Process Optimization in Hole Machining of Glass-Fiber Reinforced Polymer Composite

Ataollah Jalalian Alhashemi

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Prof. Dr. Elvan Yılmaz
Director

I certify that this thesis satisfies the requirements as a thesis for the degree of Master of Science in Mechanical Engineering.

Assoc. Prof. Dr. Uğur Atikol
Chair, Department of Mechanical Engineering

We certify that we have read this thesis and that in our opinion it is fully adequate in scope and quality as a thesis for the degree of Master of Science in Mechanical Engineering.

Assist. Prof. Dr. Ghulam Hussain
Supervisor

Examining Committee

1. Prof. Dr. Majid Hashemipour
2. Assist. Prof. Dr. Ghulam Hussain
3. Assist. Prof. Dr. Neriman Özada

ABSTRACT

As Fiber Reinforced Polymer composites (FRPC) in the defense, space and aerospace industries have enjoyed a steady upward trend in usage in recent years, the importance of their machining processes have inevitably been brought to the foreground.Our knowledge of machining FPRC does not seem to be yet fully developed to be applied in its copious fields of applications. As a result, material properties and theoretical mechanics are of great significance in the relevant field of research. Cost effectiveness in production techniques is important to obtain manufacturing cycles which are completely automated and large-scale. There is a need for a certain degree of machining FPRCs to be performed to achieve close fits and tolerances and to get to near-net shape, even though they are normally molded. Unfortunately, as they are anisotropic and non-homogeneous, more often than not, FPRCs encounter serious problems while being machined such as fiber pull-out, delamination, burning and the like. This issue is the significant and dividing difference between machining composite materials and other commonly used metals and their alloys.

Because of different mechanical behavior, hole-machining in glass fiber reinforced polymer composite (GFRPC) is substantially different from that in metallic materials. The drilling of this material may generate delamination of drilled holes on work piece. The purpose of this thesis is to investigate the influence of the cutting parameters, such as rotational speed of spindle and feed rate, on delamination and surface quality of holes in GFRPC and material strength after machining. The said effect of parameter variation was studied for two machining processes namely, milling and drilling. A comprehensive test plan was prepared using a robust design of experiments method, called D-optimal method (a statistical technique). It was found that end milling is better than drilling process to machine holes. Further, in order to control surface quality and delamination, the ratio of rotational speed to feed rate needs to be set around 1. Moreover, in the applications where strength of machined components is an important factor, the processing should be carried out with intermediate values of parameters (i.e., rotational speed= 4100rpm and feed rate= 3100mm/min). Finally, an empirical formula was developed. This formula is deemed to serve as guideline to choose optimal parameters and process in order to produce good quality holes in GFRPCs.

Keywords: GFRPC, Drilling, Milling, Composite, ANOVA

ÖZ

Son yıllarda, fiber savunmalı Polimer kompozitlerin (FRPC) takviyeli olarak kullanılmıs, uzay ve havacılık endüstrileride bir artış gostermıstır. FPRC işleme hakkındaki bilgilerimiz onun henüz tam olarak her alanda uygulanacak ve geliştirilecek bir işlem olarak gostermıyor. Sonuç olarak, malzeme özellikleri ve teorik mekanik araştırma, ilgili alanda büyük öneme sahiptir. Üretim teknikleri, tamamen otomatik ve büyük ölçekli üretim döngüleri elde etmek için önemlidir. Yakın şekilde ve toleranslar elde etmek ve yakın net şekil elde etmek için yapılması gereken işleme FPRCs belli bir derece için bir ihtiyaç normalde kalıplanmış halde bulunmaktadır. Onlar anizotropik ve homojen olmayan olarak ne yazık ki, çoğu zaman, FPRCs elyaf çek gibi işlenmiş olurken, ciddi sorunlarla karşılaşabilirsiniz delaminasyon, yanma ve benzeri. Bu sorun işleme kompozit malzemeler ve diğer sık kullanılan metaller ve alaşımlar arasındaki önemli bir farktır.

