This step involves the user to specify the categoric factor that is being used in the experiment. For this experiment, the categoric factor would be named as tools as the type of tools would be parameters being studied. The units specified for this

categoric factor would be named material as the type of tools differ in this experiment and lastly the levels specified here is three as there are three types of tools used to complete the experiment. The treatment column here is named based on the names of the tools used in this experiment. Here as known, user should specify the names of the tools accordingly. For this experiment, the names of the tools were typed according to the sequence used in the experiment which is the SPF drill, the PVD multilayered drill and lastly the K20 jobber drill. There are two categoric constraints which requires the software requires the user to specify namely the ordinal and the nominal constraints. The nominal constraints are used if the levels of the categoric factors are stated with their names typed. The ordinal constraints here is only used if the level of the categoric factors are typed as "1", "2", "3" and so on. Since, the name of the tools is specified here, therefore the nominal constraints is selected. This option is important as it would affect the construction of the model and the layout of ANOVA.

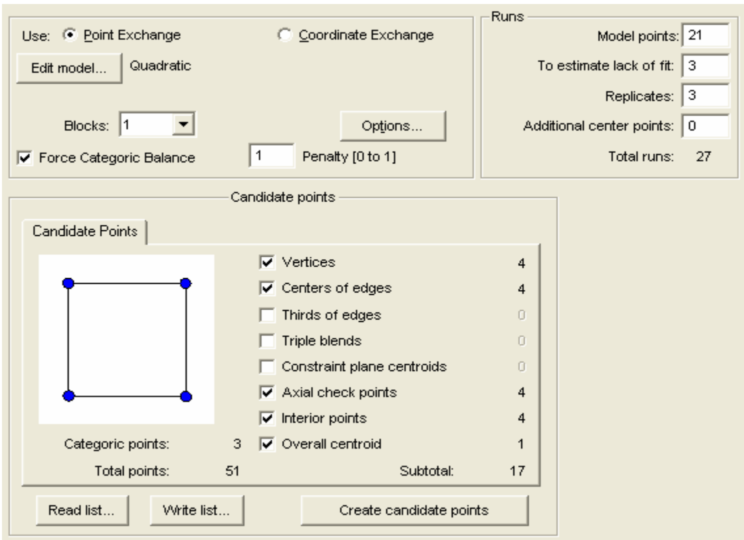

Figure 4.13: Specifying the D optimal Design

This would be the step where the d optimal design is specified. The default setting which is point exchange is left by itself. The number of the runs specified here requires the user to carefully select their total points which is the actual design points. The number of design points depends on the number of factors (k) in the design and the number of coefficients in the model selected. Basically, as stated above, the model points are selected based on the number of levels of the categoric factors. Since there are three levels or three types of tools available, therefore, the number of runs should be divisible by three s as to divide the model points equally among the three tools. There is an option that should be selected in this window which is named the force categoric balance. By clicking on this option, the software will automatically divide the model points equally to three tools. The number of runs should be a total of 27 as 27 runs were done in the actual experiment. The "model" points stated are equal to the number of coefficients. The points are selected based on the D optimal criteria. For this experiment, the model points are keyed in as 21 as the software will be able to choose 21 suitable points to construct the model. The "Lack-of-Fit" points are selected using the distance criterion. As for this experiment, three lack of fits are selected based on the levels of the tools and lastly the "Replicate" column which will enable the points with the highest leverage to be replicated. For this experiment, three replicates were keyed in to balance the number of lack of fits and replicates. Lastly, after specifying all these, the Create candidate Points will calculate the candidate points identified for the experiment and will select d-optimally the points needed at a minimum for the quadratic model. In this case, 51 candidate points were identified and 17 points were selected d-optimally. Then there will be three more runs added with uniquely different combination factors for testing lack of fit and finally three of the points will be replicated.

Table 4.10: Number of Responses

Responses	2

Table 4.11: Name and Unit of Responses

Name	Units
Thrust Force	N
Delamination	mm

Table 4.10 and 4.11 shows the number of response, name and units. Since this is a multi objective optimization, therefore the number of responses studied here is stated which is two. The name and the units of the response are entered as shown. The first response studied would be thrust force with the unit N or Newton and the second response studied is delamination with a unit of mm or millimeters. By entering these units, the software will perform the analysis based on the response as stated above.

