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A.P Dr. Faiz Ahmad

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UNIVERSITI TEKNOLOGI PETRONAS

DISSERTATION TITLE: DRILLING BEHAVIOUR OF FIBER COMPOSITES AND HYBRID FIBER COMPOSITES AT VARYING DRILLING PARAMETERS

By

MOHD AZUWAN BIN MAOINSER

The undersigned certify that they have read, and recommend to The Postgraduate Studies Programme for acceptance, for the fulfillment of the requirements for the degree stated.

Signature: ______________________________

Main supervisor: __A.P Dr. Faiz Ahmad__________

Signature: ___None______________________

Co-Supervisor: ___None______________________

Signature: ______________________________

Head of Department: ______________________________

Date: ______________________________

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PERAK

JANUARY, 2010

DECLARATION OF THESIS

Title of thesis	Drilling behavior of fiber composites and hybrid fiber composites at varying drilling parameters

I MOHD AZUWAN BIN MAOINSER

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Signature of Author

Permenent adress: No. 64, Bt 10 ½,

Jalan Kenangan, 42200, Kapar,

Klang, Selangor Darul Ehsan

Date : ___________________

Signature of Supervisor

Name of Supervisor

A.P. Dr. Faiz Ahmad

Date:

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ABSTRACT

Nowadays, fiber composites and hybrid fiber composites are widely used in aerospace industry to replace conventional materials due to weight to strength ratio and resistance to corrosion. These attractive properties resulted in increased machining fiber composites and hybrid fiber composites such as drilling. However, drilling fiber composites and hybrid fiber composites are very problematic compared to that with conventional materials because they are non-homogenous material. The problems encountered during drilling fiber composites and hybrid fiber composites include damage at hole interface, and damage at the drilled holes wall. The aim of this research was to investigate the influence of drilling fiber composites and hybrid fiber composites at various cutting speed, feed rate, different types and thickness of composites materials on damage factor (F_d), surface roughness (Ra), and surface microstructure. The fiber composites used in this research were glass fiber reinforced polyester (GRP) and glass fiber reinforced epoxy (GRE). The hybrid fiber composites used in this research were glass fiber and carbon fiber reinforced polyester (GCRP) and glass fiber and carbon fiber reinforced epoxy (GCRE). Fiber composites and hybrid fiber composites were fabricated using hand lay-up technique. Each composite was fabricated in two different thicknesses (3 mm and 10 mm). 55% fiber volume fraction (FVF) was used to fabricate the fiber composites and hybrid fiber composites to expedite the wear process of the drill bit. In order to maintain the properties of the composites for two different thicknesses, stepped structure design was used to fabricate the fiber composites and hybrid fiber composites. In this research the drilling parameters used to drill fiber composites and hybrid fiber composites were cutting speed (from 1000 rpm to 3000 rpm) and feed rate (from 0.05 mm/rev to 0.2 mm/rev). The damage of the drilled holes was evaluated based on three different evaluations; damage factor (F_d), surface roughness of the drilled holes (Ra) and surface microstructure. The damage factor (F_d) for GCRP (hybrid) fiber composites was lower than GRP fiber composites for 3 mm and 10 mm thickness. The damage factor (F_d) of

GCRE (hybrid) fiber composites was lower than GRE fiber composites for 3 mm thickness and 10 mm thickness. The surface roughness of GCRP (hybrid) fiber composites was lower than GRP fiber composites for 3 mm and 10 mm thickness. The surface roughness (Ra) of GCRE (hybrid) fiber composites was lower than GRE fiber composites for 3 mm thickness. The surface roughness (Ra) of GRE fiber composites was lower than GCRE (hybrid) fiber composites due to matrix smearing occurred during drilling of GRE fiber composites for 10 mm thickness. Scanning electron microscopy (SEM) evaluation showed that the damage occurred during drilling of fiber composites and hybrid fiber composites were due to fiber pull-out, fiber-matrix debonding and delamination. It can be concluded that drill GCRP (hybrid) fiber composites at 3 mm thickness with lowest cutting speed and feed rate were more suitable compare to GRP fiber composites. On the other hand, it was more suitable to drill GRE fiber composites at 10 mm thickness with lowest cutting speed and feed rate compare to GCRE (hybrid) fiber composites.

ABSTRAK

Hari ini, komposit fiber dan komposit fiber (hibrid) digunakan secara meluas di dalam industri aero-angkasa bagi menggantikan bahan konvensional disebabkan oleh nisbah berat kepada kekuatan dan rintangan terhadap karat. Sifat-sifat ini telah menarik perhatian yang telah menyebabkan peningkatan dalam pemesinan seperti penggerudian komposit fiber dan komposit fiber (hibrid). Walaubagaimanapun, penggerudian komposit fiber dan komposit fiber (hibrid) adalah sangat bermasalah berbanding bahan konvensional kerana mereka merupakan bahan yang tidak mempunyai sifat dasar yang sama. Masalah-masalah yang dihadapi semasa penggerudian komposit fiber dan komposit fiber (hibrid) termasuk kerosakan pada permukaan lubang dan kerosakan pada permukaan dinding lubang. Tujuan penyelidikan ini ialah untuk menyelidiki pengaruh perbezaan kelajuan pemotongan, kadar penggerudian, perbezaan jenis dan ketebalan bahan komposit dalam penggerudian komposit fiber dan komposit fiber (hibrid) terhadap faktor kerosakan (F_d), kekasaran permukaan (Ra) dan mikrostruktur permukaan. Komposit fiber yang digunakan dalam penyelidikan ini adalah glass fiber reinforced polyester (GRP) dan glass fiber reinforced epoxy (GRE). Komposit fiber (hibrid) yang digunakan dalam penyelidikan ini adalah glass fiber dan carbon fiber reinforced polyester (GCRP) dan glass fiber dan carbon fiber reinforced epoxy (GCRE). Komposit fiber dan komposit fiber (hibrid) diperbuat menggunakan teknik layuran tangan. Setiap komposit diperbuat di dalam dua ketebalan berbeza (3 mm dan 10 mm). 55% nisbah isipadu fiber (FVF) digunakan untuk memperbuat komposit fiber dan komposit fiber (hibrid) bagi mempercepatkan proses penghausan mata gerudi. Reka bentuk “stepped structure” digunakan dalam memperbuat komposit fiber dan komposit fiber (hibrid) bagi memastikan sifat-sifatnya dipelihara walaupun diperbuat dalam dua ketebalan yang berbeza. Dalam kajian ini, parameter yang digunakan untuk menggerudi kompit fiber dan komposit fiber (hibrid) adalah kelajuan pemotongan (daripada 1000 rpm sehingga 3000 rpm) dan kadar pemotongan (daripada 0.05 mm/rev sehingga 0.2 mm/rev). Kerosakan lubang yang digerudi dinilai dengan menggunakan

tiga penilaian yang berbeza; faktor kerosakan (F_d), kekasaran permukaan lubang yang digerudi (Ra) dan mikrostruktur permukaan. Faktor kerosakan (F_d) untuk GCRP komposit fiber (hibrid) adalah lebih rendah berbanding GRP komposit fiber untuk ketebalan 3 mm dan 10 mm. Faktor kerosakan (F_d) untuk GCRE komposit fiber (hibrid) adalah lebih rendah berbanding GRE komposit fiber untuk ketebalan 3 mm dan 10 mm. Kekasaran permukaan (Ra) GCRP komposit fiber (hibrid) adalah lebih rendah berbanding GRP komposit fiber untuk ketebalan 3 mm dan 10 mm. Kekasaran permukaan (Ra) untuk GCRE komposit fiber (hibrid) adalah lebih rendah berbanding GRE komposit fiber untuk ketebalan 3 mm. Kekasaran permukaan (Ra) untuk GRE komposit fiber adalah lebih rendah berbanding GCRE komposit fiber (hibrid) disebabkan oleh pelumuran "matrix" berlaku semasa penggerudian GRE komposit fiber untuk ketebalan 10 mm. Penilaian dengan menggunakan mikroskop pengimbas elektron (SEM) menunjukkan bahawa kerosakan berlaku semasa penggerudian komposit fiber dan komposit fiber (hibrid) adalah disebabkan oleh fiber tertarik keluar, pemisahan fiber-matrix dan pemisahan antara laminasi fiber. Dapat di simpulkan bahawa GCRP komposit fiber (hibrid) dengan ketebalan 3 mm, kelajuan pemotongan dan kadar pemotongan yang paling rendah adalah lebih sesuai untuk digerudi berbanding GRP komposit fiber. Sebaliknya, adalah lebih sesuai untuk menggerudi GRE komposit fiber dengan ketebalan 10 mm, kelajuan pemotongan dan kadar peenggerudian yang paling rendah berbanding GCRE komposit fiber (hibrid).

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Table of Contents

List of Tables

List of Figures

List of Abbreviations

FRC – fiber reinforced composites

SEM – scanning electron microscope

GRP – glass fiber reinforced polyester

GRE – glass fiber reinforced epoxy

GCRP – glass fiber and carbon fiber reinforced polyester

GCRE – glass fiber and carbon fiber reinforced epoxy

CNC – computer numerical control

UTM – universal testing machine

E-glass – electronic-glass

PAN – polyacrylonitrile

UP – unsaturated polyester

MEKP – methyl ethyl ketone peroxide

FVF – fiber volume fraction

HSS – high speed steel

PCD – polycrystalline diamond

GFREC – glass fiber reinforced epoxy composites

GFR – glass fiber reinforced

CFRPs – carbon fiber reinforced plastics

GFRP – glass fiber reinforced polyester

Gr/Bi – graphite/ bismalide

HSS-Co – high speed steel cobalt

CFRP – carbon fiber reinforced plastic

RPM – revolution per minute

NRCC – National Research Council Canada

List of Nomenclature

F_d – Damage Factor

Ra – Surface Roughness

D_{max} – Maximum diameter

D – Hole diameter

CHAPTER 1
INTRODUCTION

1.1 Background

Composites material consists of two or more materials that combined to form a useful engineering material having properties different from its constituents [1]. Nowadays, fiber reinforced composites (FRC) is a type of composite material used to substitute steel for certain parts in the automobile and aerospace industries due to its light weight, high strength and resistance to corrosion [2]. The application of FRC has increased due to particular properties such as high specific stiffness and strength, high damping, good corrosive resistance and low thermal expansion [3].

In recent years, huge enhancement in composites material technology was achieved in aerospace industries. The composite mass percentage used in aircraft is increasing from less than 10% usage in Vautour aircraft in 1970 and near to 20% usage in Airbus A-340 in 1990 [4]. Increasing composite mass percentage used in aircraft has increased the drilling of composites for airframe assembly using mechanically fastened joints. Mechanically fastened joints are considered as better joints compared to adhesive bonded joints. For example, disassembly of composites component will not damage the composite structure resulting in reduced the manufacturing cost, no preparation required before joining the composites components and easier joining inspection compared to adhesive bonded joints [5].

There are several ways of drilling of composites for airframe assembly using mechanically fastened joints including conventional drilling, ultrasonic drilling, laser drilling and water jet drilling proposed for a variety of economic and quality reasons [6]. However, conventional drilling is widely used in industry due to low cost and easier to handle compare to the others [7].

Composites materials are classified as polymer matrix composites (PMCs), metal matrix composites (MMCs) and ceramic matrix composites (CMCs) where PMCs are commercially used in composites industries due to its low weight and high strength [8]. It is important to understand the effect of drilling fiber composites on damage factor (F_d), surface roughness (Ra) and surface microstructure because it is a non-homogenous material as compared to drilling a metal (homogenous materials) [9]. Hence, this research is focused on the effects of drilling of fiber composites and hybrid fiber composites using different drilling parameters on damage factor (F_d), surface roughness (Ra) and surface microstructure of the drilled holes. The problems of drilling fiber composites are discussed in the following section.

1.2 Problem Statement

Drilling fiber composite affected its structure such as the damage around the drilled hole, the roughness of the hole wall, fiber pull out, fiber-matrix debonding and delamination [9]. The damages reduced the structural integrity of the material resulting in poor assembly tolerances and failure to perform for long term [10]. The damage can also cause unavoidable stress concentration at the mechanically fastened joints which influence the mechanical characteristics of the material around the hole [11]. The damages around the drilled hole, the roughness of the hole wall, fiber pull out, fiber-matrix debonding and delamination lead to 60% of all parts rejection during final assembly of an aircraft [12-15].

The quality of the drilled holes is greatly influenced by drilling variables such as feed rate and cutting speed [16]. Other factors that influenced the quality of the drilled holes are types of fiber and matrix used to fabricate the composites and the composite thickness. The quality of drilled holes is evaluated based on some characteristics such as damage factor (F_d), the surface roughness (Ra) measured in μm and the surface microstructure under scanning electron microscope (SEM).

1.3 Research Objectives

The objectives of this study is to investigate the influence of drilling fiber composites and hybrid fiber composites at various cutting speed, feed rate, different types and thickness of composites materials on damage factor (F_d), surface roughness (Ra), and surface microstructure. The sub-objectives of this study are:

1. To fabricate fiber composites and hybrid fiber composites in different thickness using stepped structure design, ensuring uniform process condition.
2. To study the damage around the hole by comparing the damage factor (F_d) between the fiber composites and hybrid fiber composites of different thickness after drilling using different cutting speed and feed rate.
3. To study the surface roughness (Ra) of the drilled hole wall between the fiber composites and hybrid fiber composites after drilling using different cutting speed and feed rate.
4. To study and compare surface microstructure of the drilled hole of the fiber composites and hybrid fiber composites using scanning electron microscopy (SEM).
5. To indentify suitable cutting speed, feed rate and thickness to drill fiber composites and hybrid fiber composites fabricated in this research.

1.4 Scope of Study

The coverage of this study was to fabricate fiber composite and hybrid fiber composites fabricated using hand lay-up technique. Reinforcement materials used in this research were woven glass fiber, woven carbon fiber while polyester resin and epoxy resin were used as matrix materials. Fiber composites fabricated in this research were glass fiber reinforced polyester (GRP) and glass fiber reinforced epoxy (GRE). Hybrid fiber composite fabricated in this research were glass fiber and carbon fiber reinforced polyester (GCRP) and glass fiber and carbon fiber reinforced epoxy (GCRE). The fiber composites and hybrid fiber composites were fabricated in 3 mm and 10 mm thickness using stepped structure design.

The density of fiber composites and hybrid fiber composites were measured and mechanical properties of fiber composites and hybrid fiber composites were tested. Then, fiber composites and hybrid fiber composites were drilled using different cutting speed (1000 rpm – 3000 rpm) and feed rate (0.05 mm/rev – 0.2 mm/rev). The quality of the drilled holes in fiber composites and hybrid fiber composites was studied and evaluated based on damage factor (F_d), surface roughness (Ra) and surface microstructure.

Finally, the findings of this research were used to determine the suitable drilling parameters used to drill fiber composites and hybrid fiber composites. They were also used to find out the suitable thickness of fiber composites and hybrid fiber composites laminates in drilling process.

1.5 Organization of the Thesis

This thesis is divided into five chapters. Chapter 1 introduced the research project under five sections; research background, problem statement, research objectives and scope of study. Background of this research mentioned about the importance of composite in industries, its application in industries, classification of composites and types of composite used in this study. Then the importance of drilling process, the examples of drilling and the effect of drilling on fiber composite and hybrid fiber composite were also elaborated in the background of the study. The problem statement further discussed the significance of studying on drilling behavior of composites. The objectives of this research were mentioned after the problem statement. Five objectives were listed to be studied in this research. The scopes of this research were explained well after the research objectives to tell the reader the limits of the study including the evaluation criteria of the drilled holes. Finally, the content of this research was briefly explained in the organization of the thesis.

Chapter 2 covered the critical review of related theories and literature survey in drilling fiber composites and hybrid fiber composites and associated problems. Reinforcement materials were described first, followed by matrix materials. The physical and mechanical properties of the materials were compared based on engineering composite handbook. Next, fabrication of fiber composite and hybrid fiber composite were explained briefly. The reason for choosing hand lay-up technique to fabricate fiber composite and hybrid fiber composite was explained in detail. Previous studies on drilling fiber composite and hybrid fiber composite and its effect on damage factor (F_d), surface roughness (Ra) and surface microstructure of the drilled holes were discussed critically in this section as guidelines for the current research direction.

In chapter 3, the details of experimental procedures are explained. The descriptions of the materials were obtained from the supplier and compared with that from literature. Fabrication of fiber composites and hybrid fiber composites are discussed where the stepped structure design was applied by using hand lay-up process. The steps of hand lay-up technique were shown in detail. Fiber composites and hybrid fiber composite density was measured using Mettler Toledo AX405. Universal Testing Machine (UTM 100KN), Zwick Roell H100 was employed to test the tensile properties and the procedure to handle this machine was briefly explained. Finally, the drilling steps and the drilling parameters on fiber composites and hybrid fiber composites were successfully explained in detail.

Chapter 4 discussed the results and related analysis. Physical properties and mechanical properties of polyester resin, epoxy resin, glass fiber, carbon fiber, fiber composites and hybrid fiber composites tested in the laboratory were compared and discussed. Then, the results obtained from the effect of drilling fiber composites and hybrid fiber composites on the damage factor (F_d) were discussed. The results were compared for composites drilled at varying feed rates (0.05 mm/rev, 0.1 mm/rev and 0.2 mm/rev) and cutting speed (1000 rpm, 2000 rpm and 3000 rpm) for all materials; GRP fiber composites with GCRP (hybrid) fiber composites and GRE fiber composites with GCRE (hybrid) fiber composites. Based on this comparison, the finest results of damage factor (F_d) were obtained. After that, the surface roughness (Ra) of the drilled holes were also compared and discussed. The surface microstructure of the drilled holes related to the damage factor (F_d) and surface roughness (Ra) of the fiber composites and hybrid fiber composites drilled holes were also elaborated.

Finally, the effects of drilling of fiber composite and hybrid fiber composite on damage factor (F_d), surface roughness (Ra) and surface microstructure were summarized in the conclusion section. Suitable materials and thickness of fiber composites and hybrid fiber composites to be used in drilling process were proposed. It also suggested suitable cutting speed and feed rate to be used in drilling process. Recommendations for future study were also stated here to enhance understanding of drilling behavior of fiber composites and hybrid composites.

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

In this chapter, related theories and literature of previous work will be discussed. Reinforcements and matrix materials are two important constituents to fabricate fiber composites and hybrid fiber composites. They are available in many forms. Section 2.2 will discuss the available reinforcement materials in industries and the reason for selecting E-glass fiber and carbon fiber as reinforcement's to develop fiber composite and hybrid fiber composites in this research. The advantages of using glass fiber and carbon fiber as reinforcements are also mentioned in this section to be used as reference. Matrix materials that are available in industry are discussed in section 2.3. The reason of selecting unsaturated polyester resin and epoxy resin are also discussed in the sub-chapter of this section. The advantages of using polyester and epoxy resin as matrix materials are also discussed. The fabrication technique that mostly used to fabricate composites in composites industries is discussed in section 2.4. In section 2.5, the drilling of composites is discussed together with the analysis of related works.

2.2 Reinforcement Materials

Reinforcement materials of composites are divided into two categories; fibrous reinforcement and particle reinforcement. The used of these materials are to increase the strength and/or stiffness of the composite materials [17 - 19].

In particle reinforced composites, the matrix bears the main load and the used of the particles is to obstruct the dislocation occurred in the matrix materials [18]. Particle is a non-fibrous reinforcement with shorter dimension compared to that of a fiber [19]. Therefore, it has lower resistance to fracture and could not stop the growth of incipient cracks that may lead to the composite's failure.

Fibers reinforcements are more effective in improving facture resistance compared to particle reinforcements because it has long dimension that can discourage the growth of incipient cracks. Fibers are fabricated in various forms; woven fabric, filament wound and braided structures. Table 2.1 shows the physical and mechanical properties of E-glass fibers and carbon fibers provided by the Composites Engineering Handbook [20]. The advantages of woven fabric compared to the other forms are; the strength and stiffness is available in two directions, easy to handle and have a good drape [21].

Table 2.1: Physical and mechanical properties of E-glass fiber and carbon fiber [20].

Fibers	Density (kg/m^3)	Modulus of Elasticity (GPa)	Tensile Strength (MPa)
E-glass	2580	75	3500
PAN-Based Carbon	1760	235	3200

2.2.1 Types of Fiber

Fibers are divided into two categories; natural fibers and synthetic fiber. Natural fibers are made from animals and plants while synthetic fibers are the man-made fibers [22]. Natural fiber is not used in this research due to the disadvantages of this fiber compared to synthetic fibers. The disadvantages are the surface of the fibers needs to be modified to be compatible with the matrix before fabricating composite materials, pressure application is needed during composite preparation, higher amount of moisture are absorbed during composite curing [23]. These disadvantages resulted in lower physical and mechanical properties of natural fibers and it is not suitable for drilling process compared to synthetic fiber.

The synthetic fibers that are commonly used in industrial applications are Kevlar fiber, carbon fiber and glass fiber. However, Kevlar fiber was not used in this research due to the high cost compared to glass fiber and carbon fiber. Glass fiber was used in this research due to lower cost compared to Kevlar and carbon fiber with moderate strength. The alternating carbon fibers in the hybrid fiber composites offer greater ability to control its structure compared to that of glass fiber reinforced composites [24].

2.2.2 Advantages of using Glass and Carbon Fiber as Reinforcement Materials

Glass fiber are the most common of all reinforcing fibers used for developing polymer matrix composites. There are several types of glass fiber with 4 different forms; roving, chopped strand, chopped strand mat, and woven roving. In this research E-glass fiber are used as the primary reinforcements. Code "E" in E-glass fiber stands for electrical [24]. 90% of the composites fabrication in aerospace industry used this fiber as reinforcements due to high resistant to corrosion, high strength-to-weight ratio, low thermal conductivity, longevity, adequate optical properties, low transportation costs, low installation costs, low resistance to flow, low electrical conductivity, dimensional stability, ease of installation, good energy savings and light in weight [25]. In this research, E-glass fiber in woven roving form is used as reinforcement material to produce fiber composites and hybrid fiber composites due to the advantages mentioned in section 2.2.