Çünkü farklı mekanik davranış, cam elyaf takviyeli polimer kompozit (GFRPC) delik-işleme Metalik malzemelerin bu önemli ölçüde farklıdır. Bu malzemenin sondaj iş parçası üzerinde açılan deliklerin delaminasyonu oluşturabilir. Bu tezin amacı delaminasyonu ve işleme sonra GFRPC ve malzeme gücü delik yüzey kalitesi, böyle mil ve ilerleme hızı dönme hızı gibi kesme parametreleri, etkisini araştırmaktır. Parametre varyasyon etkisi freze ve delme, yani iki işleme süreçleri için incelenmiştir söyledi. Kapsamlı bir test sistemi D-uygun yöntem adı deneysel yöntem sağlam bir tasarımı, (bir istatistik tekniği) kullanılarak hazırlandı. Bu son freze deliklere süreci delme daha iyi olduğu bulunmuştur. Bundan başka, yüzey kalitesini kontrol etmek ve delaminasyon amacıyla, hızı ihtiyaçlarını doyurmaya dönme hızının oranı yaklaşık 1 ayarlanmalıdır. Ayrıca, işlenen parçaların mukavemeti önemli bir faktör olduğu uygulamalarda, işleme parametrelerinin ara değerlere (örneğin, dönme hızı = 4100 ve besleme hızı = 3100mm/min) ile yapılmalıdır. Son olarak, ampirik formülü geliştirilmiştir. Bu formül GFRPCs iyi kaliteli delik üretmek için en iyi parametreleri ve proses seçmek için kılavuz olarak hizmet sayılır.

Anahtar Kelimeler: GFRPC, Delme, Freze, Kompozit, ANOVA

To The Most Precious Family

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ABBREVIATION

GFRP	Glass Fiber Reinforced Polymers
FRP	Fiber Reinforced Polymers
DOE	Design Of Experiment
RSM	Response Surface Methodology
FVF	The Vertical Force
MRPI	Multi Response Performance Index
R_a	Average Arithmetic Value of Roughness
R_q	Root-Mean Square Height
R_p	Pick to Mean Height
R_v	Valley to Mean Height
R_z	Ten-Point Average Height
R_t	Peak To Valley Height
R^2	Multiple Correlation Coefficient
CNC	Computer Numerically Control

Chapter 1

INTRODUCTION

1.1 General

According to its definition, a composite is something which is made from two or more ingredients which in this study they are a fiber and a resin. The idea of composites is far from being novel. The story goes that Prophet Moses (P.B.U.H) floated down the river Nile lying in a basket produced with papyrus reeds covered with pitch. Papyrus, which is a fiber reinforced paper, could be easily used as water-resistant basket due to its structure. It is ancient knowledge that filling bricks with small pieces of straw increase their strength. Reinforcement of mud huts in Africa was made possible with the help of grasses and thin pieces of wood or stick. Furthermore, the Buster Hill farm revealed that sticks which were woven and firmly fixed with a mixture of cow dung and mud were made used of to put up house walls in England in about 3500 years ago. The fact that how they came up with the correct mix ratio for the mud and cow dung is amazing. The walls made of lath and plaster in old houses of England can also be considered as composite. Although the idea is an ancient one, the materials used today have dramatically changed. Carbon, glass fibers and aramid are much more costly in comparison to cow dung and mud mixture used in the past.

The good news is that a certain amount of new materials with the same weight significantly outperform the ancient ones. Besides, natural composites like wood are also used. A tree's structure is composed of long fibers of cellulose which are fixed together by lignin, a protein containing substance. The fibers which go up the stem or trunk and along the branches are arranged in the best way possible to counter the strains of earth gravity and wind forces. Huge radii exist at the trunk to branch and branch to branch joints in order to minimize concentrations of stress at points with high load.

The production of composite materials is through putting different materials together so that they serve as one mechanical unit. The features of so manufactured materials differ in type and size from their ingredients. Therefore, incorporation or changing their properties has become feasible. Moreover, combining the properties and features such as high strength and stiffness at high temperatures is no a possibility. One way to categorize composites is as follows:

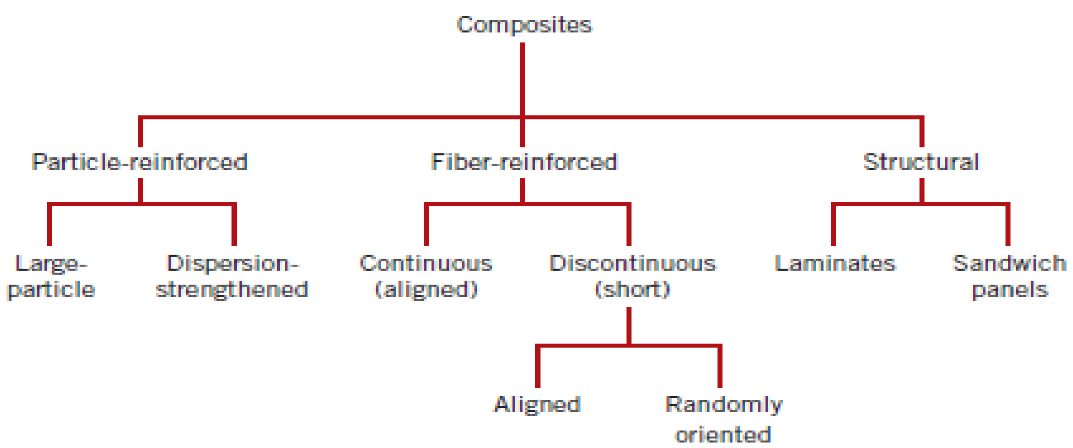


Figure 1: Composites Categorization

Nowadays, glass fiber reinforced polymer (GFRP) composite materials are now a possible choice to engineering materials. It is because they possess great properties and that they have found their way in in copious engineering applications. Unfortunately, their anisotropic features have been problematic for the users at machining stage.

Fiber glass composites are gradually taking the place of numerous materials in various industries which is due to their being economical. These days, the GFRPs are made use of in diverse applications including gas, oil and corrosive environments. The need to machine FRP composites arises from the fact that it is required to converse raw composite materials into engineering component in spite of the capability to produce near net shape constituents. The problem is that the current theory of metal cutting is aimed at continuous materials while FRP composites contain separated fiber bonding in the machine's path. In other words, the how of machining materials of this nature is yet to be explored. FRPs are hard to machine materials due to their arrangement which has resulted in discontinuity in the fiber when machining the composite parts which lowers the performance of that part.

1.2 What Is FRPC?

Fiberglass reinforced plastic, also known as fiberglass, became commercially available after the second world war and ever since, its use has increased exponentially. Fiberglass can also be characterized as a thermosetting plastic resin which is reinforced with glass fibers. Here, the more common terms of fiber reinforced polymer/composites or FRP/composites will be used to describe these highly beneficial material systems. Plastic resins are available in two different types: thermoset and thermoplastic. Practically speaking, thermoset keeps its molded shape when highly heated and it is resistant to melting and reshaping. However, on the other hand, thermoplastics melt at a certain temperature and it is possible to solidify them into novel shapes through by decreasing the ambient temperatures.

The fibers used in reinforcing are glass, carbon, aramid among other artificial and natural material which will be described in the reinforcement section. They are applied in diverse forms and combinations to achieve the desired properties. The plastic resin systems pinpoint the various chemical, electrical and thermal properties and on the other hand fibers give the material its strength, dimensional stability and resistance to high temperatures. Besides, the additives serve as color, pinpointing surface finish and have an effect on properties such as weathering and resistance to flame.

1.3 What Makes a Material a Composite?

Composite materials are formed by combining two or more materials that have quite different properties. The different materials work together to give the composite unique properties, but within the composite you can easily tell the different materials apart – they do not dissolve or blend into each other. Composites exist in nature. A piece of wood is a composite, with long fibers of cellulose (a very complex form of starch) held together by a much weaker substance called lignin. Cellulose is also found in cotton and linen, but it is the binding power of the lignin that makes a piece of timber much stronger than a bundle of cotton fibers.

1.4 Composite's Phases

Composites are materials comprised of two or more constituents which are chemically different from one another on a large scope. Their interfaces clearly differ from each other and regarding their bulk properties, they are noticeably distinct from any other component. Phases of composite material are categorized as follows:

- Matrix phase
- Reinforcement phase

1.4.1 Matrix Phase

Matrix, which is the first phase with a continuous character, is described as being more ductile and less stiff. Polymers, ceramics or metal are the three possible materials of matrix. It is worth mentioning that the bulk part of the composite is provided by the matrix.