4.5 ANALYSIS BY DESIGN EXPERT 7.1

Table 4.12: DOE Table Generated By the Software

Std	Run	Factor 1 A:Feedrate mm/min	Factor 2 B:Spindle Speed rpm	Factor 3 C:Tools material	Response 1 Thrust Force N	Response 2 Delamination mm
16	1	200.00	2000.00	PVD	245.02	1.5343
28	2	600.00	8000.00	K20	248.6	0.9191
13	3	200.00	5000.00	PVD	248.15	0.612
18	4	400.00	2000.00	K20	251.35	0.954
31	5	600.00	8000.00	SPF	246.88	0.5981
3	6	600.00	2000.00	SPF	240.25	0.9831
30	7	600.00	2000.00	PVD	247.06	0.8717
21	8	200.00	8000.00	K20	248.62	1.31
27	9	600.00	8000.00	PVD	247.8	0.645
20	10	400.00	2000.00	PVD	248.29	0.9032
10	11	200.00	8000.00	SPF	246.4	1.048
23	12	400.00	6500.00	SPF	244.12	0.5903
6	13	200.00	2000.00	SPF	239.52	0.9641
4	14	200.00	2000.00	K20	249.54	0.7474
24	15	200.00	5000.00	K20	248.92	0.6251
5	16	600.00	8000.00	PVD	247.8	0.645
9	17	600.00	8000.00	SPF	246.88	0.5981
2	18	200.00	8000.00	PVD	247.64	0.584
26	19	300.00	3500.00	SPF	242.81	0.4485
1	20	600.00	8000.00	K20	248.6	0.9191
12	21	400.00	8000.00	PVD	247.5	1.002
22	22	500.00	5000.00	PVD	247	0.9803
15	23	200.00	5000.00	SPF	243.94	1.1304
25	24	600.00	5000.00	K20	248.88	0.7566
17	25	400.00	2000.00	SPF	242.81	0.4485
7	26	200.00	8000.00	K20	248.62	1.31
8	27	600.00	2000.00	PVD	247.06	0.8717
14	28	600.00	2000.00	K20	248.19	0.7089
29	29	200.00	8000.00	SPF	246.4	1.048
19	30	600.00	5000.00	SPF	245.06	1.1743
11	31	400.00	5000.00	K20	247.69	0.874

The DOE table generated by Design Expert was similar to the experiment conducted with a few replicates and points added. The lack of fit points had its own range of values and by specifying it accordingly, and by adding all the values from the actual experiment; the software generated a somewhat similar table to the real experiment. This could easily prove that this software and the D optimal method chosen is quite reliable as it could select suitable points effectively. The software selects the lack of fit points based on the suitability of the experiment. Points which the software thinks are good enough to compute the optimal parameters.

Response 1 Thrust Force Transform: None

Sequential Model Sum of Squares [Type I]

Source	Sum of Square	df	Mean Square	F Value	pvalue Prob > F	
Mean vs Total	1.887E+006	1	1.887E+006			
Linear vs Mean	145.87	4	36.471	4.89	< 0.0001	
2FI vs Linear	42.61	5	8.52	8.50	0.0002	Suggested
Quadratic vs 2FI	1.27	2	0.63	0.61	0.5541	
Cubic vs Quadratic	15.07	10	1.51	2.87	0.0640	
Residual	4.72	9	0.52			
Total	1.887E+006	31	60862.87			

"*Sequential Model Sum of Squares [Type I]*": **Select the highest order polynomial where the additional terms are significant and the model is not aliased.**

Lack of Fit Tests

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F
Linear	63.67	20	3.18		
2FI	21.06	15	1.40		
Quadratic	19.79	13	1.52		
Cubic	4.72	3	1.57		
Pure Error	0.000	6	0.000		

"*Lack of Fit Tests*": **Want the selected model to have insignificant lack-of-fit.**

Model Summary Statistics

Source	Std. Dev.	R-Squared	Adjusted R-Squared	Predicted R-Squared	PRESS	
Linear	1.56	0.6962	0.6494	0.5566	92.90	
2FI	1.00	0.8995	0.8564	0.7583	50.64	Suggested
Quadratic	1.02	0.9056	0.8509	0.7247	57.69	
Cubic	0.72	0.9775	0.9248	-0.7474	366.14	