Carbon fiber is used as alternating fiber in hybrid fiber composites due to their advantages such as low density, high strength and stiffness (modulus) compared to glass fiber [26]. PAN-based carbon fibers have low cost and higher compression strength compared to pitch-based carbon fiber [27 and 28]. In this research carbon fiber in woven form is used as alternating fiber in developing hybrid fiber composites due to reasons above and those in section 2.2.

2.3 Matrix Materials

In fabricating fiber reinforced composites, reinforced material is embedded in matrix material. In this research polymer matrix was selected to fabricate fiber composites and hybrid fiber composites due to its simpler processing method and do not require very high temperatures and pressures for curing process compared to the metal matrix materials [18]. Another reason for choosing this matrix materials are: higher resistance to corrosion, higher damping factor, and higher flexibility in design, light in weight and higher strength and stiffness compared to metal matrix [24].

2.3.1 Classes of Polymeric Materials

In polymeric materials, two classes of resins are used to fabricate composites materials; thermoplastic resin and thermosetting resin [29]. Thermoplastic resins soften by heating and hardened by cooling repeatedly in the softened state [17]. This resin was not used in this research because it is unsuitable to be fabricated with woven fiber in hand lay-up technique.

Thermosetting resin is cured using heat, chemical, or other means to change it into a substantially infusible and insoluble material [17]. This resin has many advantages compared to thermoplastic resin such as higher softening temperature, better creep properties, more resistant to chemical attack cross links developed during curing process [5]. The physical and mechanical properties of unsaturated polyester resin and epoxy resin as used by Matthews and Rawlings [5] as a reference for this research.

Table 2.2 : Physical and mechanical properties of unsaturated polyester resin and epoxy resin [5].

Materials	Density (kg/m^3)	Young's Modulus (GPa)	Tensile Strength (MPa)
Polyester	1.1-1.5	1.3-4.5	45-85
Epoxy	1.1-1.4	2.1-6.0	35-90

This is the main factor for selecting this resin in fabricating fiber composites and hybrid fiber composites in this study. Furthermore, Muzzy [30] mentioned that many high performance fiber composites were fabricated by thermosetting matrices. In this study, two types of thermosetting resin were used to fabricate fiber composites and hybrid fiber composites: epoxy resin and polyester resin. The reasons for selecting these two resins are mentioned in the section 2.3.2.

2.3.2 Advantages of using Polyester and Epoxy Resin as Matrix Materials

Unsaturated polyesters (UP) are generally pale yellow colored oligomers. It is widely used due to the ability of curing with catalyst at room temperature with ambient conditions and its low cost but their high shrinkage during curing (>7%) may lead to poor surface finish of the composites [31]. There are many types of catalysts suitable with this resin such as methyl ethyl ketone peroxide (MEKP), acetyl acetone peroxide, cyclohexanone peroxide and benzyl peroxide [32]. In this research, the catalyst used was methyl ethyl ketone peroxide (MEKP). The advantages of using this resin as matrix material for composites are improved tensile and flexural strength values of the composites after applying extensive annealing treatment [32 and 33].

Epoxy resin was another type of polymer matrix used in this research to fabricate fiber composites and hybrid fiber composites. This resin is mixed with curing agents or catalysts before curing process. It is cured above 40°C to 60°C or dissolved in an inert solvent for curing at room temperature due to high viscosity and to get better composites performance [33]. Other advantages of this resin are: good resistance to most chemicals, good resistance to creep and fatigue, high strength and good electrical properties [34]. However, it is more expensive compared to the polyester resin.

2.4 Composites Fabrication Technique

There are several ways to fabricate fiber composites and hybrid fiber composites: compression molding, pultrusion, filament winding, spray-up and hand lay-up technique, depending on the design and the constituent materials used [34]. The advantages of fabricating fiber composites and hybrid fiber composites using thermosetting resin as matrix materials compared to other matrix include easy to handle due to liquid state of the resin system, enhanced fiber wetting resulting in less voids and porosity, less heat and pressure required during processing and simple low-cost tooling system [34].

The first technique to be discussed here is compression molding. This technique was used to fabricate fiber composite with Class A surface. The overall percentage of the fiber volume fraction (FVF) in Class A surface is limited to 30% to optimize the smoothness of the surface [34]. So, this technique is not suitable for this research due to the FVF used to fabricate fiber composites and a hybrid fiber composite is 55%. Furthermore, the cost of the mold used to fabricate the composites material is very expensive and not worth to produce small amounts of sample.

The next technique is pultrusion. This is a low cost technique that can produce high volume of samples. In this technique, unidirectional fibers that impregnated into the resin are pulled through a die to fabricate the composite parts [34]. This technique is not suitable for this research due to multidirectional fiber used to fabricate fiber composites and hybrid fiber composites in this research.

The third technique discussed here is filament winding. In this technique, fibers are impregnated into thermosetting resin and wound over a rotating mandrel at desired angle [34]. It is only used to produce closed or convex structures. This technique is not suitable to be used in this research because fiber composite and hybrid fiber composite produced are open structures.

The fourth technique is spray-up. This technique used spray gun to apply the mixture of resin and short fiber reinforcements with capacity 1000 to 1800 lb materials delivered per hour on the open mold structure [34]. It is not suitable because long fiber reinforcements are used to fabricate fiber composites and hybrid fiber composites in this research. Furthermore, it cannot be used to control the fiber volume fraction (FVF) required to fabricate the composite materials.

The final technique discussed here is hand lay-up. This technique is very flexible as it allows the user to place different types, size and thickness of fabric materials in fabricating composite materials [34]. Based on previous statement, this is the most suitable technique to fabricate fiber composites and hybrid fiber composites with stepped structure design in this research compared to other techniques discussed previously. In addition, the cost of this technique is lower compared to other techniques and it is suitable to produce sample in small volume [34].

2.5 Drilling of Composite Materials

Drilling composite materials is more practical compared to placing a hole during molding due to shrinkage problem during processing. Conventional drilling is widely used in industry due to easy handling and low cost compared to the other technique such as ultrasonic drilling, laser beam drilling and water jet drilling [7]. There are many types of conventional drilling machine such as hand drill, bench drill and computer numerical control (CNC) drill. CNC drill was used in this research because it can be used to control feed rate compared to other types of drilling.

Accurate holes dimension and surface roughness are very important in drilling fiber composites and hybrid fiber composites to allow precision fitting of components into an assembly [35]. In this study, solid carbide drill was used together with CNC machine to drill fiber composites and hybrid fiber composites because it allows more holes to be drilled compare to high speed steel (HSS) drill and lower in cost compare to polycrystalline diamond (PCD) drill [36 - 41].

2.5.1 Drilling of Fiber Composite

Research on drilling of fiber composites started since 1970. Some authors wanted to find the correlation between drilling parameters such as cutting speed and feed rate and the drilled hole quality in terms of damage factor (F_d) and surface roughness. Others wanted to find the effects of drilling different thickness and types of composites on the drilled hole quality.

El-Sonbaty et.al [3] studied on the drilling of glass fiber reinforced epoxy composites (GRE) using different cutting speed (from 218 rpm to 1850 rpm), feed rate (0.05 mm/rev to 0.23 mm/rev) and drill size (8 mm to 13 mm). The GRE was made up of different fiber volume fraction (from 0% to 23.7%) of chopped-strand mat having 8.5 mm thickness. They concluded that the surface roughness of GRE was improved by increasing cutting speed and fiber volume fraction (FVF). The surface roughness of GRE with lower FVF is higher at lower feed rate compare to higher feed rate. However, the surface roughness of GRE with higher FVF is lower at lower feed rate compared to that at higher feed rate.

In [16], Khashaba performed drilling operation on different type, thickness and FVF of glass fiber reinforced (GR)-thermoset composites. The drilling variables used in his study were cutting speed (from 455 rpm to 1850 rpm) and feed rate (0.03 mm/rev to 0.3 mm/rev). They concluded that the delamination of the woven/epoxy composites decreased with increasing cutting speed. However, the delamination of woven/epoxy composites increased with increasing feed rate due to increasing in thrust force. The delamination of woven/polyester composites was higher compared to woven/epoxy composites when drilling at the same feed rate.

Davim and Reis [43] performed the drilling on carbon fiber reinforced plastics (CRP) with 55% FVF using different cutting speed (from 1000 rpm to 2000 rpm) and feed rate (0.04 mm/rev to 0.15 mm/rev). The CRP was made up of 16 layers of fiber with 0/90° orientation having 4 mm thickness. They concluded that higher cutting speed and feed rate resulted in higher damage factor (F_d).

Abrao et. al [44] have drilled glass fiber reinforced epoxy resin laminates. The composites were made up of 50% weight of woven glass fiber with an orientation of 0/90° having 2.5 mm thickness. The composites are drilled using different cutting speed (from 1751 rpm to 2737 rpm) and feed rate (from 0.05 mm/rev to 0.20 mm/rev). They concluded that the damage on top surface increased considerably with feed rate and moderately with cutting speed.

Davim et al. [45] have drilled glass fiber reinforced polyester (GRP). The GRP's were made of 65% FVF of glass fiber having 22 mm thickness. The GRP's are drilled using different cutting speed (from 3501 rpm to 5475 rpm) and feed rate (0.05 mm/rev to 0.2 mm/rev). They concluded that the damage factor (F_d) increased as the cutting speed and feed rate increased. However, the surface roughness (Ra) increased as the feed rate increased and decreased as the cutting speed increased.

It can be concluded that, damage factor (F_d) and surface roughness (Ra) are important in measuring the level of damage occurred at the drilled holes when drilling at different cutting speed and feed rate. Both measurements are used to evaluate the quality of the of the drilled holes surface. Most of the studies show that increasing cutting speed and feed rate will increase the damage factor (F_d) and surface roughness (Ra) of the drilled holes when drill fiber composites at the FVF higher than 23%.

2.5.2 Drilling hybrid fiber composites

Hybrid composite of contains at least two distinct types of matrix or reinforcement. In this research, the hybrid fiber composites consist of glass fiber and carbon fiber embedded in polyester resin or epoxy resin. The combination of glass fiber and carbon fiber with polymer matrix in hybrid fiber composites produced a composite with low cost due to glass fiber and better mechanical properties due to carbon fiber [46]. The studies on drilling of hybrid composites have focused on finding suitable drill bit to drill the hybrid composites.

Ramulu et. al [47] performed a study on drilling of hybrid composites consists of graphite/bismalide (Gr/Bi) and titanium stacks having 3.1 mm thickness. The Gr/Bi was made up of multidirectional graphite fiber with 2 mm thickness. They drilled the hybrid composites using three different drill bit; high speed steel (HSS), high speed steel cobalt (HSS-Co) and solid carbide drill. They concluded that minimal damage was produced at the Gr/Bi composites interface using carbide drill compare to that using HSS and HSS-Co due to higher hardness of carbide drill.

Luis et.al [48] performed a study on drilling of hybrid fiber composites consist of 25% carbon/epoxy and 75% glass/epoxy. They drilled using 5 different drill bit; HSS twist drill, carbide twist drill, carbide brad drill, carbide dagger drill and carbide special step drill. They conclude that using carbide twist drill have lower damage factor (F_d) compare to the other drill bits. Based on these two researches, carbide twist drills were used to drill fiber composites and hybrid fiber composites in this research.

In conclusion, no significant studies found on drilling hybrid fiber composites at different thickness, cutting speed and feed rate especially in using synthetic fiber with polymer matrix. This research focus on the study on drilling hybrid fiber composites using solid carbide drill bit.

2.6 Drilled Hole Quality Classification

Drilling of fiber composites and hybrid fiber composites at different drilling parameters, different materials and its thickness resulted in varying quality of the drilled holes. In this research, the quality of the drilled holes was measured in terms of damage factor (F_d), surface roughness (Ra) and microstructural observation. The following section discussed on each quality criterion.

2.6.1 Damage factor (F_d)

Damage factor (F_d) was used to measure the entry delamination and exit delamination as shown in Figure 2.1. It is a ratio between the maximum diameter of the damage zone and the hole diameter as shown in Eq. (2.1) [43].

$$F_d = \frac{D_{max}}{D} \qquad (2.1)$$

F_d = Damage factor

D_{max} = maximum diameter of the damage zone

D = hole diameter

Davim and Reis [43] used shop microscope Mitutoyo TM-500 to measure the damage around the holes of the carbon fiber reinforced plastics (CRP). They used Eq. (2.1) to determine the damage factor (F_d). Figure 2.1 illustrates the methods used to determine the damage factor (F_d).

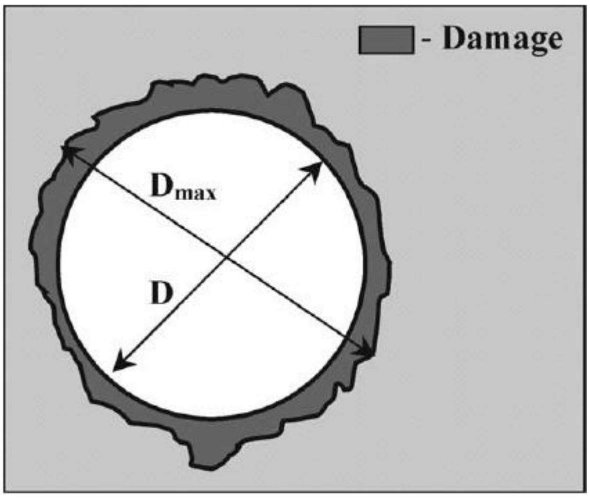
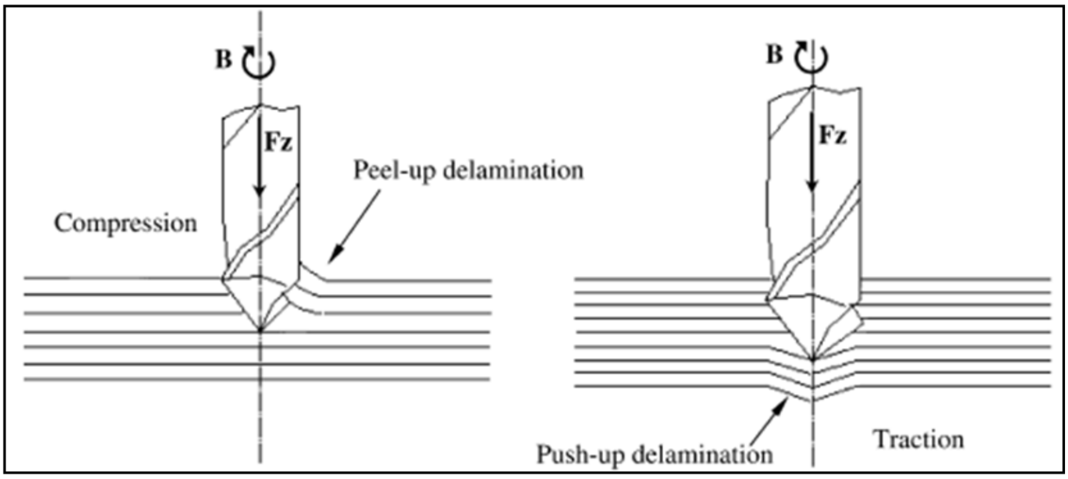


Figure 2.1: Methods used to measure the damage factor (F_d) of the drilled holes [43].



(a) (b)

Figure 2.2: (a) Entry delamination (Peel-up delamination) (b) Exit delamination (Push-up delamination) [50].

Delamination is the separation of two laminate plies at their interface [49]. Two types of surface delamination occurred during drilling of fiber composites and hybrid fiber composites are entry delamination or peel-up delamination and exit delamination or push-out delamination. These delaminations happened when the thrust force exceeded the interlaminar shear strength of the laminates. Figure 2.2 shows the mechanisms of entry delamination and exit delamination.

Other researcher like Isik and Ekici [51] also using the same technique and machine (MITUTOYO TM-500 digital indicator microscope) to observe the deformation at the hole entrance and exit.

Ramon et.al [52] also employed the same technique and machine (Mitutoyo TM 500 microscope) with 30x magnification and 1 μm resolution to measure the damage around the holes. Tsao and Hocheng [53] utilized the same technique but with different machine (Ultrasonic C-Scan) to measure the damage around the holes.

2.6.2 Surface Roughness (Ra)

Roughness of the drilled holes occurred due to surface irregularities resulted from the various machining condition such as cutting speed and feed rate. It was measured in terms of average surface roughness (Ra). The higher surface roughness resulted in lower contact area between the fastener and the hole surface area compared to lower surface roughness. So, it is indirectly affecting the load bearing strength of the holes.

Sonbaty et.al [3] performed drilling on glass fiber reinforced (GR)/epoxy composites. They used Taylor Hobson Surtronic 3+ to measure the surface roughness (Ra). They concluded that surface roughness decreased as the drill diameter increased at high feed rate due to increase cutting temperature that lead to matrix deformation resulted to smooth cutting surface. Low feed rate increased the temperature between the drill and the materials resulted in fuzzy and rough cut on the fiber that may lead to the rougher surface of the drilled holes.

Davim et.al [45] drilled glass fiber reinforced plastics (GRP). They used

Hommeltester T1000 profilometer to evaluate the surface roughness (Ra) of the drilled holes. They concluded that surface roughness (Ra) increased as the feed rate increased.

Ramulu et.al [47] performed surface roughness (Ra) measurement on drilled holes using Surfanalyzer System 4000. They mentioned that the surface roughness (Ra) of the drilled hole occurred due to the matrix being destroyed by the accumulated heat around the tool edge. They found that surface roughness (Ra) decreased at high spindle speed due to matrix smearing and surface roughness (Ra) increased due to fiber pull-out from the matrix materials.

Chambers and Bishop [55] drilled carbon fiber polymer matrix composites. They used surface profilometer to measure the drilled holes. They concluded that carbon/epoxy composites have rougher surface at low feed due to generated temperature resulted in burnt resin.

2.6.3 Surface Microstructural Damage

Scanning electron microscopy (SEM) is used to evaluate the damage occurred at the surface of the drilled holes at higher microstructure level. It is used to investigate the microstructural changes and damages such as matrix cracking, fiber matrix debonding and fiber pull-out. These damages lead to higher surface roughness (Ra) of the drilled holes wall. The following section discussed briefly for each of the possible microstructural damage occurring at the drilled holes.

2.6.3.1 Fiber-Matrix Debonding

Fiber-matrix cracking occurred when matrix cracking approaches neighboring fibers. It happens to strong fibers with weak interface [56]. It occurrs during drilling due to intense drilling stress on the fiber composites [57]. Extensive fiber-matrix cracking may lead to delamination of composites due to increasing impact energy and resulted in reducing the interface strength.

2.6.3.2 Matrix Cracking

Matrix cracking observed during drilling of fiber composites and hybrid composites are due to the brittle fracture behavior of thermosetting polymer. It is also known as intralaminar cracking [57]. Formation of this damage is influenced by the internal and external geometries of the laminates including ply fiber orientations, ply thickness, and ply stacking sequence [57].

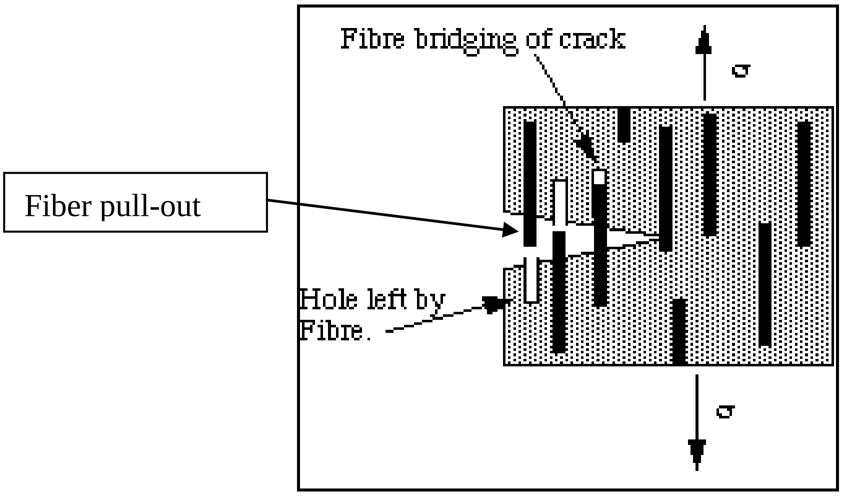


Figure 2.3: Fiber pull-out.

2.6.3.3 Fiber Pull-Out

Matrix cracking may lead to the fiber bridging where no more matrix covered on the fiber. When the crack extend, the fiber bridging will be broken resulted in fiber pull out (Figure 2.3) [58]. This problem can also happen to brittle or discontinuous fiber embedded in a tough matrix [59].

CHAPTER 3
METHODOLOGY

3.1 Introduction

This chapter will discuss on the experimental material used in this study, fabrication of fiber composites and hybrid fiber composites, fiber composites and hybrid fiber composites testing on physical and mechanical properties, drilling of fiber composites and hybrid fiber composites and observation on the effect of drilling fiber composites and hybrid fiber composites at different drilling parameters in terms of damage factor (F_d), surface roughness (Ra) and surface microstructure. Below is the flow chart of the methodology.