1.4.2 Reinforcement

The other phase of a composite, reinforcement, is integrated in the matrix in a non-continuous fashion. This dispersed phase is generally stiffer and stronger than the previous continuous phase. It provides the composite with strength as well as enhancing and compensating for the total mechanical properties of the matrix.

What gives the FRP/composites their strength are type, amount and the arrangement of applied fiber reinforcement. Although a staggering 90% of the used reinforcements are fiber glass, other reinforcements have also found their own place. E-glass, which is the most widely exploited reinforcement, is not only strong but also resists and relatively high temperatures and shows rich electrical properties. In certain cases where higher performance is needed, S-glass is used as it provides higher resistance to heat as well as one-third higher tensile strength, albeit with at a higher cost, in comparison to E-glass. Also, another kind of reinforcement called carbon fiber or graphite comes in a broad spectrum of properties and costs. Interestingly enough, such fibers provide light weight along with noticeably high strength and modules of electricity. These very modules of electricity are a criterion for the level stiffness or hardness in a certain material. When high stiffness is a necessity, they easily outperform others as they are on a par with steel in modules of electricity. FRP/composites made with carbon fiber reinforcement are outstanding in their fatigue properties. In industries such as aircraft and aerospace were having the minimum weight possible is a major concern, carbon fiber is extensively used. However, the commercial exploitation of carbon fiber is under the shadow of its high cost and it is more freely used in low material contents such sport gear.

On the other hand, the aromatic polyamide fibers or aramid in short (Kevlar or Twaron) make the composite highly strong with a density 40% lower than glass and high modules. Such fibers can be made use of in many a polymer and are widely exploited in high impact usages like ballistic resistance. On the other hand, natural fibers like sisal, hemp and flax have had numerous usages when low strength was required and are confined to usages where moisture or high humidity resistance are not a necessity. Direction and level of strength achieved in a molded FRP/composite are determined by the arrangement of the glass fibers which is the way the strands are placed.

The three fundamental arrangement of glass fiber reinforcement are categorized as unidirectional, bidirectional and multidirectional. The first type of arrangements, the unidirectional arrangements make the highest strength in the direction of the fibers possible. It is possible to have continuous or intermittent unidirectional fibers which are purposed according to the part shape and the applied process.

It provides extremely high reinforcement loading for the highest strengths possible. The second arrangement, the bidirectional arrangement, as the name suggests, have two directions which are normally 90^o to each other, making the highest strengths possible in those directions. It is not necessary to apply equal numbers of fibers in both of the directions. While woven bidirectional reinforcements provide high fiber loading, multidirectional or random arrangements allow basically balanced strength in all directions.

1.5 Advantages and Disadvantages of Composites

Composite parts have both advantages and disadvantages when compared to the metal parts they are being used to replace.

1.5.1 Advantages

1. Composites have comparably higher performance with less weight which results in less fuel consumption. Also, they possess lower weights but higher

strength and stiffness. Such a feature is best displayed by *strength divided by density* and *stiffness or modules divided by density*. These are referred to as "specific" strength and "specific" modules features. As pointed out, weight saving is the most salient feature and merit of the composites. Such an advantage point can be expressed through the ratio of strength to weight. It goes without saying that different materials have different strengths or in other words, any material is capable of bearing varying loads for the equal volume (cross-sectional area) of a certain material. For a specific design, the applied material has to display enough strength to counter the load which is supposed to be exerted. If the chosen material is not robust enough, it must be compensated by extending the part to enhance its load bearing capacity. Obviously, such an action raises the bulk and weight of that part. Still, some opt to replace the original material with a material which can tolerate higher strength and hence obviate the unwanted need for higher weight.

2. It is possible to manipulate laminate patterns and ply build up in a part so that it provide the desired mechanical features in ample directions.

3. Obtaining flat and smooth aerodynamic profiles for reducing drag is simpler. It is possible to make intricate double curvature parts with an even and smooth surface finish in a single production operation.

4. They provide magnificent resistance to the elements/water. Such materials barely corrode, absorb insignificant amount of water which result in economical maintenance in a long term.

5. Material can be designed to adapt. This means that it can be made suitable for the loads/performance the final product needs to have optimum performance in its length of time.