"*Model Summary Statistics*": **Focus on the model maximizing the "Adjusted R-Squared" and the "Predicted R-Squared".**

Figure 4.14: Fit Summary Analysis for Thrust Force

Figure 4.14 shows the Fit Summary analysis done by the Design Expert software for thrust force. Based on this analysis one could interpret the model suggested for the thrust force values entered. Based on the results of the thrust force, the model suggested for the thrust force values are 2FI which is similar to a linear graph. This results is in accordance to previous studies whereby the graphs obtained are linear to the spindle speed and feed rate. Since the model is not aliased in any way therefore, based on the results produced by the software, the next steps could be computed without any hassle. Notice that the adjusted R-Squared value for the model selected is 0.8564.

Response 2 Delamination Transform: None

Sequential Model Sum of Squares [Type I]

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Mean vs Total	23.18	1	23.18			Suggested
Linear vs Mean	0.19	4	0.047	0.66	0.6254	
2FI vs Linear	0.43	5	0.085	1.24	0.3258	
Quadratic vs 2FI	0.056	2	0.028	0.39	0.6848	
Cubic vs Quadratic	1.34	10	0.13	22.98	< 0.0001	Suggested
Residual	0.052	9	5.810E-003			
Total	25.24	31	0.81			

"*Sequential Model Sum of Squares [Type I]*": **Select the highest order polynomial where the additional terms are significant and the model is not aliased.**

Lack of Fit Tests

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F
Linear	1.87	20	0.094		
2FI	1.44	15	0.096		
Quadratic	1.39	13	0.11		
Cubic	0.052	3	0.017		
Pure Error	0.000	6	0.000		

"*Lack of Fit Tests*": **Want the selected model to have insignificant lack-of-fit.**

Model Summary Statistics

Source	Std. Dev.	R-Squared	Adjusted R-Squared	Predicted R-Squared	PRESS	
Linear	0.27	0.0922	-0.0475	-0.3050	2.69	
2FI	0.26	0.2991	-0.0012	-0.6224	3.34	
Quadratic	0.27	0.3265	-0.0634	-0.9201	3.96	
Cubic	0.076	0.9746	0.9154	-0.8770	3.87	Suggested

"*Model Summary Statistics*": **Focus on the model maximizing the "Adjusted R-Squared" and the "Predicted R-Squared".**

Figure 4.15: Fit Summary Analysis for Delamination

Figure 4.15 shows the Fit Summary analysis done by the Design Expert software for delamination. Based on this analysis one could interpret the model suggested for the delamination values entered. Based on the results of the delamination, the model suggested for the delamination values is a cubic graph. Since the model is not aliased in any way therefore, based on the results produced by the software, the next steps could be computed without any hassle. Notice that the adjusted R-Squared value for the model selected is 0.9154.

Constraints [redacted]

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
Feedrate	is in range	200	600	1	1	3
Spindle Speed	is in range	2000	8000	1	1	3
Tools	is in range	SPF	K20	1	1	3
Thrust Force	minimize	240	245	1	1	3
Delamination wic	minimize	0.45	0.65	1	1	3

Solutions for 3 combinations of categoric factor levels

Number	Feedrate	Spindle Speed	Tools	Thrust Force	Delamination w	Desirability	
1	238.68	2000.00	SPF	240.81	0.449984	0.915	Selected
2	248.38	2000.01	SPF	240.828	0.357939	0.913	
3	289.47	2000.01	SPF	240.903	0.127911	0.905	
4	306.34	2000.01	SPF	240.934	0.0987057	0.902	
5	310.55	2000.01	SPF	240.941	0.0965328	0.901	
6	312.85	2000.00	SPF	240.945	0.096155	0.901	

6 Solutions found

Number of Starting Points: 115 for 3 combinations of categoric factor levels

Figure 4.16: Constraints table

Figure shows the constraints table generated and the number of 115 combinations together with the selected parameters. Basically, the user is required to key in the goalsq for each parameters and the range of goals. As for this experiment, the goal is to minimize the thrust force and delamination within the experimental values obtained, therefore the specified range is keyed in. The second part shows the selected solutions out of 115 combinations. These selected parameters are based on the value of desirability. The function of desirability is used to calculate this value. From the figure, one could conclude that the chosen parameters are 238.68mm/min, 2000 rpm and the SPF tool. Based on the software’s prediction, the thrust force and delamination generated using these values would be 240.81 N and a delamination length of 0.449984mm.