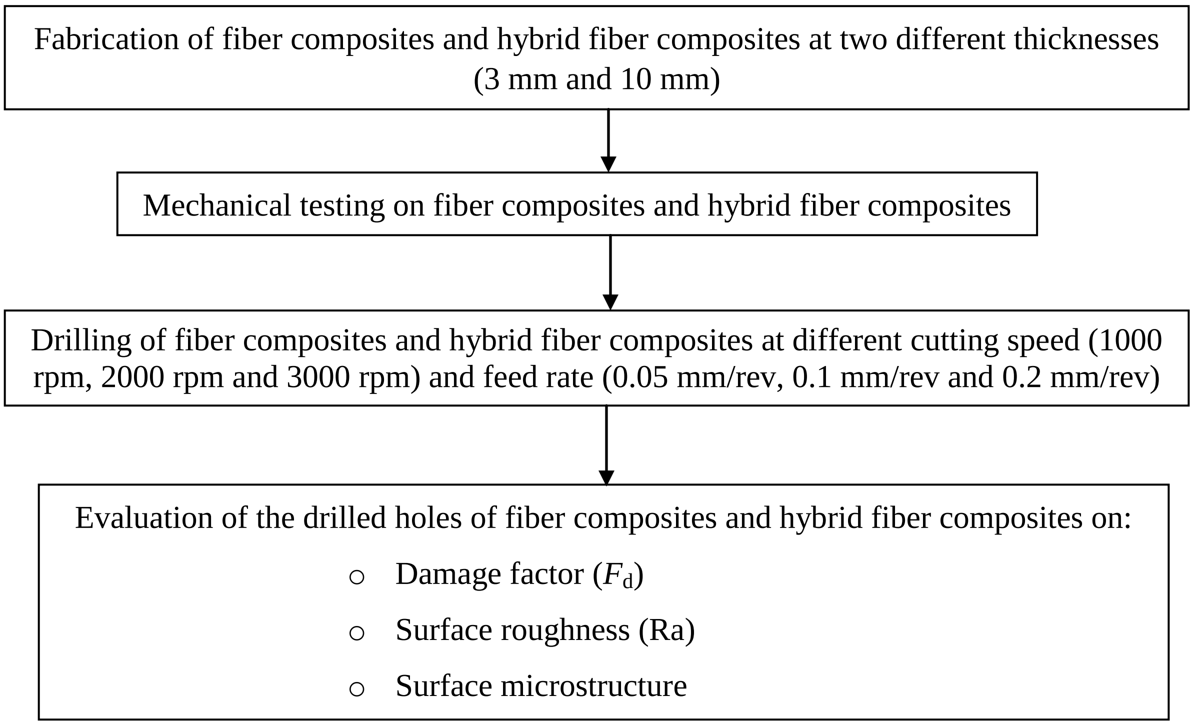


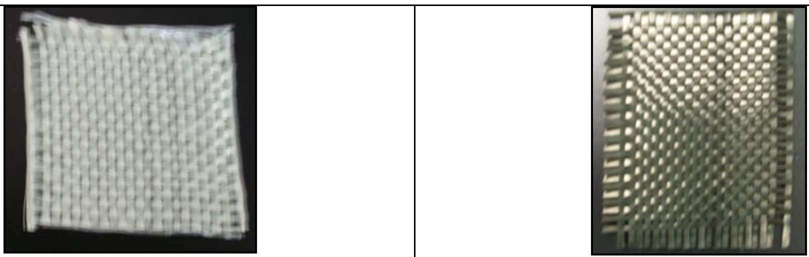
Figure 3.1: Flow chart of this research.

3.2 Experimental Materials

Glass fiber and carbon fiber were used as the reinforcement materials while polyester resin and epoxy resin were used as the matrix materials to fabricate fiber composites and hybrid fiber composites in this study. Physical and mechanical properties of the reinforcements and matrix materials were mentioned here. Areal density and density were classified as the physical properties of the reinforcements while tensile strength and modulus of elasticity were classified as mechanical properties of the reinforcements. For matrix materials, the density was classified as physical properties while tensile modulus and tensile strength were classified as mechanical properties.

3.2.1 Fibrous Materials

Two types of woven fiber, E-glass fiber, Figure 3.2(a) and carbon fiber, Figure 3.2(b) were used as reinforcement materials to fabricate fiber composites and hybrid fiber composites in this research. Both fibrous materials were supplied by S&N Chemicals Sdn. Bhd. All composites fabricated were of orientation of 0/90 degrees.



(a) (b)

Figure 3.2: (a) E-glass woven fiber, (b) carbon woven fiber used in this study.

Physical and mechanical properties of both fibrous materials employed are listed in Table 3.1.

Table 3.1: Physical and mechanical properties of fibrous materials used in this study [60].

Materials	Areal density (kg/m^2)	Density (kg/m^3)	Tensile Strength, σ (MPa)	Modulus of Elasticity, E (GPa)
E-glass Fiber	0.385	2500	2400	73
Carbon Fiber	0.250	1800	4500	251

3.2.2 Polyester Resin and Epoxy Resin

Thermosetting resins, polyester and epoxy resin supplied by S&N Chemicals Sdn. Bhd were to fabricate fiber composites and hybrid fiber composites. The physical and mechanical properties of the resin matrices are listed in Table 3.2. Methyl ethyl ketone peroxide (MEKP) was used as a hardener for polyester resin and curing time for polyester resin composite was 8 hours under ambient temperature. In order to get the best results in curing polyester resin, weight ratio of 50:1 (Polyester: MEKP) was used to fabricate fiber composites and hybrid fiber composites and which resulted in good cured composites.

For epoxy based composites, amine was used as hardener; both fiber composites and hybrid fiber composites were cured in an oven at $60^{o}C$ temperature for 6 hours.

Table 3.2: Physical and mechanical properties of matrix materials used in this research [60].

Materials	Density (kg/m^3)	Tensile Modulus, E (GPa)	Tensile Strength, σ (MPa)
Polyester Resin	1300	2.09	41.8
Epoxy Resin	1200	3.83	83.6

3.3 Fabrication of Fiber Composites and Hybrid Fiber Composites

Stepped structure design is used for fabricating fiber composites and hybrid fiber composites and hand lay-up technique was used to fabricate both types of composites.

3.3.1 Concept of Designing Stepped Structure

The reason of selecting stepped structure as a design to fabricate fiber composites and hybrid fiber composites in this study are to have consistent properties for both composites by curing the different laminate thickness in the same condition and temperature. For 3 mm thickness, 9 laminates of fiber were cut into 340 mm x 400 mm dimension. For 10 mm thickness, 20 laminates of fiber were cut into 170 mm x 400 mm dimension and added on top of the 9 laminates of fiber at one side. Both thickness were fabricated and cured in one mold to produce different thickness of fiber composites and hybrid fiber composites with consistent properties.

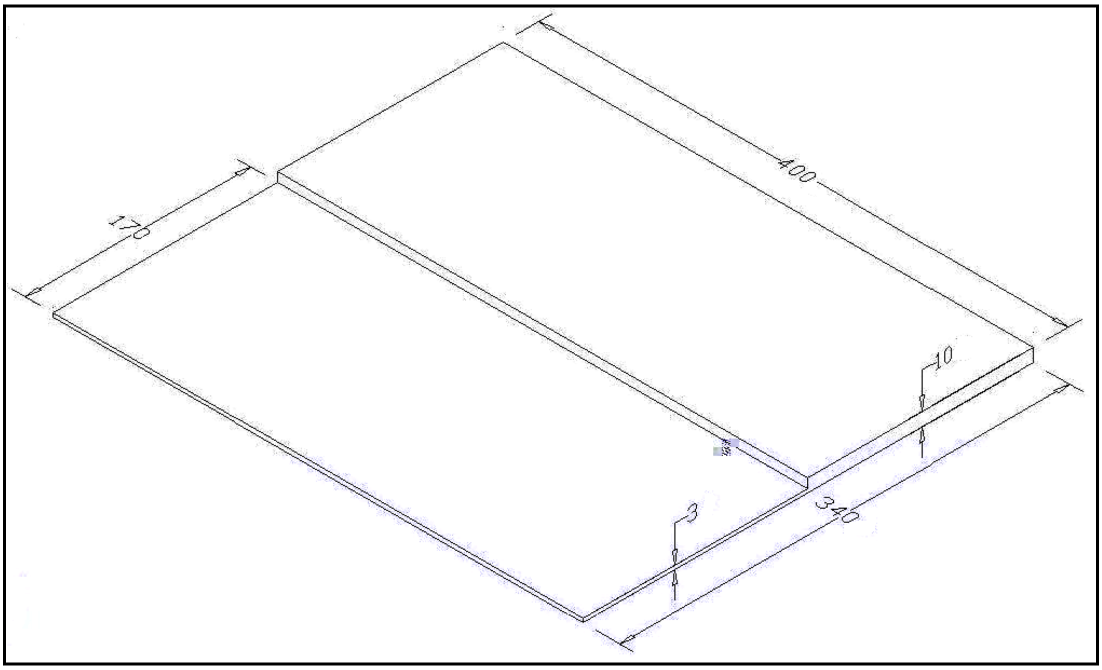


Figure 3.3: Stepped structure design.

3.3.2 Fiber Content

Fiber composites were fabricated by reinforcing 55% fiber volume fraction (FVF) glass fiber in each polyester and epoxy. For hybrid fiber composites, a combination of glass and carbon fiber were used. To maintain 55% FVF of fiber in hybrid fiber composites fabrication, 35% FVF of glass fiber and 20% FVF of carbon fiber were used. The percentage of fiber used in fabricating hybrid fiber composite using polyester and epoxy resin is shown in Table 3.3.

Table 3.3 : FVF for fiber composite and hybrid fiber composite.

	Fiber composite	Hybrid fiber composite	
FVF / Matrix	E-glass fiber (%)	E-glass fiber (%)	Carbon fiber (%)
Polyester	55	35	20
Epoxy	55	35	20

Table 3.4 : Numbers of layers and stacking sequences for 3 mm and 10 mm thickness of fiber composite and hybrid fiber composite samples.

Materials	Thickness	No. of layers		Stacking sequences
		E-glass fiber		
Fiber composite	3mm	9		$(0/90)_g - (0/90)_g$
	10mm	20		$(0/90)_g - (0/90)_g$
Material	Thickness	E-glass fiber	Carbon fiber	Stacking sequences
Hybrid fiber composite	3mm	5	4	$(0/90)_g - (0/90)_c - (0/90)_g$
	10mm	20	20	$(0/90)_g - (0/90)_c - (0/90)_g$

Table 3.4 shows a total of 29 layers of fibers were used to fabricate stepped structure for 3 mm and 10 mm thickness fiber composites; 9 layers of 340 mm x 400 mm were used to produce the 3 mm thickness section and 20 layers of dimension 170 mm x 340 mm were used to produce 10 mm thickness. The dimensions section of the composites structure were selected to provide suitable distance between drilled holes to avoid drilling stress from damaging the composites' structure.

For hybrid fiber composite, these 29 layers consist of alternate layers of glass fiber and carbon fiber of the same dimensions. The hybrid fiber composites were fabricated to compare the properties and the results of the drilled holes with fiber composites

3.3.3 Hand Lay-up Technique

Hand lay-up technique was used for fabrication of fiber composites and hybrid fiber composites from polyester and epoxy. The following steps were involved in hand lay-up technique. A schematic of hand lay-up process is illustrated in Figure 3.4.

A mold with the dimension of 400 mm x 340 mm x 15 mm was developed to fabricate fiber composites and hybrid fiber composites. The selected dimension was to ensure certain numbers of holes were drilled in each thickness with a specified distance to avoid stresses to the neighboring hole.

Polyester resin was homogenized with hardener methyl ethyl ketone peroxide (MEKP) in the ratio of 50:1 to fabricate both fiber composites and hybrid fiber composites. Epoxy resin was homogenized with amine in the ratio of 10:6 in weight to fabricate fiber composites and hybrid fiber composites.

29 layers of glass fiber were used to fabricate the stepped structure of 3 mm and 10 mm thickness. 9 layers of 340 mm x 400 mm were used to make 3 mm thickness and 20 layers of dimension 170 mm x 340 mm were used to fabricate the thickness of 10 mm. For hybrid fiber composite fabrication, these 29 layers consist of alternate layers of glass fiber and carbon fibers of the same dimension were used.

Finally, the polyester based fiber composites or polyester based hybrid fiber composites were cured for 8 hours at ambient temperature. For epoxy based fiber composites or epoxy based hybrid fiber composites was cured at 60°C in the oven for 6 hours.

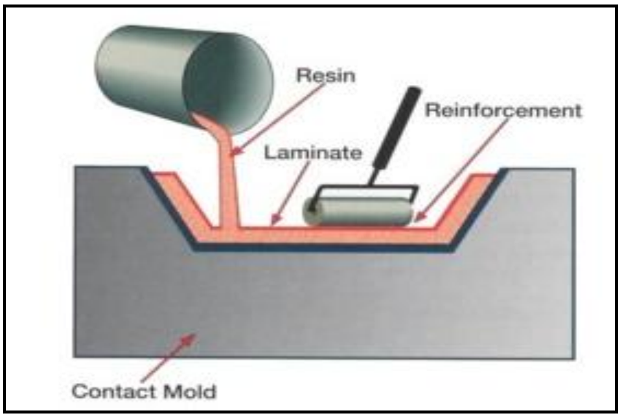


Figure 3.4: Schematic of hand lay-up technique used in fabrication of fiber composites and hybrid fiber composites.

3.4 Physical and Mechanical Properties Measurements

Density was measured to study the physical properties of fiber composites and hybrid fiber composites. The mechanical properties of fiber composites and hybrid fiber composites were tested using Universal Testing Machine (UTM 100 KN), Zwick Roell H100.

3.4.1 Density Measurement

The density of the fiber composites and hybrid fiber composites was measured using Mettler Toledo AX405 based on Test Method A in ASTM D0792. The specimens were cut to the dimension of 1x1x1 cm^3. Averages of 5 readings were taken to get the accuracy of the data.

3.4.2 Mechanical Testing

The mechanical properties of fiber composite and hybrid fiber composites were measured using Universal Testing Machine (UTM 100 KN), Zwick Roell H100 with Workshop Release Software at room temperature. The upper clamp was connected to the load cell and the lower clamp was connected to the drive motor. Extensometer was used together with the machine to find the strain value of the materials. The mechanical testing was run according to ASTM D3039.

3.4.2.1 Procedure

A diamond abrasive cutter was used to cut the dimension to 25 mm wide x 250 mm long. The specimen was gripped 10 mm from the top and 10 mm from the bottom of the specimen. Emery cloth was attached at the gripped part of the specimen to avoid the slippage of the specimen. Extensometer was attached in the middle of the specimen. The test was run at the speed of 100 mm/min. The data presented in this investigation was based on accuracy of five tests.

3.5 Drilling of Fiber Composite and Hybrid Fiber Composite

MTAB Denford CNC Milling Trainer (XLMILL) machine was programmed using CAD-CAM software to drill fiber composites and hybrid fiber composites. The CNC machine has the ability to control feed rate compared to conventional drilling machine. The maximum cutting speed of the machine is 3000 rpm. The maximum feed rate of the machine was 1500 mm/min which is equal to 0.2 mm/rev. Fiber composites and hybrid fiber composites were cut into 150 mm wide and 86 mm long due to the dimension of working table surface of the machine. The machine was installed with safety guards to protect user from hazards and dust when drilling fiber composites and hybrid fiber composites. The drilling parameters are summarized in Table 3.5.

Mitsubishi solid carbide drill bit (MZE type) was used together with CNC drilling machine to drill fiber composites and hybrid fiber composites. The drill bit was selected because it can produce better holes than HSS drills at a relatively low cost compared to polycrystalline diamond (PCD) drills [36 - 40]. A 5 mm diameter drill was selected in this research due to limitations of 3D non-contact machine in examining the damage radial distance of the drilled holes. The L/D ratio of the drill bit was 2:1 and was considered suitable to drill a hole in a laminate of 10 mm thickness.

Table 3.5: Drilling parameters used in this study.

Level	Thickness, *T* (mm)	Cutting Speed, *V* (rpm)	Feed Rate, *f* (mm/ rev)
1	3	1000	0.05
2	10	2000	0.1
3	-	3000	0.2

3.5.1 Preparations of Composites Sample for Drilling

Stepped structure specimen of fiber composites and hybrid fiber composites was marked to drill 36 holes (9 columns and 4 rows) keeping a distance of 16 mm between each hole. This distance was kept equal in length and width of the stepped structure to avoid drilling stress on neighboring holes. The schematic of the holes layout is shown in Figure 3.5.

For drilling columns 1, 2 and 3, cutting speed was constant at 1000 rpm while the feed rate were 0.05 mm/rev, 0.1 mm/rev and 0.2 mm/rev respectively to study the effect of feed rate on the quality of the drilled holes keeping the drilling speed constant. Similarly, columns 4, 5 and 6 were drilled at the same three feed rates but at 2000 rpm. Likewise, columns 7, 8 and 9 were drilled at the same feed rate but at 3000 rpm. Effectively, 4 holes were drilled at each feed rate and each cutting speed.

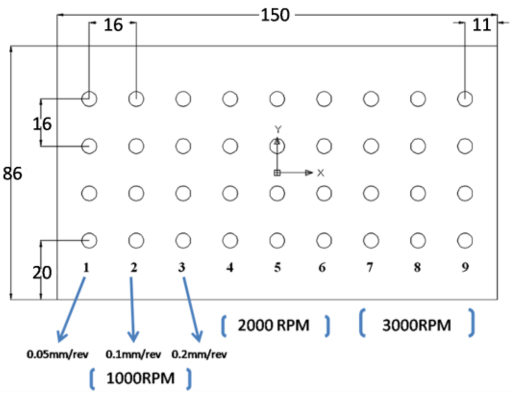


Figure 3.5: Design of the drilling holes layout on fiber composite and hybrid fiber composite samples.

3.6 Evaluation of the Drilled Holes

The drilled specimens of fiber composites and hybrid fiber composites were evaluated for damage around the holes, surface roughness through the hole wall and microstructural changes of the interior wall of the drilled holes.

3.6.1 Measurement of Damage Factor

Mitutoyo 3D Non-Contact was used together with QVPAK software to measure the damage occurred around the holes during drilling process. The machine is capable of measuring damage factor (F_d) at higher speed and accuracy provided the image obtained was clear. The important feature of the machine is that it works on non-contact principle and this is an important feature of the machine to avoid any type of the damage or contamination to the surface of the holes.

Equation 2.1 is used to calculate the damage factor (F_d) of the drilled holes. Figure 3.6 shows the technique to evaluate the damage factor (F_d) of the drilled holes.

$$F_d = \frac{D_{max}}{D} \quad \text{---(2.1)}$$

F_d = Damage factor

D_{max} = maximum diameter of the damage zone in mm

D = diameter of the drilled holes = 5 mm

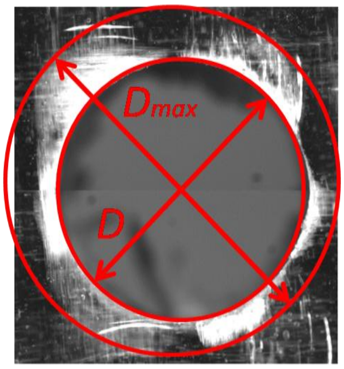


Figure 3.6: Evaluation of the damage factor (F_d).

3.6.1.1 Procedures

The surface of the drilled holes was cleaned and hanged between two bars for sufficient lighting from top part and bottom part of the materials. The lenses were adjusted using the joystick for clear image of the video. The settings of light used produced precise images and are shown in Table 3.6.

Table 3.6: Light setting to measure damage factor (F_d) of drilled holes in fiber composite and hybrid fiber composite.

	Stage (%)	Coaxial (%)	Ring Front (%)	Ring Back (%)	Ring Right (%)	Ring Left (%)	Ring Position (%)
Light	**14**	**0**	**26**	**26**	**26**	**26**	**6**

The light setting shown above gave 14% of light to the specimen and produced no light from the coaxial; the part that transferred the image from specimen to the video, ring light around the coaxial was separated into 4 parts; front, back, right and left which gave 26% of light and the ring position emitted 6% of light onto the specimen.

To ensure the position of optical lens was at the right spot; sufficient light was supplied onto the specimen and the damage observed around the drilled holes was captured and analyzed. The damage around the drilled holes was analyzed by selecting three different locations with maximum damage around the drilled holes. Average of 5 readings were taken and reported.

3.6.2 Surface Roughness Measurement across the Depth of the Drilled Holes

Surface roughness of the drilled holes was measured using Perthometer Concept, MAHR GMBH machine. The machine was used together with the CONCEPT software. Surface roughness of the drilled holes was measured in Ra value.

The technique to measure the surface roughness of the drilled holes is shown in Figure 3.7 and further explained in 3.6.2.1.

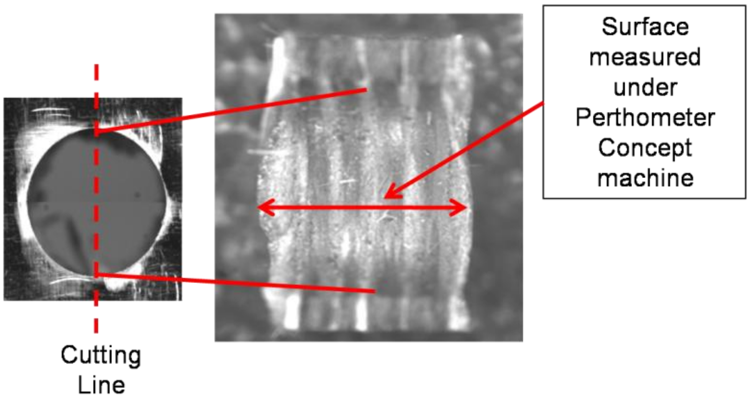


Figure 3.7: Technique to measure surface roughness of the drilled holes.

3.6.2.1 Procedure

The test samples with the drilled holes were cut through the center of the holes for measurement of the surface roughness across the depth of the hole as shown in Figure 3.7. A diamond abrasive cutter was used to cut the drilled holes precisely. After cutting, the surface of holes was cleaned with soft brush and compressed air to remove any trapped dust at the holes surface during cutting.

The specimen was clamped onto the machine. The depth of the specimen to be measured was keyed in the software. The stylus was brought down and touched the specimen drilled holes surface. The stylus moved and scratched the surface of the hole walls and stopped when it reached the maximum length set earlier in the software. The surface roughness value was obtained. Averages of 5 readings were taken to ensure for good reproducibility of the readings.