6. Composites display magnificent resistance to chemical attack, corrosion and the elements. However, certain chemicals are a menace to composites like paint stripper and therefore researchers are looking for newer kinds of paint and stripper to avoid this problem. Also, some thermoplastics show less than desirable resistance to certain solvents.

7. Economical assembly as they have fewer detail parts and fasteners. Composites provide us with a noteworthy less need for effort to assemble and reduced number of used fasteners. It is possible to merge the detail parts into a unitary cured assembly either during the first cure or by later binding them with adhesives.

1.5.2 Disadvantages

Despite the fact that composites have obvious merits, they have some downsides in comparison to other materials.

1. Manufacturing composites is quite expensive. This problem is being tackled with emergence of more advanced manufacturing methods and it is hoped to have them produced at higher volumes but less expensive.

2. They fail to be strong enough in the out of plane direction where the matrix is the main load bearer. In other words, they ought not to be applied in cases where load paths are intricate like lugs and fittings.

3. The chances of damage and delamination or ply separations are higher and it is relatively burdensome to repair them in comparison to metallic structures.

1.6 Applications of Composite Materials

Reinforced plastics are the material of choice in surface transportation as there gigantic sizes. They make it possible to have rich scope and acceptance of design changes, material and processes. They display comparatively higher strength-weight ratio. Besides being having easily obtainable raw materials, their stiffness and reasonable cost make them a tempting choice hard to resist in surface transportation.

They are also made use of in heavy transport vehicles for economically processing of constituents. Good composites are expected to have good reproductivity and flexible handling by skilled enough workforce. Although it is true that obtaining advanced composites for the sake of savings in weight when it comes to vehicle production is not convincing, carbon fibers reinforced exposits have found their way in racing cars and even car safety.

The first ever applications of composites were polyester resin with suitable fillers and reinforcements in road transportation. It was chosen simply because of its tempting properties like cheapness, simplicity of designing and manufacturing of functional parts, etc. Polyester with diverse reinforcements persists to be applied in enhancing the system and additional applications.

Furthermore, the majority of thermoplastics are mixed with reinforcing fibers in varying degrees and equations. A number of techniques are applied in the production of vehicle parts out of thermoplastics. Besides being economical and having mechanical strength, the ultimate nature of the constituent and the volume needed are deemed when choosing the material.

Where common paint finishing is used, components are produced with thermosetting resins and on the other hand, thermosetting resins are usually applied when manufacturing parts which are molded and can be pigmented. Press molded reinforced polyester are capable of producing huge parts with high volumes and at reasonable cost.

Glass and sisal fibers are normally the most common in producing automobile parts. Sisal is very cheap and this very feature has been the driving force behind much research to find applications for sisal where it is main reinforcing material in filled polyester resin as well as parts where certain mechanical features are demanded with the condition that the appearance is not an issue. One of the uses of sisal is in heater housings which are manufactured by the compression molding technique. As glass fibers come in various forms, it has use in reinforcing a wide spectrum of parts belonging to various types.

1.7 Objective

This study focuses on quantifying the amount of machining damage on a GFRP composite material undergoing trimming operation based surface roughness and its parameters. The purpose is to identify the effect of process parameters such as spindle speed (ω) and feed rate (f) on the surface quality of machined GFRP parts using statistical methods. Moreover, objective is to finding out a machining database to obtain quality GFRP parts by optimizing spindle speed and feed rate. Besides, comparing the results have been made by different type of tools as end mill and drill for the drilling processes.

This process leads us to bargain an optimal solution for successful hole machining. From the other point of view, studying how the different parameters of machining affect surface finishing, also damages are induced.

1.8 Thesis' Report Organization

This report is comprised of five chapters. The first Chapter is Introduction. The second chapter provides background information literature review machining of GFRP. Chapter three discusses the experimental set up and measurement procedures used for the current research work. Chapter four deals with analysis of results of the experiment. Chapter five discusses conclusions as it does also about the future works.

Chapter 2

LITERATURE REVIEW

2.1 Earlier Experiments

Having outstanding features like high strength/weight ratio, composites have found their righteous place as some of the most beneficial and state-of-the-art materials. Therefore, such materials are widely used in a variety of industries such as automotive, aerospace, civil engineering structures and many others. A composite is best defined as a material with different phases which displays a very satisfying level of its component phases so that improved combined properties are achieved. While composites are man-made, there are also naturally occurring forms. Also, the component phases need to have different chemical properties and we should be able to split them by a clear-cut interface. Experience shows that damages brought out by machining may significantly diminish the mechanical material properties (Nobre, 2011).