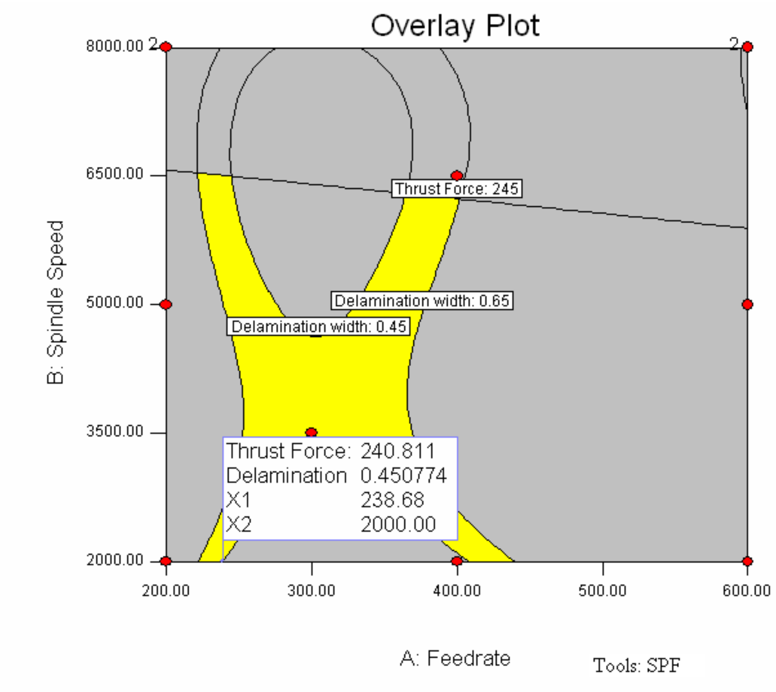

Figure 4.17: Overlay Plot for SPF drill

Figure 4.17 shows the overlay plot generated to obtain the optimal parameters. As seen, the flagged area shows the region of optimality. There are two colored regions namely grey and yellow. It is known that the yellow region is the desired area and the grey region is the undesired area. Therefore, this overlay plot shows users a graphical view of the optimal parameters which is directly interpreted from the constraints table.