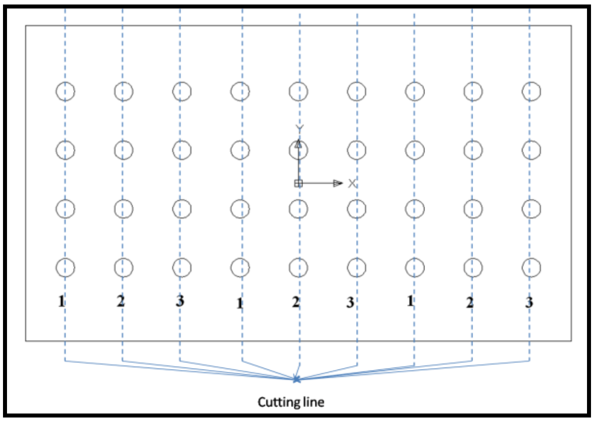


Figure 3.8: Layout of the cutting line of the drilled holes on composite specimen.

3.6.3 Microstructural Observation of the Drilled Holes using Scanning Electron Microscope (SEM)

SEM LEO VP 1430 was used to explore the surface microstructure of the drilled holes. The machine can only examine conducting materials. Hence, the specimen was coated in low vacuum sputter coating for 30 minutes to enable it to conduct electron.

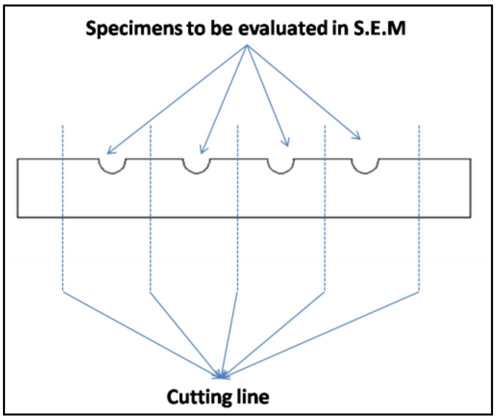


Figure 3.9: Layout of the cutting lines on the composite specimens for SEM observation.

3.6.3.1 Procedure

The specimens used for surface roughness were cut as shown in Figure 3.9 and examined under SEM for possible microstructural damage. The surface roughness of the drilled holes depends on the microstructural damage such as fiber pull-out, matrix microcracking, fiber/matrix debonding and porosity. This microstructural damage can only be observed under SEM.

CHAPTER 4
RESULTS AND DISCUSSION

4.1 Introduction

In this section, results obtained from the testing and measurements on the drilled holes of the fiber composites and hybrid fiber composites will be discussed. The results of physical and mechanical testing and effects of drilling on the hole quality using different parameters will be highlighted.

4.2 Physical Examination of Fiber Composites and Hybrid Fiber Composites

Fiber composites and hybrid fiber composites were fabricated using two different matrices; polyester and epoxy. The fiber composites fabricated in this study are glass fiber reinforced polyester (GRP) composites and glass fiber reinforced epoxy (GRE) composites. Typical composite surface finishes of fiber and hybrid fiber composites are shown in Figure 4.1 (a) and (b), respectively. Hybrid fiber composites fabricated in this study were combination of glass fiber and carbon fiber with either polyester or epoxy. It was noted that the surface were free from air-trapped within the matrix.

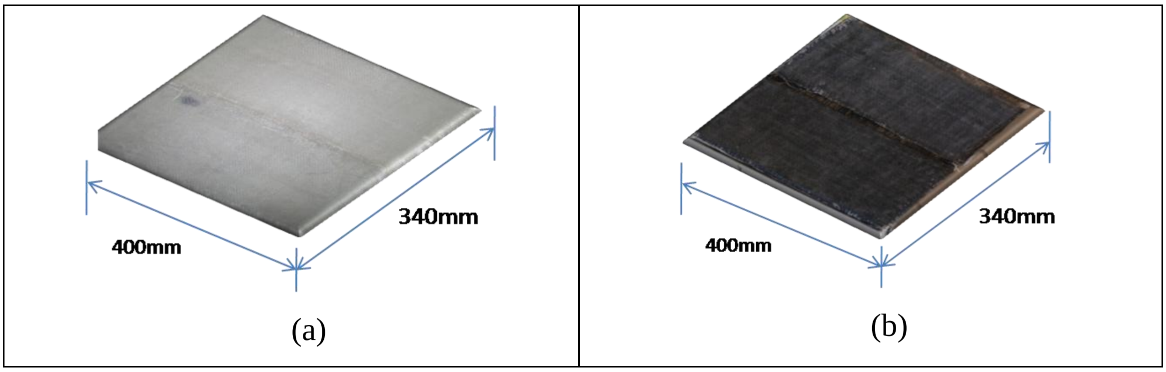


Figure 4.1: Typical surface finish of (a) a fiber composites, (b) a hybrid fiber composites.

4.2.1 Density of the Fiber Composites and Hybrid Fiber Composites

The density data recorded for fiber composites and hybrid fiber composites are shown in Table 4.1. The results show that GRP fiber composites have density of 1785 kg/m^3 which is 0.06% lower than the theoretical. This result indicates negligible defects in the fiber composites.

The density measured for GCRP (hybrid) fiber composites is 1625 kg/m^3 which was 0.31% lower compared to its theoretical value. Addition of carbon fiber into the GCRP (hybrid) fiber composites resulted in 8.96% reduction of density compared to that of GRP fiber composites. This is because carbon fiber have lower density compared to glass fiber as given by the S&N Chemicals Sdn. Bhd.

The density of GRE was 1694 kg/m^3 which are 0.53% lower than its theoretical value. The density of the GCRE (hybrid) fiber composites is 1532 kg/m^3 which are 0.39% lower than its theoretical value and 9.56% lower than the density of GRE fiber composites. Carbon fiber makes the density of GCRE (hybrid) fiber composites lower than that of the GRE fiber composites because it has lower density compared to glass fiber.

Table 4.1 shows that the density of the composites using epoxy as resin has lower density than the composites using polyester as resin. This is due to the lower density of epoxy resin compare to polyester resin supplied by the S&N Chemicals Sdn. Bhd. It can be concluded that the damage occurred at fiber composites and hybrid fiber composites during fabrication process such as porosity were negligible because the percentage difference is less than 10% compare to the theoretical value. Alternating carbon fiber in hybrid fiber composites resulted in lower density compare to those fiber composites.

Table 4.1: Density of fiber composites and hybrid fiber composites.

Materials	Theoretical Density (kg/m^3)	Density (kg/m^3)	Difference between theoretical and measured density (%)	Difference between fiber composites and hybrid fiber composites (%)
GRP composite	1786.0	1785.0	0.1	9.0
GCRP composite	1630.0	1625.0	0.3	
GRE composite	1700.0	1694.0	0.5	9.6
GCRE composite	1538.0	1532.0	0.4	

4.3 Mechanical Properties of Fiber Composites and Hybrid Fiber Composites

The mechanical properties of fiber composites and hybrid fiber composites measured are shown in Table 4.2. GCRP (hybrid) fiber composites have better strength and stiffness (modulus) than GRP fiber composites. The hybrid fiber composites improved by 17% in tensile strength and 18% in tensile modulus. This is due to the alternating layers of glass fiber and carbon fiber with carbon fiber having higher tensile strength and tensile modulus compared to that of the glass fiber.

Table 4.2: Tensile properties of fiber composite and hybrid fiber composite.

Materials	Tensile Strength (MPa)	Difference (%)	Tensile Modulus (GPa)	Difference (%)
GRP composite	368	17	53	18
GCRP composite	432		63	
GRE composite	216	17	11	18
GCRE composite	253		13	

Similarly, GCRE (hybrid) fiber composites have better strength and stiffness (modulus) than GRE fiber composites. An improvement by 17% in tensile strength and 18% in tensile modulus were revised. This enhancement in mechanical properties is due to better strength and modulus of the carbon fiber.

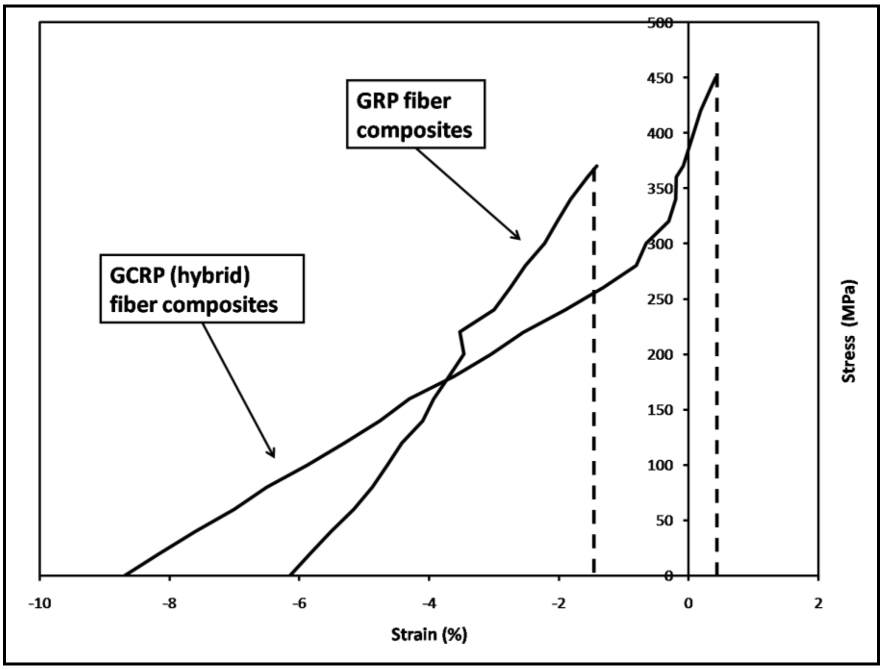


Figure 4.2: Stress versus Strain for fiber composites and hybrid fiber composites based on polyester resin.

However, the strength and stiffness (modulus) of the composites produced using epoxy resin are lower compared to those of the composites produced using polyester resin. This contradicts the results obtained by [58]. In their work, cured both resin for 7 days at 88°F and concluded that the tensile strength and modulus of the epoxy resin is 20 to 30% higher than that of the polyester based composites. In this study, both epoxy and polyester based composites were cured using different curing conditions. Composites using polyester as the resin was cured for 8 hours at 20°C (ambient temperature) while for epoxy based composites at 60°C temperatures for 5 hours. The curing condition has increased the shrinkage of epoxy based composites which may have disturbance of various surface contacts between resin and reinforcement during curing. This resulted in reduced strength and stiffness of composites fabricated using epoxy as resin compared to those fabricated using polyester as the resin.

However, current findings are in agreement with Durao et.al [59] where they compared glass/epoxy plates with hybrid plates consisting of 25% of carbon/epoxy and 75% glass/epoxy. They concluded that the hybrid fiber composites enable to increase the tensile strength and tensile modulus by 15% compared to glass/epoxy composites.

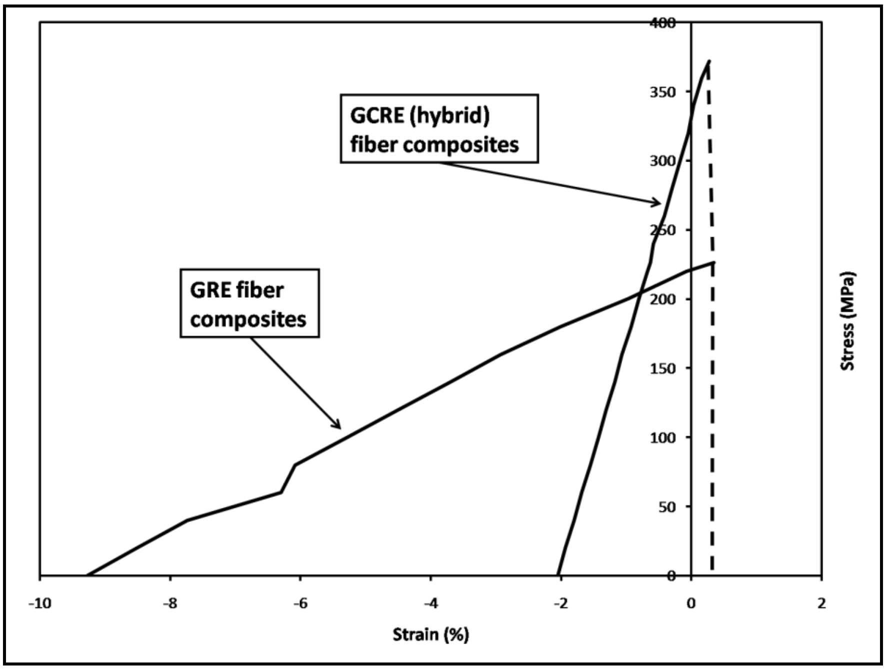


Figure 4.3: Stress versus Strain for fiber composites and hybrid fiber composites based on epoxy resin.

According to Figure 4.4 [61], GRP fiber composites were categorized as hard and brittle materials due to the lower strength and lower elongation compared to GCRP (hybrid) fiber composites as demonstrated in Figure 4.2. GCRP (hybrid) fiber composites are classified as hard and tough materials because it has higher strength and larger elongation compared to GRP fiber composites.

Even though GCRE (hybrid) fiber composites has higher strength compared to GRE fiber composites, it is considered as hard and brittle materials because it has lower elongation compared to that of GRE fiber composites. GRE fiber composites are categorized as soft and tough materials due to its lower strength and higher elongation compared to GCRE (hybrid) fiber composites.

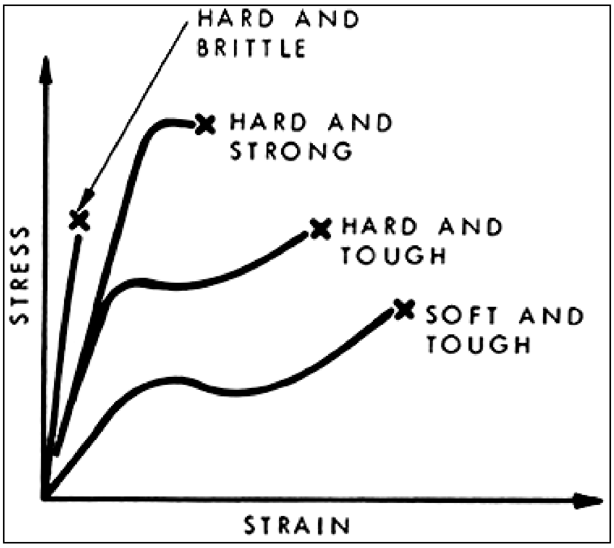


Figure 4.4: Tensile stress-strain curve for polymeric materials [61]

4.3.1 Concluding Remarks

All composites were produced with good surface condition and defects free. Alternating carbon fiber in hybrid fiber composites (GCRP composites and GCRE composites) has reduced the composites density and improved mechanical properties compared to those of fiber composites (GRP composites and GRE composites). It is due to the lower density and better mechanical properties of carbon fiber compared to those of glass fiber. In studying the stress-strain graph, it is concluded that GCRP (hybrid) fiber composites as hard and tough, GRP fiber composites are hard and brittle, GCRE (hybrid) fiber composites are hard and brittle while GRE fiber composites are soft and tough materials.

4.4 Evaluation of the Drilled Holes

The drilled holes were evaluated in 3 different ways; measurement of the damage around the hole using damage factor (F_d), measurement of surface roughness (Ra) of the hole wall and observation of microstructural of the holes wall using scanning electron microscopy (SEM). These evaluation were made as measures of level of damage possessed by the composites materials after drilling and before fastening purpose.

4.4.1 Damage Factor *(F_d)*

The damage factor quantifies the ratio of the maximum diameter of the damage around the hole to the diameter of the drill bit. The damage around the hole occurred when the drill bit entered the laminate as shown in Figure 4.5 [16] where as the cutting edge of the drill bit was in contact with the laminates, the cutting force that acted on the peripheral direction generated a peel force in the axial direction through the slope of the drill flute. This action resulted in separation of the laminates leading to delamination zone at the top surface of the laminate. Delamination zone are the damage occurred around the hole that was measured using the damage factor (F_d).

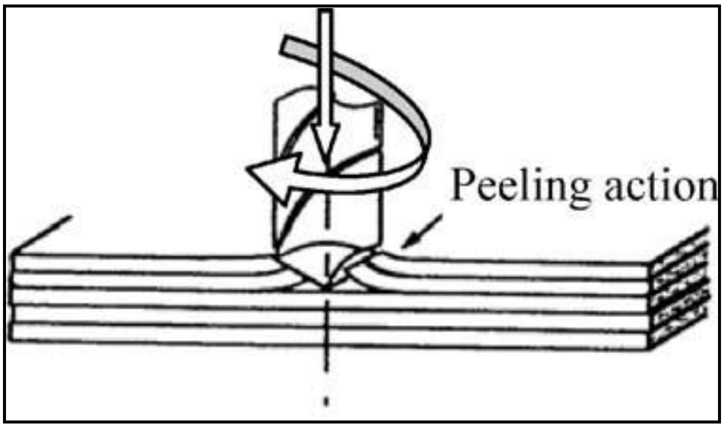


Figure 4.5: Peeling action on the surface of the composite plate as the drill entered the laminates [16].

In order to have accuracy of the results, the reading of the maximum damage was taken at 3 different points. Then, four holes were measured for each type of parameters, i.e. four holes were drilled using 1000 rpm cutting speed and 0.05 mm/rev feed rate. The average values of this result were presented in this study.

4.4.1.1 3 mm Thickness Composites using Polyester Resin as Matrix Materials

Damage factor (F_d) of glass fiber and carbon fiber reinforced polyester (GCRP) (hybrid) composites are lower compared to that of glass fiber reinforced polyester (GRP) composites as shown in Table 4.3. Hard and tough GCRP (hybrid) fiber composite can resist the cutting force that act on it due to higher tensile strength and modulus (stiffness) compared to those of the GRP fiber composites.

The percentage difference of the damage factor (F_d) decreased as the feed rate increases at 1000 rpm cutting speed (Table 4.3). It is because GCRP (hybrid) fiber composites unable to withstand the force applied on it when drilling at higher feed rate. However, GCRP (hybrid) fiber composites still have lower damage factor compare to GRP fiber composites due to higher mechanical properties. Figure 4.6 and Figure 4.7 show the evolution of the damage zone for the GRP fiber composites are not so much different as the feed rate increased from 0.05 mm/rev to 0.2 mm/rev compared to those of GCRP (hybrid) fiber composites.

Increasing feed rate from 0.05 mm/rev to 0.2 mm/rev at 2000 rpm cutting speed has increased the percentage difference of the damage factor (F_d) (Table 4.3). Damage factor (F_d) increased as the feed rate increased for both composites. But, hard and tough GCRP (hybrid) fiber composites were able to resist the force applied at this cutting speed resulted in lower damage factor (F_d) compare to GRP fiber composites. GRP fiber composites have higher damage factor (F_d) when drilling at higher feed rate due to lower mechanical properties compare to GCRP (hybrid) fiber composites. Figure 4.7 and Figure 4.8 show that the damage zone of the GRP fiber composites were larger and the evolution were more significant compared to those of GCRP (hybrid) fiber composites. The damage zone was more significant at the upper portion when the GRP fiber composites were drilled at 0.2 mm/rev feed rate (Fig. 4.7).

At 3000 rpm, percentage difference of the damage factor (F_d) decreased as the feed rate increased from 0.05 mm/rev feed rate to 0.1 mm/rev feed rate. Then, the percentage difference of the damage factor (F_d) increased as the feed rate increased from 0.1 mm/rev feed rate to 0.2 mm/rev feed rate. No significant difference of damage factor (F_d) for GCRP (hybrid) fiber composites when drilling at 2000 rpm and 3000 rpm. The damage factor (F_d) of GRP fiber composites were rapidly increased compared to those of GCRP (hybrid) fiber composites (Figure 4.5).

Table 4.3: Damage factor (F_d) measured for 3-mm thickness composites using polyester resin as matrix materials.

Cutting Speed (rpm)	Feed Rate (mm/rev)	GRP Fiber Composite (F_d)	GCRP (Hybrid) Fiber Composite (F_d)	Difference (%)
1000	0.05	1.318	1.178	10.6
	0.1	1.441	1.336	7.3
	0.2	1.522	1.462	3.9
2000	0.05	1.347	1.269	5.8
	0.1	1.445	1.295	10.4
	0.2	1.578	1.374	12.9
3000	0.05	1.458	1.254	14.0
	0.1	1.556	1.362	12.5
	0.2	1.664	1.379	17.1

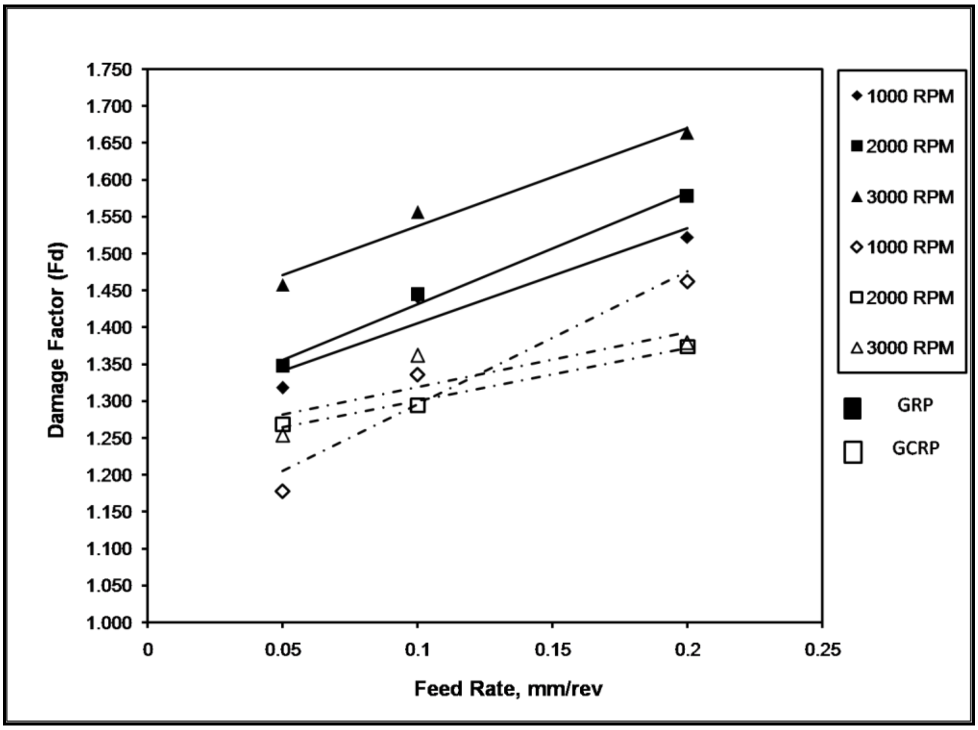


Figure 4.6: Damage factor (F_d) versus feed rate (mm/rev) for 3 mm thickness composites using polyester resin as matrix materials.