The main merit of composite materials is the fact that they are stronger and stiffer while they have low density in comparison to bulk materials which makes it possible to reduce the ultimate weight of the part.

It is the reinforcing phase that gives the composite its strength. In many a case, the reinforcement exhibits harder, stronger and stiffer properties in comparison to the matrix. Normally, reinforcement is a fiber or particulate. Particulate composites have dimensions which are almost the same in all directions. They have a variety of shapes such as spherical, platelets or other regular or irregular geometry.

Everstine and Rogers in 1971 were the first to propose and carry out the theoretical work on FRP (Everstine & Rogers, 1971). However, their work was confined to plane deformation of incompressible composites which were reinforced by robust parallel fibers. They came up with the full deformation and stress field and also they estimated the needed forced to keep continuous machining. Sakuma and Seto (Sakuma & Seto, 1981) investigated the impact of cutting temperature on tool wear. Their results indicated that the temperature at the cutting edge corresponded with how deep the cut was. In GFRP cutting, it was attempter to decrease the temperature at the cutting edge by lowering the thermal conductivity of tool materials. They discussed that for GFRP cutting it was more helpful to make use of low thermal conductivity materials since the work piece was a material which insulated heat. To make an analysis of the machinability and tool wear mechanism, Sakuma and Seto (Sakuma & Seto, 1983) measured the cutting resistance and surface roughness. Specimens of the material were turned to the left and right with multi and one layers. However, it was found out that judging impact of tool material and cutting speed on surface roughness was no easy task. Their assumption was that it may have been due to the lack of smoothness of the work piece. As for the multi-layer specimen, they realized that the cutting surface was very low for GFRP. The researchers came to this conclusion that cutting the left-hand wound specimen result in tool wear more than when they are right-hand wound.

In another study Takeyama and Iijima investigated the machinability of GFRP, chip formation, cutting force and surface quality (Takeyama & Iijima, 1988). They came up with the conclusion that fiber orientation highly controls chip formation. While up to 70 fiber angle the chip formation was like metal cutting, above 70 the chip formation became significantly harder. Also, the cutting force (average) was minimized at about 30 fiber angel. Empirically a formula was come up with for the average cutting force. Surface roughness (R_{max}) was found to have a similar trend to cutting force and had its minimal point between 30 to 60 fiber angels. The research reported that surface roughness, burs and sub-surface damage improved while using machining.

Santhanakrishnan et al explored the machined surfaces to see if they could be used in friction surfaces, material removal and tool wear in the machining of GFRP, carbon fiber reinforced polymers and Kevlar reinforced polymers (Santhanakrishnan, Krishnamurthy, & Malhotra, 1988). The authors reported that the sintered carbide tools displayed strap wear on flank and secondary sides in GFRP machining. Sang-Oak et al investigated the machinability (surface roughness) of GFRP with the help of tool materials and tool geometrics(An, Lee, & Noh, 1997). Their conclusion claimed effectiveness of low cutting force and single crystal diamond tool in manufacturing high quality surface. Also, they concluded that a straight edge tool outperformed a round edge tool. It was noted that in order to have a better surface quality feed rate needed to be lowered. Finally, their research claimed that cut depth and cutting speed were irrelevant in the surface finish.

Caprino et al (Caprino, Santo, & Nele, 1998) ran orthogonal cutting tests with the help of high speed steel tools to investigate the trend of the main forces on unidirectional-GFRP. While, the cutting direction was chosen to be the same as the fiber orientation, they changed the tool rake, relief angle and the depth of the cut. Their conclusion was the insignificance of the frictional force exerted by the chip sliding up the tool face in such a way that the interaction between the tool face and chip brought about a force which in practice was normal to the face. A significant part of the total cutting forces came from the forces of the top flank and cutting edge. The vertical force (fvf) varied with all the machining parameters as the tool was compressed against the newly created work material surface. It was possible to decrease Fvf with both the rake and relief angles and showed a linear increase by deepening of the cut.