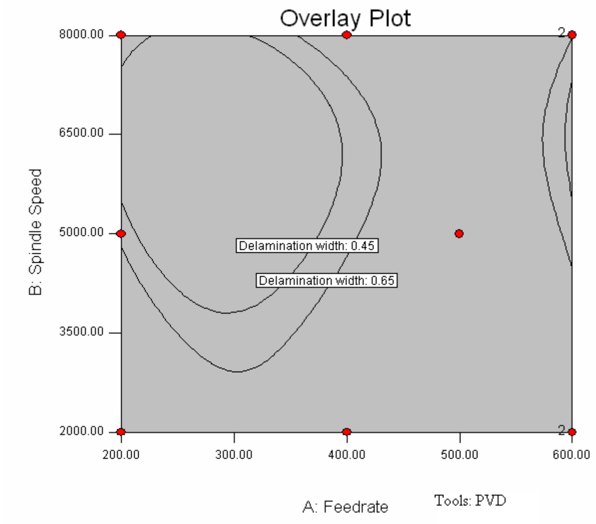

Figure 4.18: Overlay Plot for PVD drill

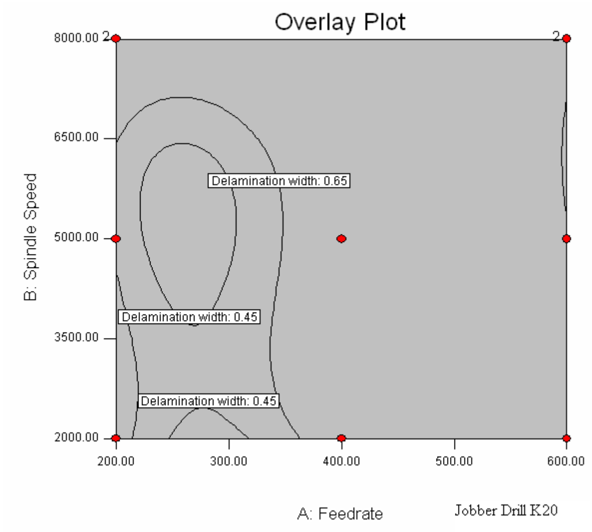

Figure 4.19: Overlay Plot for K20 drill

The two figures shown above are the overlay plots of the other two tools namely PVD and K20 respectively. Notice that these two tools do not possess a yellow region which is the desired region. Therefore, it could be concluded that these two tools are not favorable based on this experiment.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 INTRODUCTION

This chapter summarizes both the results obtained with the objective of this research. It will be based on the interpretation of data results taken during the experiment and then comparing the results obtained from the software. Theoretical review may be used as guidelines when interpreting and comparing the results. The final conclusion for these studies will be compiled and listed.

5.2. THE INCREASE OF SPINDLE SPEED, FEED RATE AND TOOL MATERIAL ON THE THRUST FORCE AND DELAMINATION

Based on previous studies, it was known that the thrust force generated will effect the delamination that will occur on the surface of the composite. Basically, a Kistler dynamometer and a charge amplifier have been used to record these generated forces during drilling. The graphs obtained have been interpreted and analyzed before presenting it in a proper manner. From the graph, one could interpret the variation pattern of the thrust force clearly with increasing feed rate.

5.3. THE OPTIMIZATION METHOD AND THE OPTIMAL PARAMATERS OBTAINED USING DESIGN EXPERT 7.1.4

The D optimal method was used to compute the optimal parameters. Users were only required to key in some basic data's related to the experiment before the software begins to compute the necessary solutions available based on the desirability function. The desirability is computed based on the goals of the experiment. This is mainly the need to minimize, or maximize the response and the desired range that we need. The optimal parameters for different types of composites are different based on its properties, characteristics and the thickness of the fiber, matrix layers.

5.4 CONCLUSION

The whole research presents an insight on the effects of spindle speed, feed rate and tool material on the delamination of CFRP. This research is also done to compute the optimal parameters for CFRP to avoid delamination the major defect that occurs on the surface of composites due to the heat generated by the tool rotation and due to the homogenous properties of the composites itself. Based on the research the thrust force generated increases with spindle speed, feed rate and type of tools used. SPF drill records the lowest thrust force generated compared to the other two tools used which is PVD multi layered and jobber drill K20.The delamination also increases with the feed rate and spindle speed used. The delamination value here differs from one tool to another. The SPF drill records the lowest delamination amongst the three tools. The optimum value for the feed rate computed using the software is 238.68mm/min for this research. The optimal value for the spindle speed is 2000 RPM for this research. Thrust force and delamination depends on each other. The higher the thrust force, the higher delamination could be noticed. Types of tools may also influence the thrust force generated and the delamination that occurs. The optimal parameters obtained from this research may differ from one composite to another based on the properties, characteristics and the thickness of the fiber, matrix layers of the composite used. The results from this research could be used in the near future to produce an almost delamination free drilling on composites especially if researchers use the same type of CFRP as used in this study.

5.5 RECOMMENDATION

Carbide drills are suitable to drill composites due to its properties. Coated carbide drills prove to drill better than solid carbide drills. The type of coating should be studied carefully before using it on a particular composite. Usage of SPF drill is recommended to drill Carbon Fiber Reinforced Plastics (CFRP) as it has been specially designed to drill these type of composites. Employing a lower spindle speed and feed rate which is suitable for the material will lower the thrust force and thus lower the effect of delamination.