The results for GRP fiber composites presented here agree with Davim et.al [45].

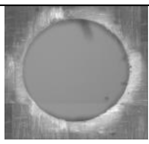
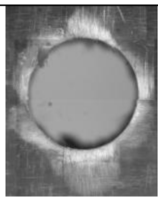
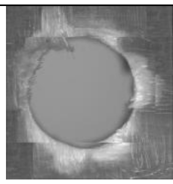
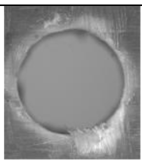
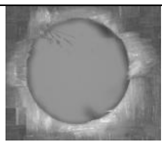
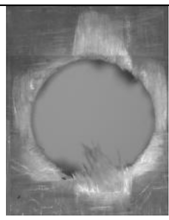
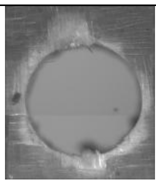
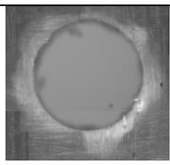
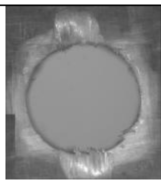
f (mm/rev) / v_c (rpm)	0.05	0.1	0.2
1000			
2000			
3000			

Figure 4.7 : Observable damage around the hole for 3 mm thickness GRP fiber composites.

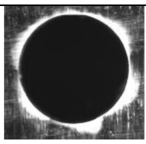
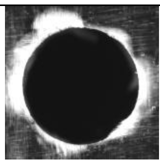
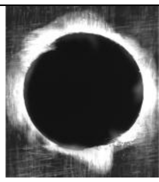
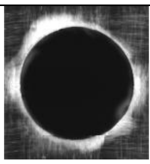
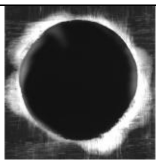
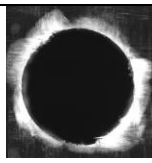
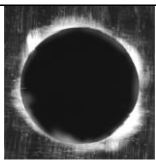
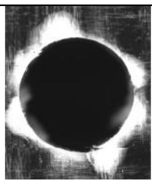
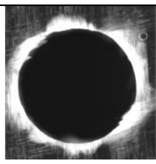
f (mm/rev) / v_c (rpm)	0.05	0.1	0.2
1000			
2000			
3000			

Figure 4.8: Observable damage around the hole for 3 mm thickness GCRP (hybrid) fiber composites.

They concluded that the damage for glass fiber reinforced polyester (GRP) with 65% fiber volume fraction (FVF) increased as the cutting speed and feed rate increased. Introduction of carbon fiber into the GRP fiber composites to become hybrid has improved the results whereby increased cutting speed has no significant effect on damage factor (F_d)

4.4.1.2 10 mm Thickness Composites using Polyester Resin as Matrix Materials

Table 4.4 shows damage factor (F_d) measured for 10 mm thickness composites using polyester resin as matrix materials. The damage factor (F_d) of GCRP (hybrid) fiber composites increased compare to GRP fiber composites during drilling at 1000 rpm and 2000 rpm cutting speed. However, the damage factor (F_d) of GCRP (hybrid) fiber composites were reduced during drilling at 3000 rpm cutting speed compared to those of GRP fiber composites. GCRP (hybrid) fiber composites which have higher mechanical properties than those of GRP fiber composites resulted in increasing cutting resistance. It was so difficult to penetrate GCRP (hybrid) fiber composites with higher cutting resistance at lower cutting speed (1000 rpm and 2000 rpm) resulted in higher damage factor (F_d).

The difference of the damage factor (F_d) reduced from 21.1% to 3.6% with the increasing feed rate from 0.05 mm/rev to 0.2 mm/rev during drilling at 1000 rpm. It is because the damage factor (F_d) of GRP fiber composite rapidly increased compare to GCRP (hybrid) fiber composite as the feed rate increased. The increment of the damage factor (F_d) for GCRP (hybrid) fiber composites is almost insignificant as the feed rate increased. At 1000 rpm cutting speed drill bit is unable to penetrate the GCRP (hybrid) fiber composite easily due to the higher mechanical properties compare to the fiber composite that lead to higher cutting resistance. Figure 4.10 and Figure 4.11 shows that the damage zone of the GRP fiber composites at 0.05 mm/rev feed rate is almost insignificant compare to the damage zone at 0.1 mm/rev and 0.2 mm/rev and the damage zone of the GCRP (hybrid) fiber composites.

The difference of damage factor (F_d) is increased from 0.3% at 0.05 mm/rev to 2.6% at 0.1 mm/rev feed rate and remain constant at 0.2 mm/rev feed rate. It is because the damage factor (F_d) of both composite almost have the same value at the initial feed rate and increased at their own phase as the feed rate increased. The damage factor (F_d) of GCRP (hybrid) fiber composites with higher mechanical properties have insignificant affect compare to GRP fiber composites when drilling at lower feed rate due to the same cutting forces applied on both composites.

Table 4.4: Damage factor (F_d) measured for 10 mm thickness composites using polyester resin as matrix materials.

Cutting Speed (rpm)	Feed Rate (mm/rev)	GRP Fiber Composite (F_d)	GCRP (Hybrid) Fiber Composite (F_d)	Difference (%)
1000	0.05	1.144	1.386	21.1
	0.1	1.208	1.437	19.0
	0.2	1.403	1.455	3.6
2000	0.05	1.312	1.316	0.3
	0.1	1.353	1.388	2.6
	0.2	1.453	1.491	2.6
3000	0.05	1.275	1.165	8.6
	0.1	1.356	1.287	5.1
	0.2	1.416	1.351	4.6

The damage zone of the GRP fiber composites is almost insignificant when drilled at 0.05 mm/rev feed rate at 2000 rpm cutting speed. The damage zone are only significant at the area near to the 0° and 180° of the drilled holes when the GRP fiber composites are drilled at 0.1 mm/rev feed rate and 0.2 mm/rev feed rate (Fig. 4.9). Figure 4.10 shows that the damage zone is more significant when the GCRP (hybrid) fiber composites were drilled at 0.05 mm/rev feed rate and 0.2 mm/rev feed rate.

The percentage difference of the damage factor (F_d) decreased as the feed rate increased from 0.05 mm/rev to 0.2 mm/rev. It is because GCRP (hybrid) fiber composites have lower damage factor (F_d) compare to GRP fiber composites at 3000 rpm cutting speed because the cutting energy was able to overcome the cutting resistance possessed by the hybrid fiber composite lead to less contact time between the tool and the material.

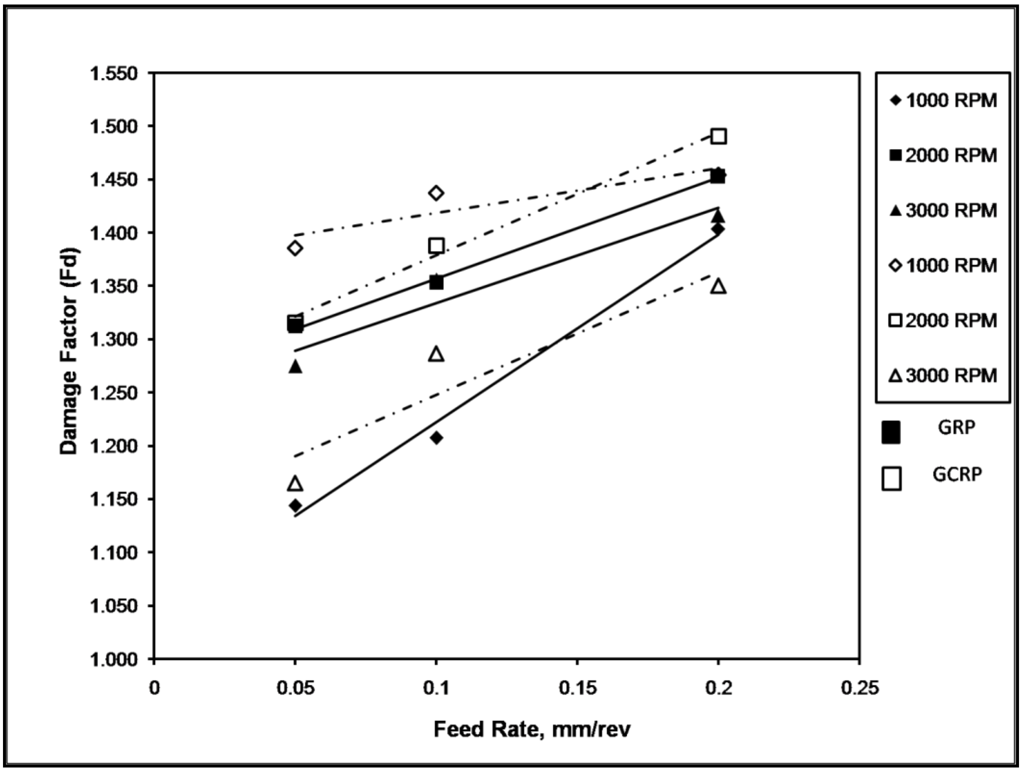


Figure 4.9: Damage factor (F_d) versus feed rate (mm/rev) for 10 mm thickness composites using polyester resin as matrix materials.

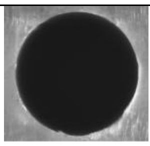
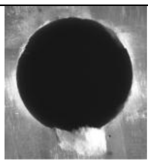
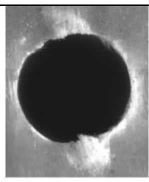
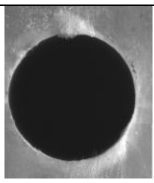
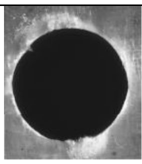
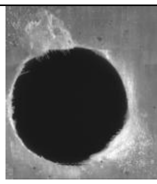
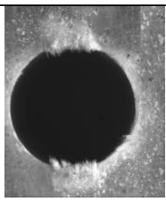
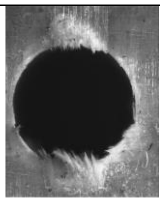
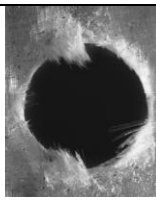
f (mm/rev) / v_c (rpm)	0.05	0.1	0.2
1000			
2000			
3000			

Figure 4.10 : Observable damage around the hole for 10 mm thickness GRP fiber composites.

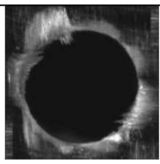
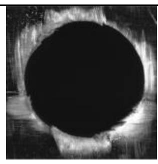
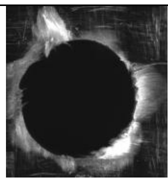
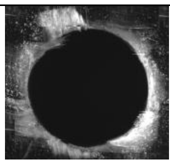
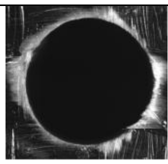
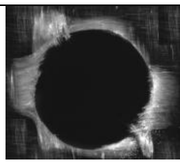
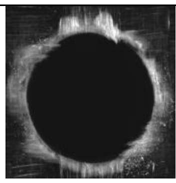
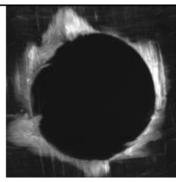
f (mm/rev) / v_c (rpm)	0.05	0.1	0.2
1000			
2000			
3000			

Figure 4.11: Observable damage around the hole for 10 mm thickness GCRP (hybrid) fiber composites.

The difference of the damage factor (F_d) decreasing from 8.6% to 4.6% (Table 4.4) due to the damage factor (F_d) of GCRP (hybrid) fiber composite is increased compare to GRP fiber composites as the feed rate increased. Figure 4.10 shows that the damage zone more significant as the feed rate increased from 0.05 mm/rev to 0.2 mm/rev. For GCRP (hybrid) fiber composites, no significant evolution of damage zone can be seen at Fig. 4.11.

4.4.1.3 3 mm Thickness Composites using Epoxy Resin as Matrix Materials

Table 4.5 shows the damage factor (F_d) measured after drilling 3 mm thickness composites using epoxy resin as matrix materials. The percentage difference shows that the damage factor (F_d) of GCRE (hybrid) fiber composites are increased compared to the damage factor (F_d) of the GRE fiber composites. This refer to higher interlaminar strength occurred when epoxy resin is mixed with carbon fiber and glass fiber that resulted in higher cutting resistance during drilling process.

Percentage difference of the damage factor (F_d) increased when the feed rate increased from 0.05 mm/rev to 0.1 mm/rev and decreased when the feed rate increased to 0.2 mm/rev at 1000 rpm cutting speed (Table 4.5). Figure 4.11 shows that the damage factor (F_d) is slightly increased during drilling GRE fiber composites from 0.05 mm/rev to 0.1 mm/rev feed rate compare to GCRE (hybrid) fiber composites. However, the damage factor (F_d) is rapidly increased during drilling GRE fiber composites at 0.2 mm/rev feed rate compare to GCRE (hybrid) fiber composites. This results are refer to the higher cutting force are suddenly applied on the GRE fiber composites surface that lead to higher damage factor (F_d) during drilling at 0.2 mm/rev feed rate.

The percentage difference of damage factor (F_d) increased as the feed rate increase from 0.05 mm/rev to 0.1 mm/rev and remain constant as the feed rate increased to 0.2 mm/rev during drilling at 2000 rpm cutting speed (Table 4.5). At this stage, the damage factor (F_d) of GRE fiber composites rapidly increased as the feed rate increase from 0.05 mm/rev to 0.2 mm/rev feed rate compare to GCRE (hybrid) fiber composites (Figure 4.12). This shows GRE fiber composite more delaminated at the earlier stage because the strength of fiber/matrix bonding reduced when higher cutting speed and feed rate is applied.

Table 4.5: Damage Factor (F_d) measured for 3 mm thickness composites using epoxy resin as matrix materials.

Cutting Speed (rpm)	Feed Rate (mm/rev)	GRE Fiber Composite (F_d)	GCRE (Hybrid) Fiber Composite (F_d)	Difference (%)
1000	0.05	1.248	1.283	2.8
	0.1	1.282	1.363	6.3
	0.2	1.418	1.437	1.4
2000	0.05	1.243	1.269	2.1
	0.1	1.325	1.380	4.1
	0.2	1.361	1.417	4.1
3000	0.05	1.265	1.277	0.9
	0.1	1.288	1.331	3.3
	0.2	1.376	1.451	5.5

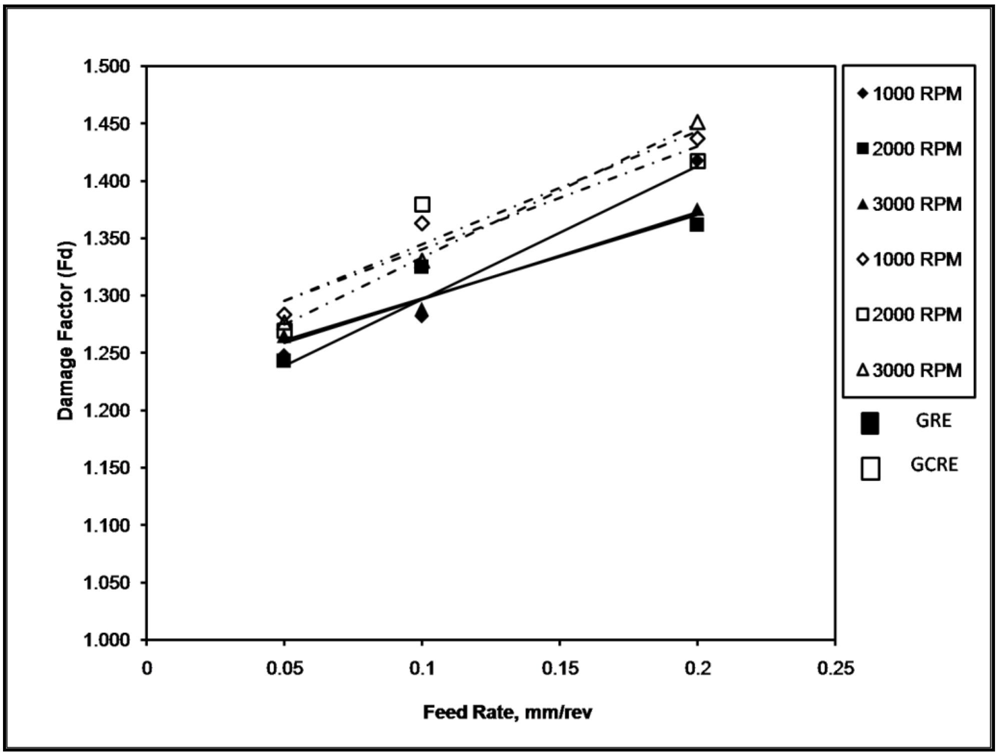


Figure 4.12: Damage factor (F_d) versus feed rate (mm/rev) for 3 mm thickness composites using epoxy resin as matrix materials.

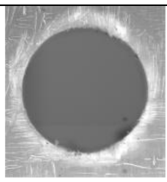
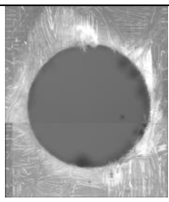
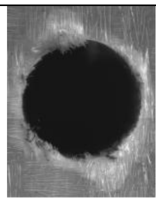
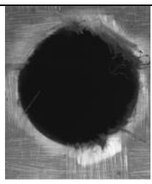
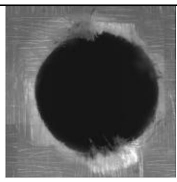
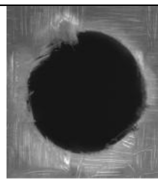
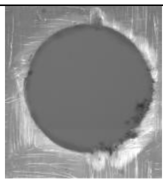
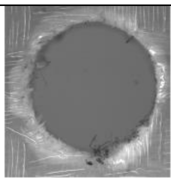
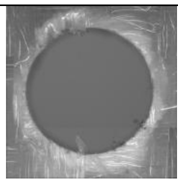
f (mm/rev) / v_c (rpm)	0.05	0.1	0.2
1000			
2000			
3000			

Figure 4.13 : Observable damage around the hole for 3 mm thickness GRE fiber composites.

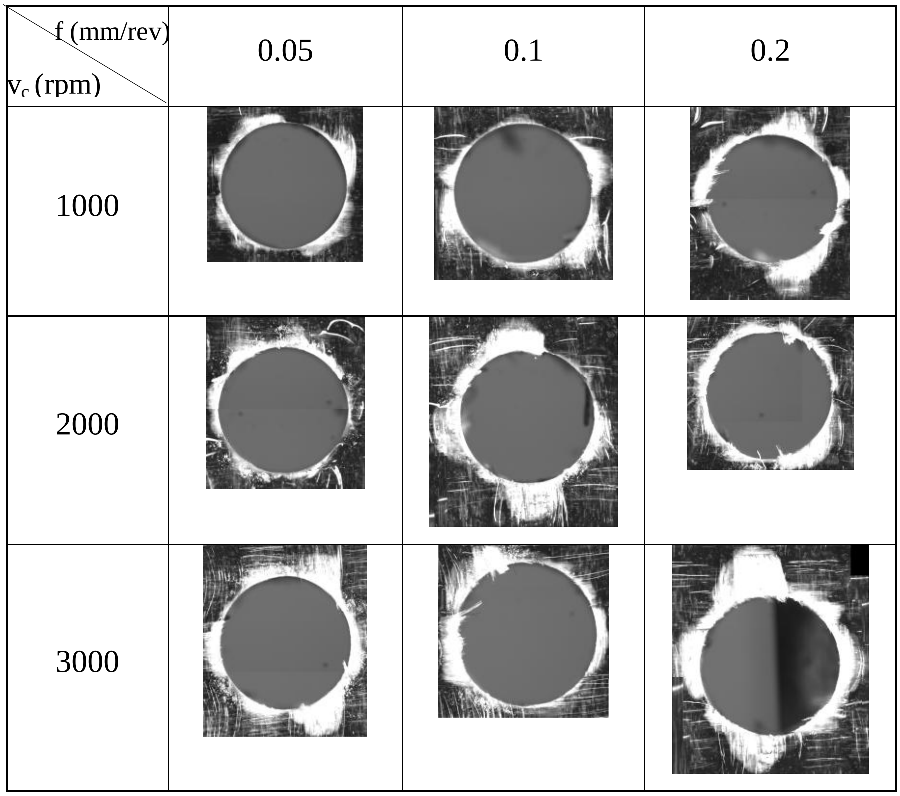


Figure 4.14 : Observable damage around the hole for 3 mm thickness GCRE (hybrid) fiber composites.

Drilling the composites at 3000 rpm cutting speed shows that the percentage difference increased as the feed rate increased (Table 4.5). Figure 4.12 shows that the damage factor (F_d) increased linearly as the feed rate increased for GCRE (hybrid) fiber composites compare GRE fiber composites due to increased in tool's vibration.

4.4.1.4 10 mm Thickness Composites using Epoxy Resin as Matrix Materials

10 mm thickness GCRE (hybrid) fiber composite has lower damage factor (F_d) than GRE fiber composites (Table 4.6). This is due to the strength of fiber/ matrix bond at the surface of the hybrid fiber composite is higher compare to fiber composites. Furthermore, the brittle fracture of GCRE (hybrid) fiber composites leads to lower cutting resistance.

At 2000 rpm cutting speed, the difference of damage factor (F_d) increasing from 3.6% to 8.0% and decreasing to 2.0% as the feed rate increased. Damage factor (F_d) of GRE fiber composites is less affected by the increasing feed rate as the cutting speed increased to 2000 rpm compare to GCRE (hybrid) fiber composites (Figure 4.15). It is because the toughness of GRE fiber composites is able to resist the force as the feed rate increased.