Palanikumar et al. (Palanikumar, Karunamoorthy, & Karthikeyan, 2006) applied design of experiments for investigation and decreasing the surface roughness (R_a) during GFRP machining. The process factors they studied were cutting speed, work piece fiber orientation angle, the depth of the cut and feed rate. They improve the effectiveness of the factors under the study by applying response table and response graph, normal probability plot, interaction graphs and analysis of variance (ANOVA). Their conclusion was that, on surface roughness, the greatest influence belonged to the feed rate and cutting speed came second. The effect of fiber orientation angle and cut depth on each other is more influential in comparison to other interactions of R_a. According to the analysis, an equation was empirically reached to realize the valid surface roughness solely for a specific factor.

Palikumar et al (Palanikumar, Karunamoorthy, Karthikeyan, & Latha, 2006) applied Taguchi method with fuzzy logic to improve the machining parameters of GFRP composites with various features together with multi-response performance index (MRPI) with the help of a carbide (K10) tool material.

2.2 Mill Machining of Composites

Automation has become the buzzword amongst international competitors to enhance productivity as well as quality. In order to achieve complete automation in machining computer numerically controlled (CNC) machine tools have become popular in recent history. They have favorable features like less need for operator input, higher results in productivity and a high quality machined part. Milling is a fundamental machining operation in juxtaposition to other CNC industrial machining processes. So far, the most popular metal removal operation has been end milling. It has found numerous usages in diverse manufacturing factories such as the aerospace and automotive sectors since it is vital in the manufacturing of slots, pockets, precision molds and dies. The surface quality is very effective in improving milling since a milled surface of high quality greatly enhances fatigue strength, corrosion resistance or creep life. Besides, surface roughness plays an important role in many functional features of parts like contact causing surface friction, wearing, light inflection, heat transmission, capability to give out and keep a lubricant, coating, or resistance to fatigue,. Hence, normally the needed finish surface is made clear and the suitable processes are chosen to achieve the intended quality. Numerous factors play a role in the ultimate roughness of the surface in a CNC milling operation. The ultimate surface roughness might be deemed the result of the following two independent effects:

1) Geometry of tool and feed rate result in the ideal surface roughness

2) Aberrations in the cutting operation cause the natural surface roughness (Boothroyd & Knight, 1989).

It is possible to set up factors like spindle speed, feed rate and cut depth, all of which control the cutting operation beforehand. On the other hand there are uncontrolled factors like tool geometry, tool wear, chip load and chi formations or the material properties of both tool and work piece (Huynh & Fan, 1992). Even in the event of chatter or vibrations of the machine tool, faults in the work material structure, tool wear, or abnormalities of chip formation are effective in the surface damage during in the practical phase while machining (Boothroyd & Knight, 1989). It is required to come up with new methods of knowing the surface roughness of a product before milling so that it is possible to appraise the fitness of machining factors like feed rate or spindle speed for maintaining a favorable surface roughness and enhancing the quality of the end product. This prediction technique needs to be precise, dependable, cheap and leave no damage. Hence, this study aims at developing a surface prediction technique which is called multiple regression prediction model and after that appraise its precision of prediction.

The aforementioned machining factors such as work piece fiber orientation, cutting speed, feed rate, cut depth and machining time were improved with deeming multiple performance features of tool wear and surface roughness. The optimal settings turned out to have significant improvement in the performance characteristics. Work piece fiber orientation and machining time were reported to be more influential in machining GFRP composites. The surface finish of the machined surface GFRP pipes as investigated through Taguchi's design method proposed by Aravindan et al (Sait, Aravindan, & Haq, 2009)

The machining features were studied according to surface roughness and tool wear. The machining parameters were made more effective with ANOVA. Both simple regression and cross product regression methods were made use of. Empirically, a model was designed to realize the improvement percentage in tool wear as well as surface finish.

2.3 Drilling of Composites

The usual method of drilling with twist drill persists to be the most cost effective and effective machining process for creating a hole and also for riveting and fastening structural assemblies in industries like aerospace and automotive industries (Tsao, 2008). Drilling composites have proved to be problematic where fiber pullout, delamination, fuzziness and the like are the commonly reported complications. Such problems may be put down to the anisotropic feature of this material. Since composites contain soft epoxy matrix and hard fibers, their machining demands a renewed view of cutting processes to obtain precision and efficiency (Lubin, 1982). The whole mechanism used in machining GFRP is completely different to that of metals. While machining, some of the unfavorable features of composites are the rapid tool wear, rough surface finished on the ultimate constituents as well as a defective sub-surface layer containing cracks and delamination (An, Lee, & Noh, 1997).