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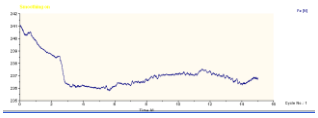
APPENDIX A

Tools and Material used in the Study

The drilled Unidirectional and Woven Graphite and Glass Cloth Faced Aramid Honeycomb Core Floor Panel Stock, BMS 4-20L

APPENDIX B

Thrust Force Graphs Generated by Kistler Dynamometer



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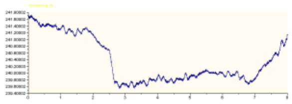

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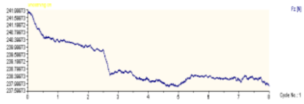

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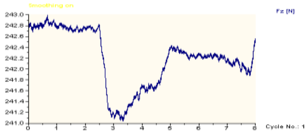

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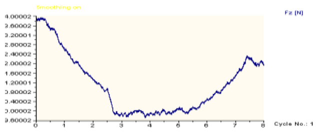

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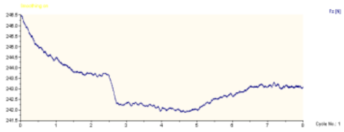

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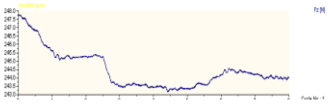

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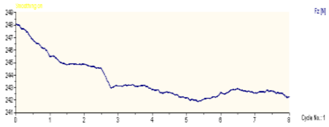

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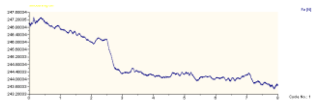

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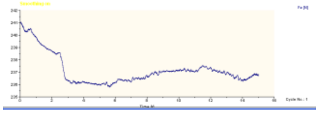

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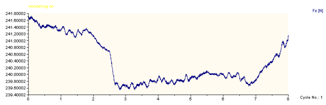

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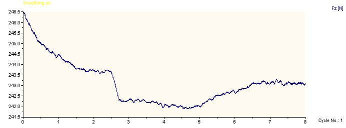

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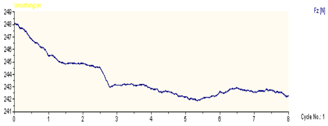

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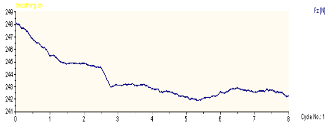

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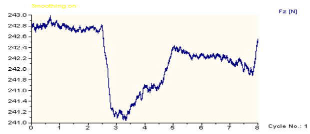

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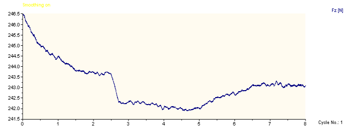

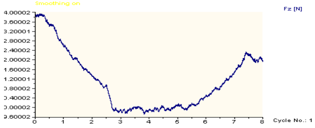

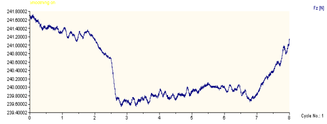

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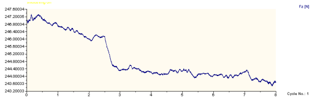
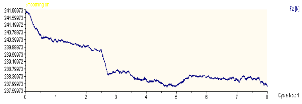
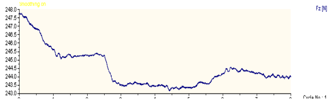
Hole 17