Table 4.6: Damage factor (F_d) measured for 10 mm thickness composites using epoxy resin as matrix materials.

Cutting Speed (rpm)	Feed Rate (mm/rev)	GRE Fiber Composite (F_d)	GCRE (Hybrid) Fiber Composite (F_d)	Difference (%)
1000	0.05	1.176	1.161	-1.2
	0.1	1.253	1.243	-0.8
	0.2	1.369	1.330	-2.9
2000	0.05	1.227	1.183	-3.6
	0.1	1.308	1.204	-8.0
	0.2	1.359	1.332	-2.0
3000	0.05	1.223	1.179	-3.6
	0.1	1.282	1.195	-6.8
	0.2	1.361	1.228	-9.8

The difference of damage factor (F_d) between is decreasing from 1.2% to 0.8% and increasing to 2.9% when drilling at 1000 rpm cutting speed as the feed rate increased. Figure 4.15 shows that GRE fiber composites have a steep increased of damage factor (F_d) compare to GCRE (hybrid) fiber composites. This is due GRE fiber composite is less brittle than GCRE (hybrid) fiber composites resulted in increasing thrust force applied on the surface of the materials.

The percentage difference of damage factor (F_d) increased from 3.6 to 9.8 with increasing feed rate when drilling at 3000 rpm cutting speed (Table 4.6). Figure 4.15 shows the damage factor (F_d) of GRE fiber composites have a steep increased compare to GCRE (hybrid) fiber composites. GCRE (hybrid) fiber composites have insignificant affect with increasing feed rate when drilling at higher cutting speed compare to 1000 rpm and 2000 rpm cutting speed due to shorter contact time between the tool and the materials. GCRE (hybrid) fiber composites are more brittle than GRE fiber composites resulted in lower cutting resistance as higher cutting speed.

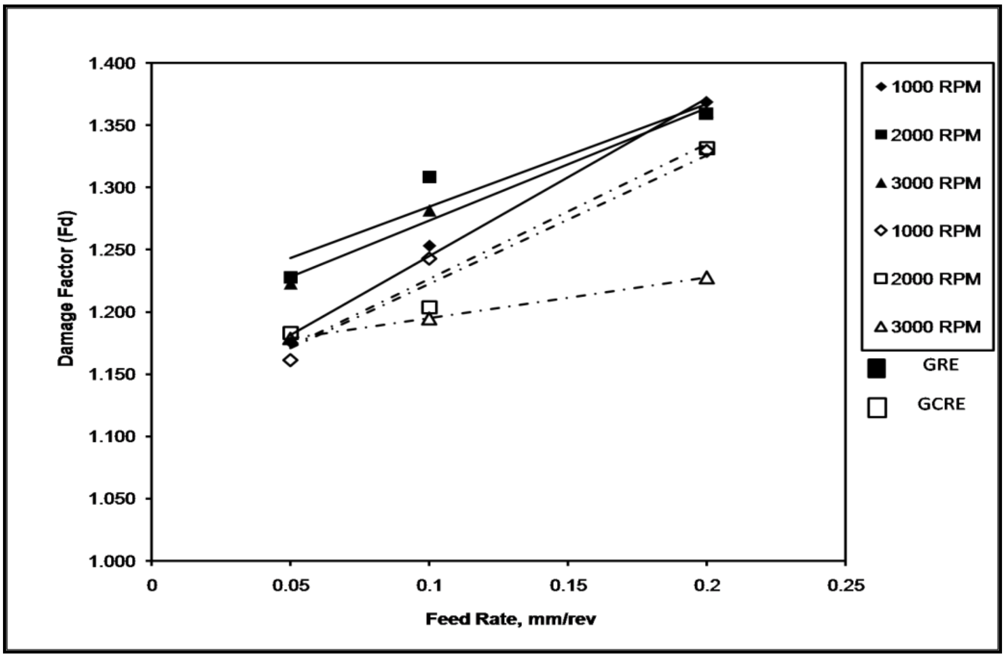


Figure 4.15: Damage factor (F_d) versus feed rate (mm/rev) for 10 mm thickness composites using epoxy resin as matrix materials.

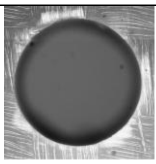
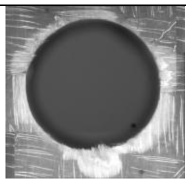
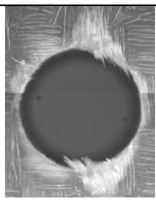
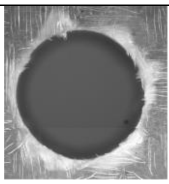
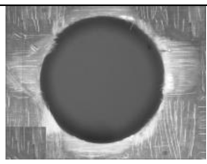
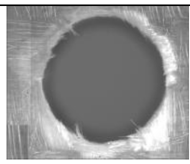
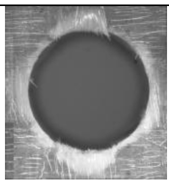
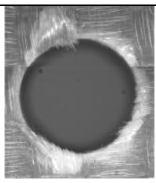
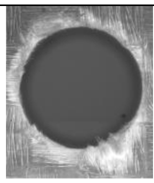
f (mm/rev) / v_c (rpm)	0.05	0.1	0.2
1000			
2000			
3000			

Figure 4.16: Observable damage produced after drilling 10 mm thickness GRE fiber composites.

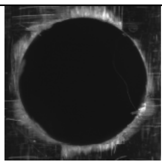
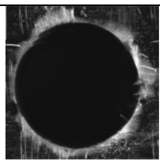
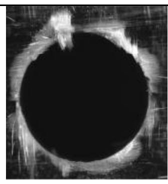
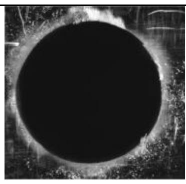
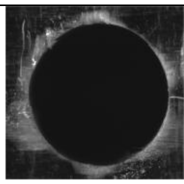
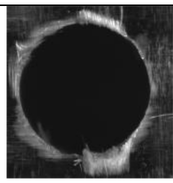
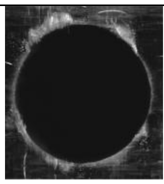
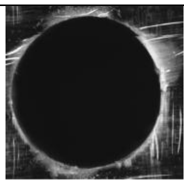
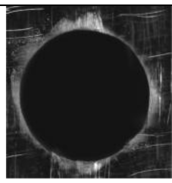
f (mm/rev) / v_c (rpm)	0.05	0.1	0.2
1000			
2000			
3000			

Figure 4.17: Observable damage produced after drilling 10 mm thickness GCRE (hybrid) fiber composites.

4.4.1.5 Concluding Remarks

Drilling 3 mm thickness composites using polyester resin as matrix materials showed that the GCRP (hybrid) fiber composites have lower damage factor (F_d) compared to those of GRP fiber composites. This is due to the higher strength and stiffness of GCRP (hybrid) fiber composites which can bear the force applied on it resulting in smaller damage zone. Furthermore, GRP fiber composites have higher cutting resistance compared to GCRP (hybrid) fiber composites that may lead to longer contact time between the drill and the materials resulted in higher damage factor.

Increasing cutting speed and feed rate increased the damage factor (F_d) of the drilled holes for GRP fiber composites and GCRP (hybrid) fiber composites. it is because the force applied on top surface of the fiber composites and hybrid fiber composites is increased as the cutting speed and feed rate increased.

Drilling 10 mm thickness composites using epoxy resin as matrix materials shows that GRP fiber composites have lower damage factor compare to GCRP (hybrid) fiber composites. It is because higher mechanical properties of GCRP (hybrid) fiber composites with higher thickness increased the cutting resistance resulted in higher damage factor (F_d) of the drilled holes. The damage zones of the drilled holes are almost insignificant when GRP fiber composites were drilled using lower cutting speed and feed rate such as 1000 rpm and 0.05 mm/rev. it is because lower cutting speed and feed rate have lower thrust force resulted in lower damage factor (F_d).

Drilling 3-mm thickness composites using Polyester resin as matrix materials shows that the GRE fiber composites have lower damage factor (F_d) compare to GCRE (hybrid) fiber composites. It is because the interlaminar strength of GCRE (hybrid) fiber composites is higher resulted in higher cutting resistance.

Increased in cutting speed and feed rate increased the damage factor (F_d) of the drilled holes for both types of composites. This is because, increased in cutting speed increased the vibration of the drill bit during drilling process. Increased in feed rate increased the thrust force applied on top surface for both type of composites.

Drilling 10 mm thickness composites using epoxy resin as matrix materials shows that GCRE (hybrid) fiber composites have lower damage factor (F_d) compare to the GRE fiber composites. The reason of this happen is due to the GCRE (hybrid) fiber composites are more brittle compare to GRE fiber composites. The brittle nature of GCRE (hybrid) fiber composites resulted in low cutting resistance that may easier for the drill to penetrate this composite.

Increased in feed rate has increased the damage factor (F_d) of the drilled holes for both composites. It was due to the higher thrust force is applied on top surface of the composites. However, the damage factor (F_d) of the drilled holes decreased with increasing cutting speed for GCRE (hybrid) fiber composites. This is due to the contact time between the tool and the materials are reduced as the cutting speed increased.

4.4.2 Surface Roughness (Ra)

Surface roughness (Ra) of the drilled holes was measured using surface profilometer. It is evaluated in terms of average surface roughness (Ra). The following section discussed on the results of the surface roughness of the drilled holes.

4.4.2.1 3 mm Thickness Composites using Polyester Resin as Matrix Materials

Table 4.7 shows that the GCRP (hybrid) fiber composites have better surface roughness (Ra) compare to GRP fiber composites. It is due to the addition of carbon fiber made hybrid fiber composites more brittle than fiber composites. The drill tends to ‘break’ instead of ‘tear’ the composites with brittle fracture.

The difference of the surface roughness (Ra) is increased as the feed rate increased from 0.05 mm/rev to 0.2 mm/rev feed rate when drilling at 1000 rpm cutting speed.The difference increased from 35.49% to 80.93%. Increasing percentage difference of the surface roughness (Ra) between GRP fiber composites and GCRP (hybrid) fiber composites due to the GRP fiber composites have sudden increased with increasing feed rate compare to GCRP (hybrid) fiber composites (Figure 4.18). This sudden increased happen due to the higher feed tend to pull the fiber instead of shearing the GRP fiber composites. This statement agreed with Ramulu et.al when they drilled Graphite/Bismalide composites using carbide drills at 660 rpm with three different feed rate (0.1 mm/rev, 0.2 mm/rev and 0.3 mm/rev) [47].

The percentage difference increased as the feed rate increased from 0.05 mm/rev to 0.2 mm/rev feed rate when drilling at 2000 rpm cutting speed. In this case, both composites have the same increasing pattern. It is because the surface roughness (Ra) of the GCRP (hybrid) fiber composites has sudden increased when drilling at 0.1 mm/rev feed rate. This is due to the increasing force during drilling at this stage tend to tear the fiber and resulted in producing rougher surface.

Table 4.7 : Surface roughness (Ra) measured for 3 mm thickness composites using polyester resin as matrix materials.

Cutting Speed (rpm)	Feed Rate (mm/rev)	GRP Fiber Composite, Ra (μm)	GCRP (Hybrid) Fiber Composite Ra (μm)	Difference (%)
1000	0.05	2.200	1.618	35.94
	0.1	2.560	1.675	52.84
	0.2	3.383	1.870	80.93
2000	0.05	2.518	2.202	14.38
	0.1	3.152	2.645	19.16
	0.2	3.942	3.268	20.60
3000	0.05	3.427	2.497	37.25
	0.1	4.100	2.542	61.31
	0.2	4.985	2.927	70.33

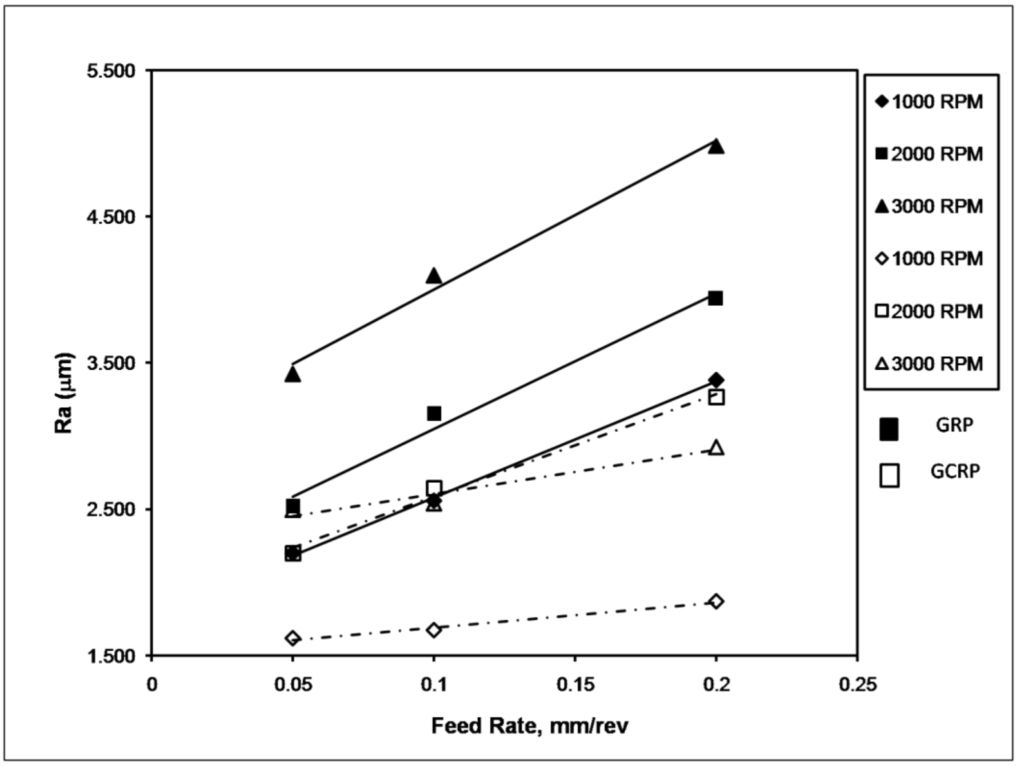


Figure 4.18: Surface roughness (Ra) versus feed rate (mm/rev) for 3 mm thickness composites using polyester resin as matrix materials.

The percentage difference of surface roughness (Ra) increased as the feed rate increased when drilling at 3000 rpm cutting speed. The pattern of the slope is most likely the same as 1000 rpm cutting speed. However, rougher surface is produced when drilling at this stage because higher speed lead to higher force and finally will increase the shear rate of the drilling process.

4.4.2.2 10 mm Thickness Composites using Polyester Resin as Matrix Materials

Table 4.8 shows the GCRP (hybrid) fiber composites have better surface roughness (Ra) compare to GRP fiber composites. Addition of carbon fiber is the main contribution of making the hybrid fiber composites more brittle compare to fiber composites. Brittle fracture of GCRP (hybrid) fiber composites made the drill shear the fiber instead of pull it during drilling process and lead to better surface roughness (Ra).

Drilling at 1000 rpm shows the percentage difference of surface roughness (Ra) between the GRP fiber composites and GCRP (hybrid) fiber composites is increased from 25.7% to 42.9% as the feed rate increased from 0.05 mm/rev to 0.1 mm/rev. Then the percentage difference decreased to 15.4% as the feed rate increased to 0.2 mm/rev. The pattern of the slope for both composites is almost the same. However, sudden increased of surface roughness (Ra) for GRP fiber composites resulted in larger percentage difference due to the ductile fracture of glass fiber.

Table 4.8 : Surface roughness (Ra) measured for 10 mm thickness composites using polyester resin as matrix materials.

Cutting Speed (rpm)	Feed Rate (mm/rev)	GRP Fiber Composite, Ra (μm)	GCRP (hybrid) Fiber Composite Ra (μm)	Difference (%)
1000	0.05	5.198	4.137	25.7
	0.1	8.527	5.965	42.9
	0.2	9.037	7.833	15.4
2000	0.05	5.912	5.792	2.1
	0.1	6.875	6.573	4.6
	0.2	7.257	7.197	0.8
3000	0.05	6.420	6.023	6.6
	0.1	9.477	7.558	25.4
	0.2	11.515	9.737	18.3

As the cutting speed increased to 2000 rpm, the percentage difference of surface roughness (Ra) is reducing to 2.1% at 0.05 mm/rev feed rate. Then, as the feed rate increase to 0.1 mm/rev feed rate; the percentage difference increased to 4.6% and decreased to 0.8% as the feed rate increased to 0.2 mm/rev feed rate. Drilling 10 mm polyester based composites at 2000 rpm cutting were having not so much difference and can be neglected due to less than 5% because both composites was experienced almost the same thrust force applied and the length of time the drills contacted the materials.

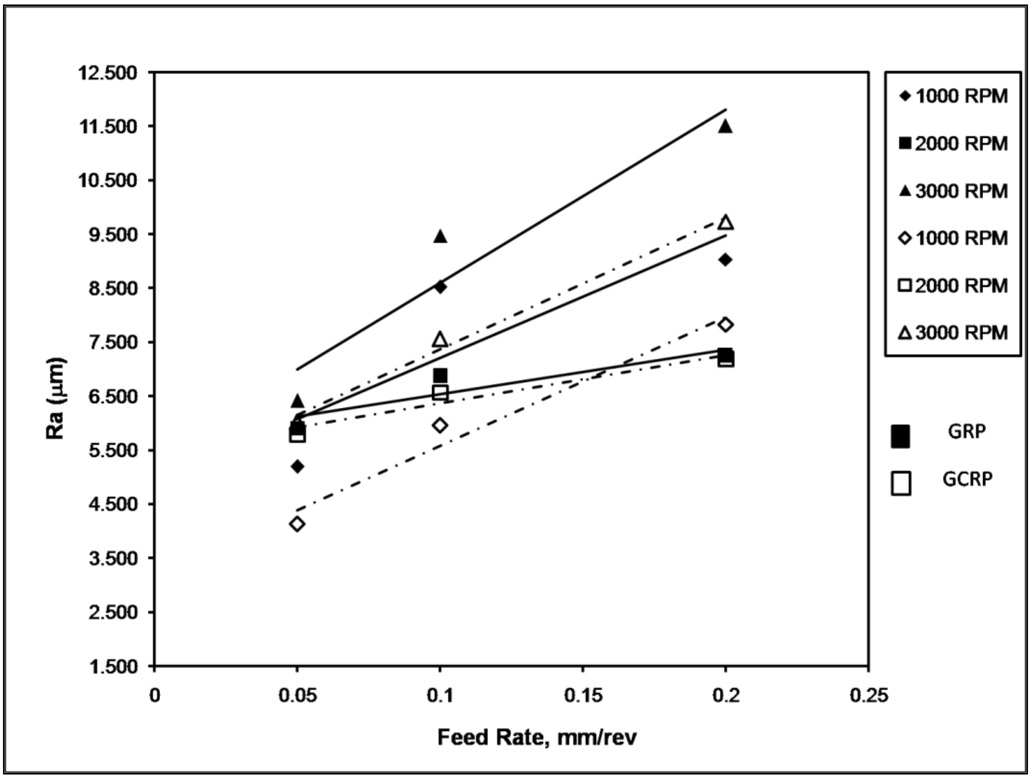


Figure 4.19: Surface roughness (Ra) versus feed rate (mm/rev) for 10 mm thickness composites used epoxy resin as matrix materials.

Drilling at 3000 rpm cutting speed shows that the bigger percentage difference occurred when drilling at 0.05 mm/rev feed rate; 6.6%. The percentage differences increased as the feed rate increased to 0.1 mm/rev (25.4%) and slightly decreased as the feed rate increased to 0.2 mm/rev feed rate (18.3%).

4.4.2.3 3 mm Thickness Composites used Epoxy Resin as Matrix Materials

Table 4.9 shows the surface roughness (Ra) is improved when using GCRE (hybrid) fiber composites compare to GRE fiber composites. The percentage difference increased as the feed rate increased when drilling with 1000 rpm cutting speed. Based on Figure 4.19, the surface roughness (Ra) of GRE fiber composites suddenly increased as the feed rate increased compare to GCRE (hybrid) fiber composites. This is due to the GRE fiber composites has less strength compare to GCRE (hybrid) fiber composites. The drills tend to pull the fiber instead of shearing them during drilling process.

Table 4.9: Surface roughness (Ra) measured for 3 mm thickness composites using epoxy resin as matrix materials.

Cutting Speed (rpm)	Feed Rate (mm/rev)	GRE Fiber Composite, Ra (μm)	GCRE (Hybrid) Fiber Composite Ra (μm)	Difference (%)
1000	0.05	2.737	2.037	25.58
	0.1	3.150	2.190	30.48
	0.2	3.507	2.288	34.74
2000	0.05	3.082	2.622	14.93
	0.1	3.560	2.635	25.98
	0.2	3.723	2.788	25.11
3000	0.05	3.410	3.025	11.29
	0.1	3.780	3.308	12.48
	0.2	4.137	3.558	13.98

Drilling at 2000 rpm cutting speed shows that the percentage difference of the surface roughness (Ra) increased from 14.93% to 25.98% as the feed rate increased from 0.05 mm/rev to 0.1 mm/rev. Then, the percentage different decreased to 25.11% as the feed rate increased to 0.2 mm/rev and it was assumed to be neglected due to less than 5% reduction. Sudden increased of surface roughness (Ra) for GRE fiber composites is shown in Figure 4.20 compare to GCRE (hybrid) fiber composites. However, the abruptness of the slope is less compare to 1000 rpm cutting speed. It is because; the contact time between the tool and material is shorter at higher cutting speed. But, increased in cutting speed lead to more cutting chip obstruct in the hole during drilling process resulted in increasing surface roughness.

GRE fiber composites and GCRE (hybrid) fiber composites were drilled with 3000 rpm cutting speed and resulted in increasing percentage difference as the feed rate increased (Table 4.9). However, the percentage is reduced because the surface roughness (Ra) for both composites is increasing as shown in Figure 4.19. Both composites have the highest Ra in their class due to the cutting chip is obstructed during drilling process at higher cutting speed. But, GCRE (hybrid) fiber composites look to have better surface roughness (Ra) compare to GRE fiber composites due to the alternating layer of carbon fiber in hybrid fiber composites.

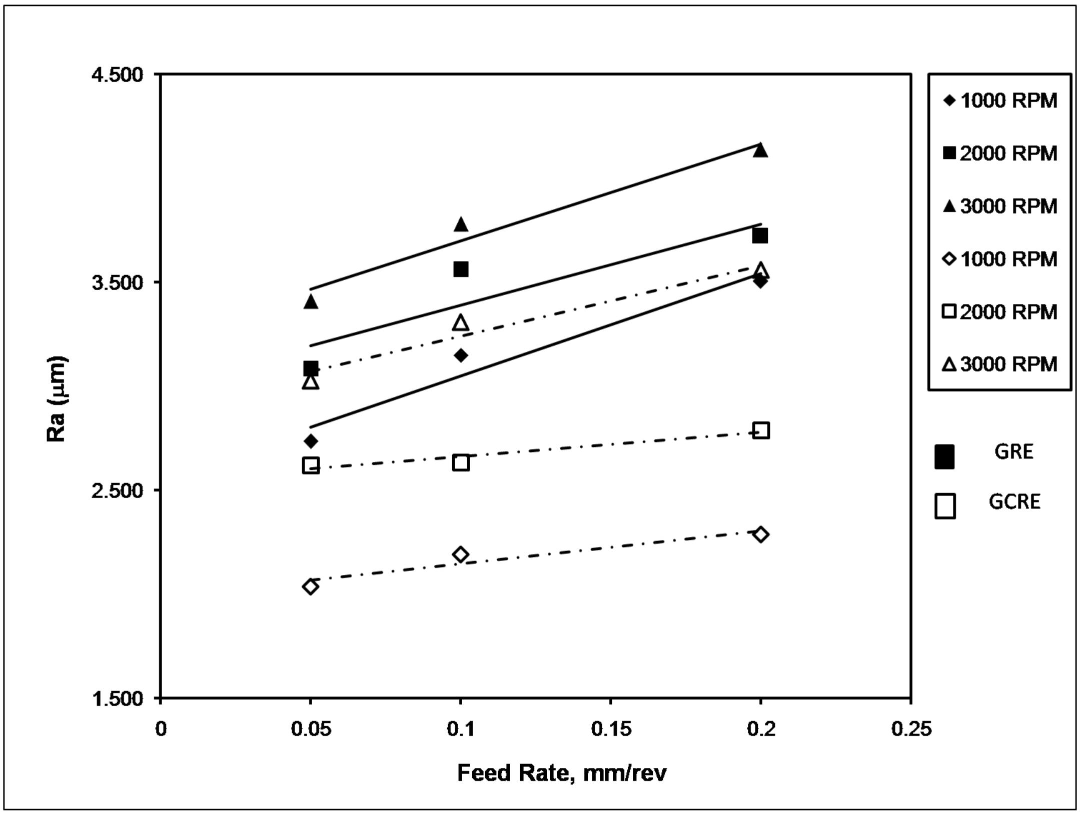


Figure 4.20: Surface roughness (Ra) versus feed rate (mm/rev) for 3 mm thickness composites using epoxy resin as matrix materials.

4.4.2.4 10 mm Thickness Composites using Epoxy Resin as Matrix Materials

Table 4.10 shows that GRE fiber composites have better surface roughness (Ra) compare to GCRE (hybrid) fiber composites. This refer to the increase in thickness of GRE fiber composites resulted in increasing the time length of the tool contacted the material that lead to matrix smearing. This happed due to the less brittle of GRE fiber composites compare to GCRE (hybrid) fiber composites.

Drilling at 1000 rpm cutting speed shows that the difference decreased from 4.3% to 2.8% as the feed rate increased from 0.05 mm/rev to 0.1 mm/rev. The difference increased to 9.2% as the feed rate increased to 0.2 mm/rev. At this stage, the GCRE fiber composites graph is steeper than GRE fiber composites due to rougher surface of GCRE (hybrid) fiber composites is produced as the feed increased to 0.2 mm/rev.

Table 4.10: Surface roughness (Ra) measured for 10 mm thickness composites using epoxy resin as matrix materials.

Cutting Speed (rpm)	Feed Rate (mm/rev)	GRE Fiber Composite, Ra (μm)	GCRE (Hybrid) Fiber Composite Ra (μm)	Difference (%)
1000	0.05	5.250	5.473	4.3
	0.1	8.265	8.500	2.8
	0.2	9.453	10.318	9.2
2000	0.05	4.790	4.872	1.7
	0.1	7.018	7.493	6.8
	0.2	8.623	8.685	0.7
3000	0.05	6.527	6.828	4.6
	0.1	8.268	8.600	4.0
	0.2	12.817	13.518	5.5

The difference increased from 1.7% to 6.8% as the feed rate increased from 0.05 mm/rev feed rate to 0.1 mm/rev feed rate for drilling at 2000 rpm cutting speed. The difference decreased to 0.7% as the feed rate increased to 0.2 mm/rev feed rate.

Drilling at 3000 rpm cutting speed shows that the difference increased from 4.5% to 4.0% then increased to 5.5% as the feed rate increased from 0.05 mm/rev to 0.2 mm/rev feed rate. Figure 4.21 show that both composites almost have the same slope pattern. At higher cutting speed, the fiber was cut at the same cutting force neglecting the strength possessed by the composites. The contact time between the tool and the materials is increasing due to increased in thickness.

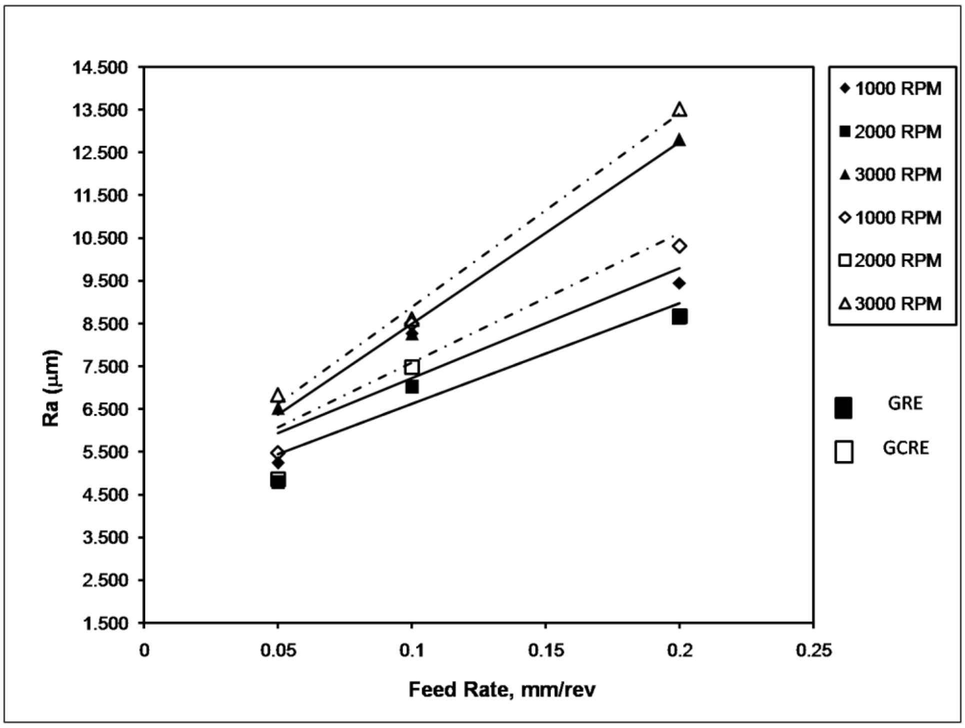


Figure 4.21 : Surface Roughness (Ra) versus feed rate (mm/rev) for 10 mm thickness composites using epoxy resin as matrix materials.

4.4.2.5 Concluding Remarks

The surface roughness of the drilled holes for 3 mm thickness composites using polyester resin as matrix materials shows that GCRP (hybrid) fiber composites have better surface roughness compare to GRP fiber composites. It is because, GCRP (hybrid) fiber composites are more brittle resulted in lower cutting resistance and the drill bit tend to break the composites instead of shearing them.

Increased in feed rate has increased the surface roughness of the drilled holes. It was due to the higher thrust force tending to shear the composites instead of breaking it. Increased in cutting speed has increased the surface roughness of the drilled holes. This is because higher speed resulted in higher force lead to increase the shear rate of the drilling process.

The surface roughness of the composites using polyester resin as matrix materials for 10 mm thickness shows that GCRP (hybrid) fiber composites have better surface roughness compare to GRP fiber composites. The ductile fracture of GRP fiber composites resulted in higher surface roughness. Increased in feed rate has increased the surface roughness of the drilled holes due to shearing force applied through out the holes.

3 mm thickness composites using Epoxy resin as matrix materials shows GCRE (hybrid) fiber composites have lower surface roughness compare to GRE fiber composites. GRE fiber composites have lower strength that unable to withstand the force applied during drilling process.

Increased in feed rate has increased the surface roughness of the drilled holes. This is due to the fiber composites and hybrid fiber composites could not withstand the higher force at higher feed rate. Increased in cutting speed has increased in surface roughness due to the cutting chip obstruct in the drilled holes during drilling.

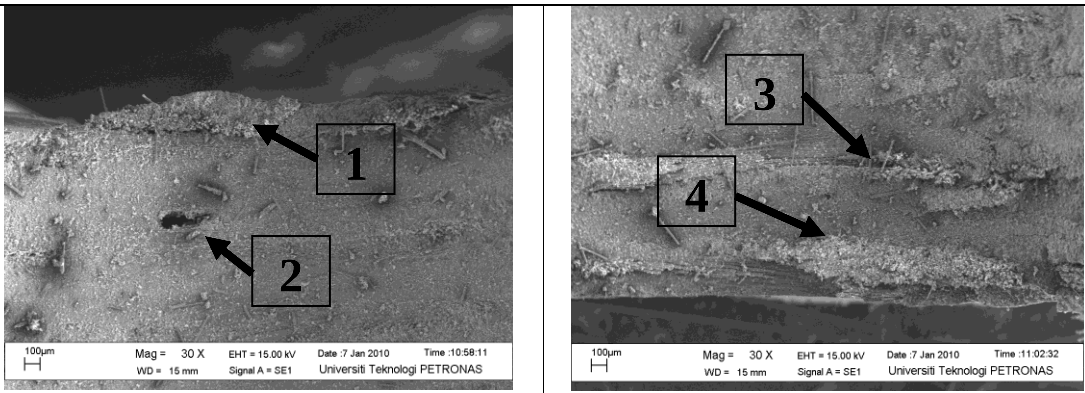
The surface roughness (Ra) of the drilled holes for 10 mm thickness composites using epoxy resin as matrix materials shows that GRE fiber composites have lower surface roughness (Ra) compare to GCRE (hybrid) fiber composites. This may be due to the matrix smearing during drilling process occurred when drilling GRE fiber composites. Increased in feed rate resulted in increasing the surface roughness (Ra) of the drilled holes. This is because the higher force applied tending to shear the glass fiber instead of breaking them.

4.4.3 Microstructure Surface of the Drilled Holes

SEM demonstrated the changes of the composites' microstructure due to the drilling process. The changes of composites' microstructure may affect resulted on the damage around the holes and damage occurred across the depth of the holes wall. The damage occurred around the holes are due to the delamination and fiber-matrix debonding. This type of damage was measured using damage factor (F_d). Matrix microcracking, fiber pull-out and fiber-matrix debonding are damages that occurred across the depth of the holes wall. These types of damages were observed using surface roughness checker before examining using SEM. This damage may lead to severe damage when the composites are used for fastening purpose.

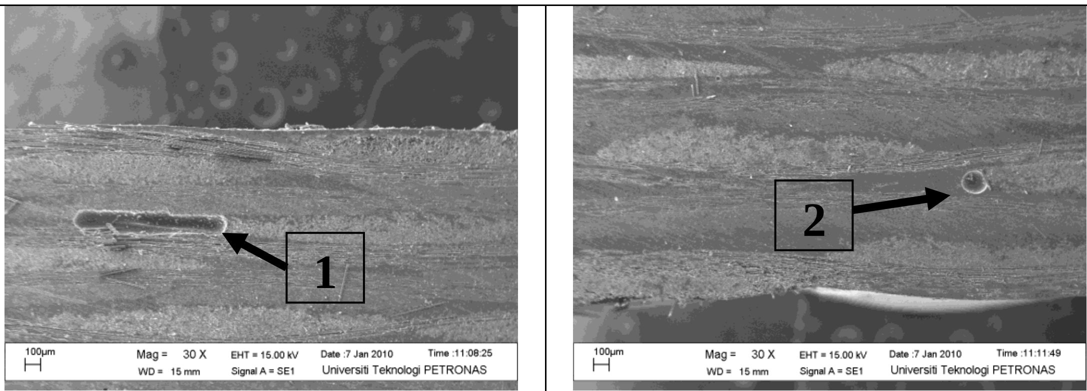
4.4.3.1 3 mm Thickness Composites using Polyester Resin as Matrix Materials

Figure 4.21 (a) shows that the damage factor (F_d) of the drilled holes was influenced by the delamination of the composites occurred on top surface of the drilled holes. The walls of the drilled holes show that the surface roughness not only influenced by the fiber pull out or matrix microcracking but also by the porosity of the holes wall and composites chips (Fig. 4.22 (a) and (b)).



(a) (b)

Figure 4.22 : Surface microstructure of the drilled holes for 3 mm thickness GRP fiber composites (a) Upper part: 1. Delamination 2. Porosity (b) Lower part : 3. Matrix Microcraking 4. Fiber pull-out



(a) (b)

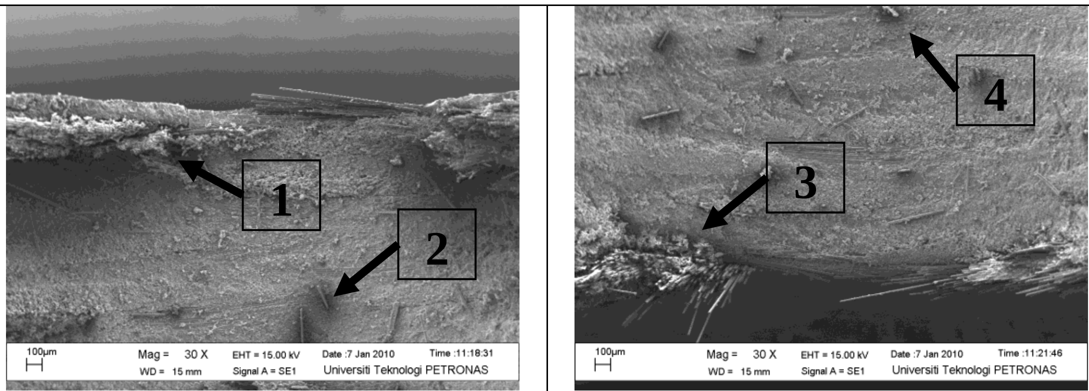
Figure 4.23 : Surface microstructure of the drilled holes for 3 mm thickness GCRP (hybrid) fiber composites (a) Upper part: 1. Porosity (b) Lower part: 2. Porosity

Figure 4.22 (a) shows the delamination on top surface of the drilled holes is almost insignificant. This agreed with the damage factor (F_d) evaluation. GCRP (hybrid) fiber composites have lower damage factor (F_d) compare to the GRP fiber composites. These figure (Fig. 4.23 (a) and (b)) shows that the walls of the drilled holes of GCRP (hybrid) fiber composites have better surface compare to GRP fiber composites. The roughness of the walls surface was influenced by the porosity.

Drilling 3 mm thickness composites using polyester resin as matrix materials shows that GCRP (hybrid) fiber composites producing less damage at the upper part influenced by the delamination. GRP fiber composites have rougher surface due to matrix microcracking, fiber pull-out and porosity. The damage of the drilled holes was affected by the drilling and the fabrication process.

4.4.3.2 10 mm Thickness Composites using Polyester Resin as Matrix Materials

Figure 4.24 shows that the damage factor (F_d) for 10-mm GRP fiber composites was influenced by the delamination. The matrix microcracking and fiber pull out is almost insignificant for this composites as shown in both figure (Fig. 4.23 (a) and (b)). The delamination is shown at the lower part of the drilled holes that contribute to higher surface roughness.



(a) (b)

Figure 4.24: Surface microstructure of the drilled holes for 10 mm thickness GRP fiber composites (a) Upper part: 1. Delamination 2. Chip formation (b) Lower part: 3. Delamination 4.Chip formation

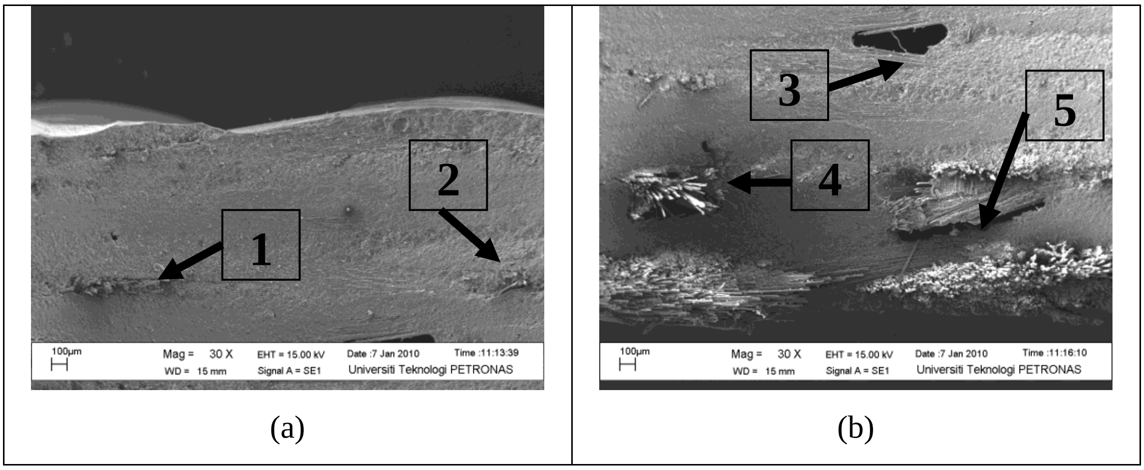


Figure 4.25 : Surface microstructure of the drilled holes for 10 mm thickness GCRP (hybrid) fiber composites (a) Upper part: 1.Fiber pull-out 2. Porosity (b) Lower part: 3. Porosity 4. Fiber pull-out 5. Fiber- matrix debonding

Figure 4.25 shows that the delamination on top surface of the drilled holes is almost insignificant. But at the wall of the drilled holes, severe damage can be seen that lead to higher surface roughness of the 10 mm thickness GCRP (hybrid) fiber composites.

For examples; fibers pull-out, matrix microcracking, porosity, fiber-matix debonding.

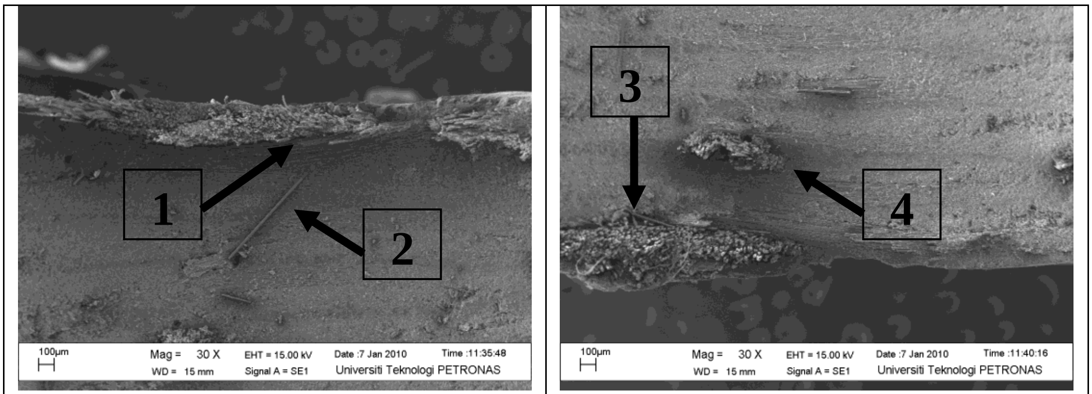
Drilling GCRP (hybrid) fiber composites reducing the delamination at the drilled entrance compare to GRP fiber composites that may increased the damage factor of GRP fiber composites. The roughness of both composites drilled holes wall were influenced by; drilling chip, fiber pull-out, porosity and fiber matrix debonding.

4.4.3.3 3 mm Thickness Composites using Epoxy Resin as Matrix Materials

3 mm thickness of GRE fiber composites shows that the damage factor (F_d) was influenced by the delamination at the entrance of the drilled holes (Fig. 4.26(a)). The surface roughness of GRE fiber composites was influenced by the drilling chips, fiber pull-out and matrix microcracking.

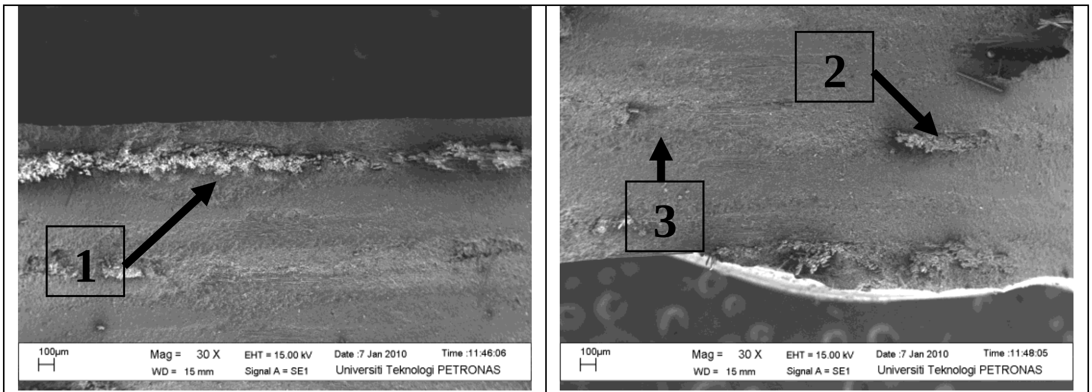
3 mm thickness GCRE (hybrid) fiber composites have almost insignificant delamination at the drilled holes entrance. But, the fiber pull out is severe just after

drilled holes entrance. This may be the factor of the damage factor occurred at this composites. The surface of the drilled holes wall is smoother than 3 mm thickness GRE fiber composites. Fiber pull-out and porosity contribute to the higher surface of the drilled holes wall.