Hole 18



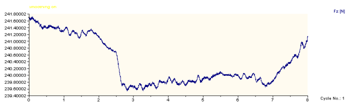


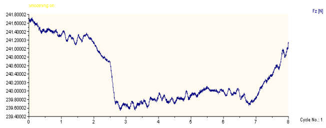


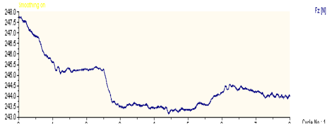
Hole 19

Hole 20

Hole 21



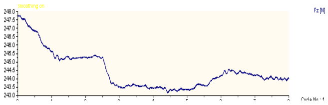


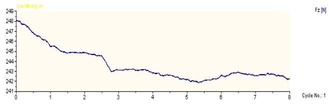


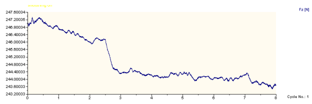
Hole 22

Hole 23

Hole 24







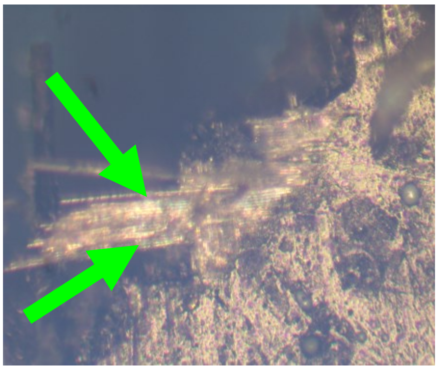
Hole 25

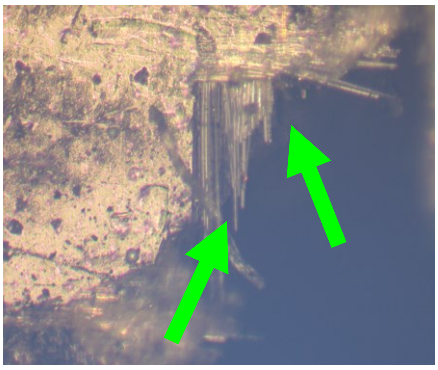
Hole 26

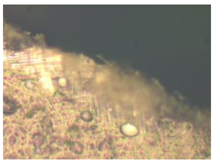
Hole 27

APPENDIX C

Delamination Seen Through Microscope







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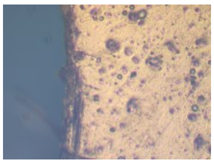

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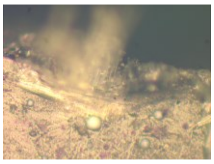
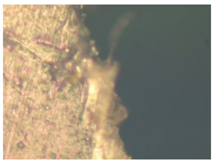


Hole 3



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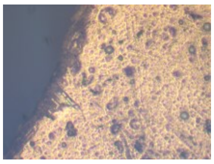

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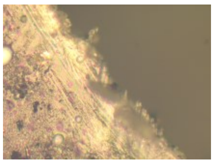

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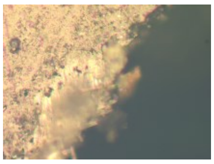

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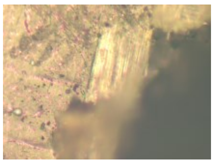

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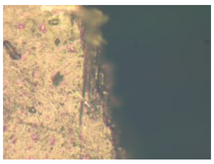

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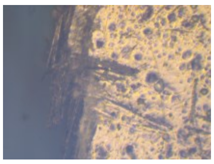

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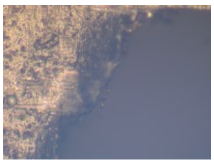
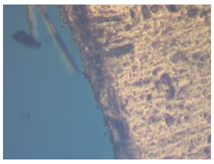


Hole 11

Hole 12

Hole 13



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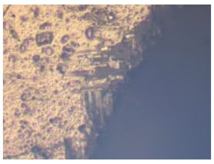

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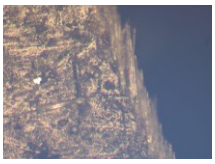

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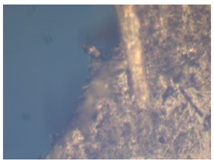

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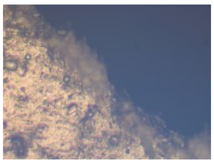

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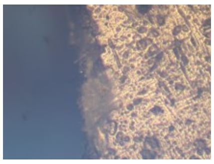

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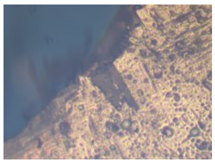

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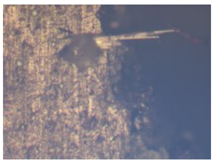

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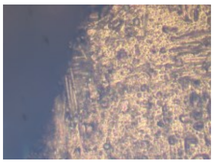

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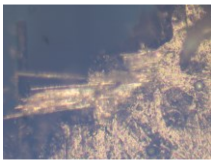

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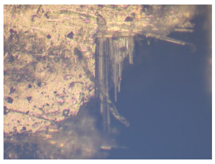

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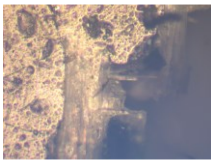

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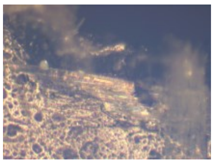

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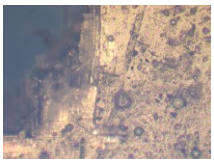

Hole 27