(a) (b)

Figure 4.26: Surface microstructure of the drilled holes for 3 mm thickness GRE fiber composites (a) Upper part: 1. Delamination 2. Drilling chips (b) Lower part: 3. Matrix microcracking 4. Fiber pull-out.



(a) (b)

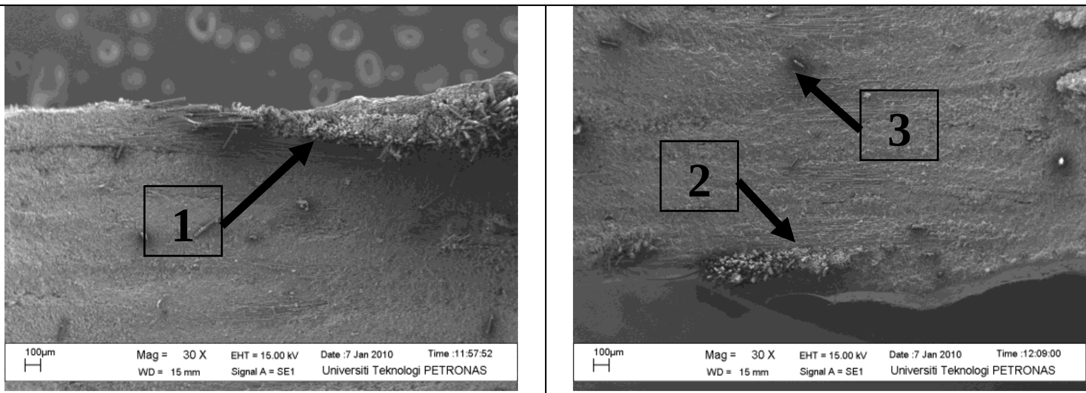
Figure 4.27: Surface microstructure of the drilled holes for 3 mm thickness GCRE (hybrid) fiber composites (a) Upper part: 1. Fiber pull-out (b) Lower part: 2. Fiber pull-out 3. Porosity.

3 mm thickness GRE fiber composites have significant damage both at the entrance and at the holes wall that leads to higher damage factor and surface roughness compare to GCRE (hybrid) fiber composites. GCRE (hybrid) fiber

composites have smoother surface compare to GRE fiber composites.

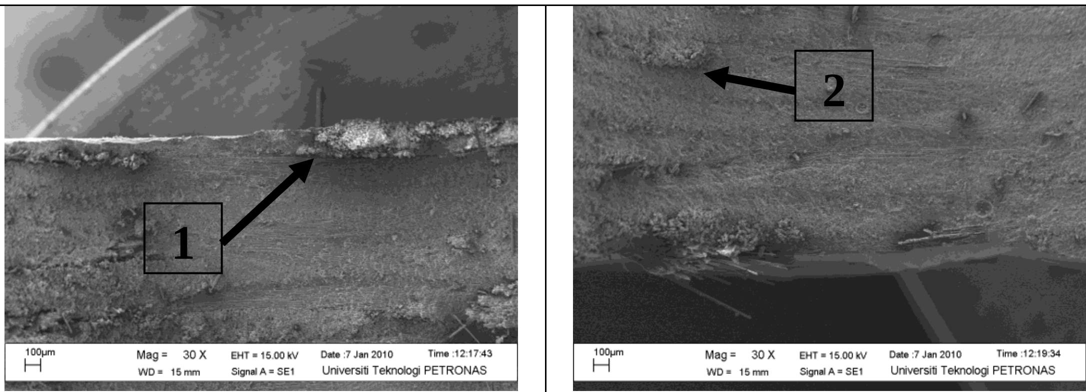
4.4.3.4 10 mm Thickness Composites using Epoxy Resin as Matrix Materials

10 mm thickness GRE fiber composites show that the damage factor of the drilled holes was affected by the delamination at the holes entrance (Fig. 4.28 (a)). No matrix cracking shows at the drilled holes wall. Fiber pull-out and drilling chips can be seen at the lower part of the drilled holes (Fig. 4.29 (b)).



(a) (b)

Figure 4.28: Surface microstructure of the drilled holes for 10 mm thickness GRE fiber composites (a) Upper part: 1. Delamination (b) Lower part: 2. Fiber pull-out 3.Drilling chips.



(a) (b)

Figure 4.29: Surface microstructure of the drilled holes for 10-mm thickness GCRE (hybrid) fiber composites (a) Upper part: 1. Delamination (b) Lower part: 2. Fiber pull-out.

Delamination at the entrance of the drilled holes can be seen when drilling 10 mm thickness GCRE (hybrid) fiber composites (Fig. 4.28(a)). The roughness of the drilled holes wall was influenced by the fiber pull out.

Both composites do not experienced matrix microcracking damage. Delamination and fiber pull out is the main concern in influencing the damage factor (F_d) and higher surface roughness of the drilled holes wall. Drilling chips is another factor of increasing the roughness of the drilled holes walls. Porosity is insignificant in fabricating 10 mm thickness composites using epoxy resin as matrix materials. It is due to the curing epoxy resin in the oven for 60°C have reducing the air trapped at the matrix materials.

CHAPTER 5
CONCLUSION

In this research, it can be concluded that both hybrid fiber composites (GCRP and GCRE) have lower density but higher strength compare to fiber composites (GRP and GRE). It is because; the alternating carbon fiber which has lower density but higher mechanical properties than glass fiber in the hybrid fiber composites has reduced the density and increased the mechanical properties of this composites.

3 mm thickness polyester based composites shows that hybrid fiber composites with higher strength resulted lower damage factor (F_d) compare to the fiber composites. As the thickness increased to 10 mm, the damage factor (F_d) of fiber composites are lower compare to hybrid fiber composites. The reason behind this was fiber composites with lower mechanical properties be able to absorb thrust force applied at the top surface when the thickness of this composites is increasing. For epoxy based composites, lower interlaminar bonding of 3 mm thickness fiber composites has reduced the cutting resistance during drilling resulted in lower damage factor (F_d). 10 mm thickness hybrid fiber composites of epoxy based has lower damage factor (F_d) compare to fiber composites due to higher interlaminar bonding.

Hybrid fiber composites of polyester based for 3 mm thickness have better surface roughness compare to fiber composites due to brittle fracture during drilling process. The brittle fracture of the hybrid fiber composites resulted in better surface roughness of the drilled holes even in higher thickness (10 mm). Alternating carbon fiber in hybrid fiber composites resulted in brittle fracture during drilling and lead to the better surface roughness even though the composites was fabricated using different matrix (epoxy) in 3 mm thickness. However, no significant different on the surface roughness between fiber composites and hybrid fiber composites of epoxy based composites as the thickness increased to 10 mm because the matrix were protecting the fiber for both type of composites.

Evaluation on the surface microstructure using scanning electron microscope (SEM) concluded that two damages occurred on the fiber composites and hybrid fiber composites. The damages were classified as damage during fabrication process and damage during drilling process. Porosity is the only damage occurred during fabrication process. delamination, fiber pull-out, fiber-matrix debonding and matrix cracking were the damages observed under SEM at the drilling process.

Based on the finding of this research, it can be concluded that drill GCRP (hybrid) fiber composites at 3 mm thickness with lowest cutting speed and feed rate were more suitable compare to GRP fiber composites. On the other hand, it was more suitable to drill GRE fiber composites at 10 mm thickness with lowest cutting speed and feed rate compare to GCRE (hybrid) fiber composites.

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APPENDIX A

A STUDY OF HYBRID COMPOSITE DRILLING USING SOLID CARBIDE DRILL AT DIFFERENT DRILLING PARAMETERS

Mohd Azuwan Bin Maoinser and Faiz Ahmad
Masters of Science in Mechanical Engineering
Universiti Teknologi PETRONAS
E-mail: azuwan_173@yahoo.com.

ABSTRACT

Drilling of materials is a common practice in industry due to the need for component assembly in mechanical pieces and structures. Drilling of composites materials is affected by the tool wear that leads to poor surface of the drilled holes and high value of damage factor which affected the dimensional precision. The aim of this paper is to study the drilling of hybrid composite developed by epoxy reinforced by glass and carbon fiber. The research focused on various thicknesses of hybrid composite and different drilling parameters. The hybrid composite is manufactured using the hand lay-up technique. A stepped structure design was chosen to fabricate the composite plate in order to achieve the consistent mechanical properties and to compare the damage at the interface, to measure the surface roughness of the drilled holes, to examine the microstructure of the holes and to study the effect of the drilling on the drill bit. The objective of this experiment is to establish correlation between the cutting velocity, different thickness of the hybrid composite with the damage radial distance, surface roughness of the drilled holes, the microstructure of the drilled holes and the tool wear of the drill bit. Based on the experimental result, it can be concluded that the optimum way of drilling hybrid composite can be achieved.

Key words: Drilling

INTRODUCTION

The use of composite materials has increased in various areas of science and technology due to their special properties. Glass and carbon fiber are the most commonly used in mechanical joints in pieces structures in industry. The combination of this fiber with the aid of the epoxy matrix results in hybrid composite. However, the drilling of hybrid composite need to be further studied since it is a new material development in composite industry. The mechanism of machining composite materials has been recognized as a process fundamentally different from that of homogenous metal removal [1]. The diverse properties of the fiber and the matrix combined with the fiber orientation have a significant effect on the machining process [2]. During machining the fibers take high proportions of the loads and according to *Koplev et al.*[3] these loaded fibers serve to impair uniform plastic deformation as would normally be seen in chip formation during metal cutting.

The works of various authors, when reporting on drilling damage of composite materials, have shown that the hole surface quality (damage radial distance and surface roughness) is strongly dependent on cutting parameters and tool wear.

The work developed by Chambers and Bishop [4] is the problems of tool wear, and concluded that it was very difficult to achieve the surface quality needed for the accurate assembly of components in mechanical structures.

Lin et al. [5] have studied on drilling composite material on high speed and concluded that an increase of the cutting velocity leads to an increasing drill wear that in turn provokes it an increase the thrust force.

There are several way of evaluating the tool wear of the drill bit, the surface roughness and damage factor of the drilled holes. M. Ramulu et al. [6] have studied on the drilling of composite and titanium stacks use the optical microscope at the flank face on the drills in order to determine the influence of spindle speed and feed when drilling Gr/ Bi – Ti stacks. D. Bhattachraya and D.P. W. Horrigan [1] study the hole drilling in Kevlar composites use Surtronic-3 to measure the surface roughness of the drilling holes. The equipments used to evaluate the damage factor for the delamination in drilling GFR-thermoset composites are: PC, color flatbed scanner and image software (Corel Draw) is used by U.A. Khashaba. [7]

The present paper used 3D Non Contact to examine the tool wear of the drill bit. Hommeltester T1000 is used to measure the surface roughness of the drilled holes and 3D Non- Contact is used to measure the damage radial distance of the drilled holes and Scanning Electron Microscope (S.E.M) to examine the microstrcuture of the drilled holes.

The main objective of the present work is to study the influence of drilling on tool wear, surface roughness and damage radial distance of the hybrid composite consist of epoxy reinforced by glass and carbon fiber. The variables cutting speed and feed rate are used in this experiment. The optimum way of drilling hybrid composite presented at the end of this paper.

EXPERIMENTAL DETAILS

Materials

The fibers used in this project are glass and carbon. All of the fibers are in woven types. The properties of the fibers used are stated below in table 1.

Fiber	Areal Density	Weight of 17cm X 40 cm for 1 Ply (g)
Glass	385	26.18
Carbon	200	13.6

Table 11: Properties of fiber

A composite is a homogenous combination of two or more materials, which are reinforcing fiber embedded in to resin system, resulted different in form of composition on a macro scale. [8] There are two different resin were used in this experiment; epoxy and polyester. The density of the epoxy is 1200 kg/m^3 while the density of the polyester is $1100kg/m^3$.

Constituent Properties	Density, ρ (kg/m^3)	Tensile Modulus, E (GPa)	Tensile Strenght, σ (MPa)	Poisson's Ratio
Polyester	1100	2.09	41.8	0.33
Epoxy	1200	3.83	83.6	0.33
Glass	2500	73	2400	0.22
Carbon	1800	251	4500	0.2
Kevlar 49	1450	125	3600	3.5

Table 12: Physical properties of fiber and matrix material

The summarized properties of the fiber and matrix material are given by SN Chemical and have been tested in laboratory [9]. In order to fabricate the composite, the rule of mixture is used to calculate the correct composition of volume fraction of fiber. Fiber Volume Fraction (FVF) used in this experiment is 55%.

Development of stepped structure

In the hand lay-up technique a liquid resin is applied to the mold and reinforcement is placed on top. Another resin and reinforcement layer is applied until a desired thickness build ups. First, a release agent is applied to the mold surface to remove the impurities and for ease of removal a sample. Then, polyester or epoxy is weighted according to the desired weight and was homogenized with hardener (MEKP for polyester) in the ratio of 50:1 and 10:6 for epoxy [9]. The desired thickness as shown in the Figure 1 of reinforcing fabrics layer is placed on the mould and then it is impregnated with polyester or epoxy resin.

A roller is used to distribute the polyester or epoxy around the surface uniformly for good fiber impregnation to remove the bubble. Another fabric is applied and poured the resin until all the desired thickness of fabrics is achieved. Finally, the stepped structure hybrid composite plate is fabricated. This stepped structure is chosen so that these two different thicknesses of hybrid composite plate will cure at the same time and have same mechanical properties.

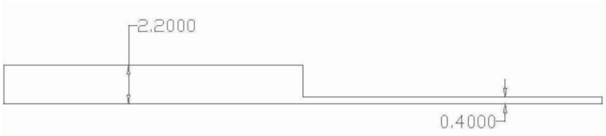

Figure 30: A composite plate with stepped structure

All the weighted polyester or epoxy resin has been prepared early is placed in to the reinforcing fabrics. Finally, the polyester or epoxy is uniformly distributed around the surface.

Drilling of hybrid composite

Drilling experiments were performed using the MTAB XLMILL CNC Trainer Milling machine with 0.5 HP and maximum spindle speed of 3000 rpm. MZE (Solid Carbide) VP15TF of 5mm twist drill with 30^{o} high angle and 140^{o} point angle is used. All tests were performed on three different speeds and feed rate (Table 3).

No.	Cutting Speed (rpm)	Feed Rate (mm/min)
1.	1000	0.05
2.	2000	0.10
3.	3000	0.20

Table 13: Cutting speed and feed rate for drilling hybrid composite plate

The holes were drilled according to the design shown in Figure 2. The distance between the holes with the edge of the hybrid composite plate is about 1.1cm. The distance between one hole to another is 1.6cm. This drilling step is important because composite posses weakest mechanical properties around the area that experience cutting process. The spacing of the drilled holes is design for the characterizing technique (surface rougness and damage factor for the drilled holes). The first three row of the holes consist of 12 holes is drilled for the first cutting speed and feed rate. The second three rows of the holes consist of 12 holes is drilled for the second speed and feed rate. The last three rows of the holes id drilled for the third cutting speed and feed rate. The tests were carried out with the use of top plate and backing plate, a common practice followed in industry to minimized damage at the enrty and exit holes.

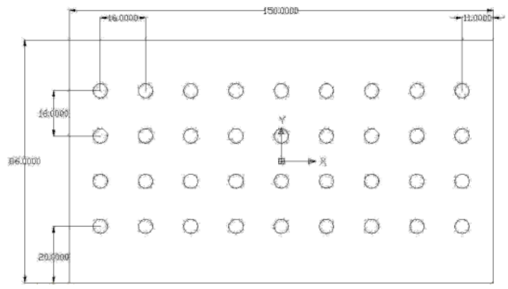

Figure 31: The holes position on the composite plate

The damage radial distance at the interface was measured using Mitutoyo 3D Non-Contact Measuring machine. The MAHR GMBH Perthometer Concept Surface Profiler was used to measure the surface roughness across the depth of the hole walls. Scanning Electron Microscope (S.E.M) machine was used to check the microstructure of the hole walls and the wear of the drill.

RESULTS AND DISCUSSION

Hole Production and Tool Wear

Figure 3 depicting the wear at the tip of the point angle and helical cutting edge of the drill used in this experiment.

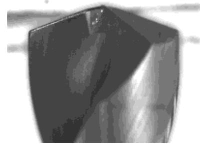	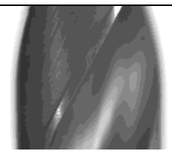
(a) Tip of the point angle	(b)Helical cutting edges

Figure 32: Micrograph showing wears at (a) tip of the point angle (b) helical cutting edge after drilling 36 holes.

S.E.M results shows that the drilling of hybrid composite at different drilling parameters did not affect the tool wear. Consequently, increasing in cutting speed and feed rate have negative effect on the drill wear.

Effect of cutting speed and feed rate on damage radial distance

The damage radial distance at the hole interface was measured using the Mitutoyo 3D Non-Contact Measuring machine. The damage was evaluated based on the discoloration zone around the holes

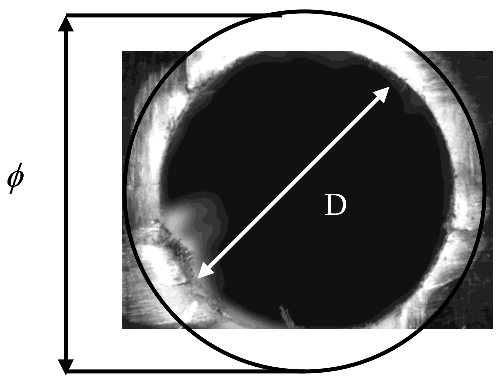

Figure 33 Damage radial distance

Equation (1) is used to measure the damage radial distance.

$$t = \frac{\phi - D}{2} \qquad (1)$$

Based on figure 5, shows that the damage radial distance increase as the feed rate increase. However, the damage radial distance was not affected by cutting speed. It is because the highest cutting speed gives the least damage radial distance. The 2000 rpm cutting speed produce the highest feed rate. Some investigation is made and we found out that the 2000 rpm cutting speed drilling area was not clamped properly.

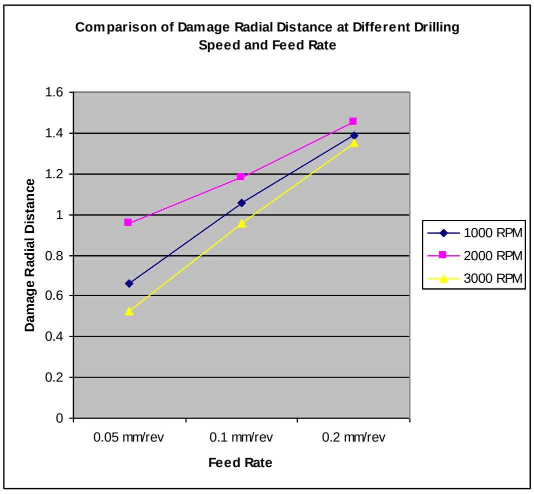

Figure 34 Damage radial distance at different cutting speed and feed rate

The damage radial distance increase as the feed rate increase beacause of the increasing in the force applied on the hybrid composite surface. Furthermore, the way to clamp the hybrid composite was important during drilling process.

Effect of cutting speed and feed rate on the surface roughness

The surface roughness across the depth of the hole wall was checked using the MAHR GMBH Perthometer Concept Surface Profiler. The roughness value was evaluated in Ra.

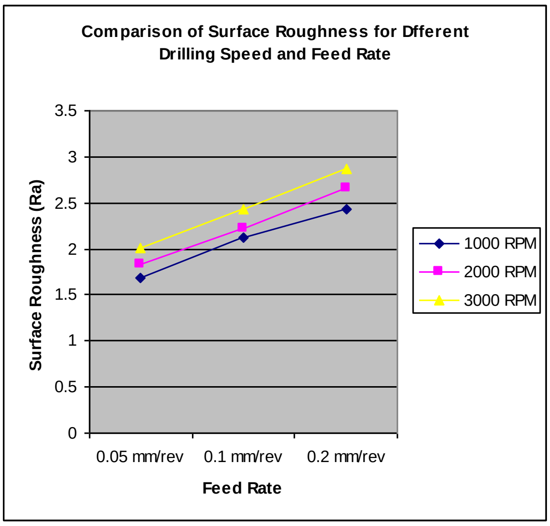

Figure 35 Comparison of surface roughness across the depth of the hole wall

Figure 6 shows that increase in cutting speed and feed rate will increase the surface roughness across the depth of the holes' wall. The temperature between the drill and the drilled holes increased when the cutting speed increased. Excessive temperature when drilling will cause matrix degradation. This lead to debonding at the fiber-matrix interface, resulting in a severe material damage. Matrix smearing also occured when high spindle speeds were used resulted in decreasing the surafce roughness. However, if the fibers were pulled out from the matrix material, the resulting damage increased the surface roughness. Feeds that are too high increase the surface roughness because the drill tends to pull the fibers instead of shearing them (referred to as fiber breakout).

CONCLUSIONS

Based on the experimental result presented, the following conclusions can be draw from drilling of Glass/ Carbon/ Epoxy composite manufactured by hand lay up.

- Economically, HSS can be used for drilling hybrid composite since no tool wear exist during drilling the hybrid composite.
- The optimum machining parameters can be achieved for better surface roughness in drilling hybrid composite
- The optimum machining parameters can be achieved to have low damage factor that affect the dimensional precision on drilling hybrid composite.

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