Researching drilling of composite materials is a popular subject amongst researchers. For example, Ogawa et al. investigated the relationship between cutting force and the surface roughness of a drilled hole wall when GFRP is drilled in a small diameter for a printed wiring board (Ogawa et al., 1997). They reported that the principal cutting edge of the drill is more influential in comparison to the chisel edge of the drill in obtaining a high quality hole.

Chapter 3

METHODOLOGY

3.1 Design of Experiment

Design of experiment also known as experimental design is a systematic and well organized method for carrying out and doing analysis on controlled tests in order to appraise the parameters that cause a response variable. The design of experiments determines the specific setting levels of the mixture of parameters for the way any test in the experiment is supposed to be run. The multi-variable testing method changes the factors at the same time. Since the changing of factors do not depend on one another, developing a rough predictive model is feasible. It should be pointed out that the obtained data from either observational studies or the ones not obtained via a design of experiments cannot go beyond establishing correlation to claim causality. The traditional experimental method of varying factors one after the other are not free of problems and they include inefficiency and incapability in pinpointing the effects brought about by many factors which work in relation with each other. Choosing the suitable combination of machining factors generate the necessary surface finish and combining such factors and parameters is vital as it pinpoints the right values of surface roughness and metal removal rate. It is required to come up with mathematical models of predicting the impact of the operating conditions. In this work, some mathematical models have been designed to predict the surface roughness and strength using response surface methodology in design of experiments.

Response Surface Method (RSM) not only feasible but also precise and simple to implement. In design of experiments (DOE), the most significant variable s and factors at play in quality are studied and a plan for carrying out such experiments is devised. The experimental data is made use of in coming up with mathematical models with the help of regression models and analysis of variance is performed to make sure the model is valid. RSM optimization procedure has been employed to optimize the output response surface roughness exposed to turning parameters which include speed, feed and type of material with the help of multi objective function model.

D-optional method was chosen as it demands fewer tests without being forced to jeopardize results accuracy. Suitability of traditional experimental designs are in the calibration of linear models in experimental settings where there is no constraint on the factors in the desired region. However, there are cases in which models are not fundamentally linear. Furthermore, in certain cases, the treatments (combination of factor levels) may not be cost effective or measurable. D-optional designs are model specific designs which attempt to compensate for the limitations of traditional design. A D-optional design is created by an iterative search algorithm and aims at lowering the covariance of parameter estimates for a certain mode.

Design expert DX7 [0] software has been employed to formulate test plan for the current work. The minimum and maximum levels as shown in Table 1 were input into software and the software in return offered a test plan of 11 experiments as listed in Table 1.

Table 1: Spindle Speeds and Feed Rates

Samples	ω (rpm)	*f*(mm/min)
1	4100	3100
2	200	6000
3	200	200
4	200	200
5	4100	3100
6	8000	200
7	8000	6000
8	8000	200
9	8000	3100
10	4100	6000
11	4100	200

Contrary to the input data, the output data have no effect on the designed experiment. It is possible to remove or add them without a change in results. In this very case, responses are R_a, R_v , R_p and tensile strength.

The experiments' plan is comprised of 11 tests (array rows) in which the first column was assigned to the spindle speed (ω) and the following the column is dedicated to the feed rate (f) and the remainder of columns were reserved for the interactions.

3.2 Material Property

The work piece material employed in this experiment is multidirectional glass fiber reinforced composite with a thickness of 1cm. The work piece was cut into blanks of 15.8 cm by 3.9 cm size for the current experience and thickness was deemed 0.9 cm. Finally, the GFRP material in this study has a 12-ply layup.

Data given was based on Load (N) and therefore all the data have been by the cross sectional area of the specimen to obtain the value of stress ($\sigma = \frac{f}{A}$). Moreover, it should be noted that changes in elongation to the initial area (Ao) is strain.

It goes without saying that in various ways, a composite may fall short of the ideal while it is manufactured or when it is used. Calling these differences to the ideal a defect depends on the required usage of the material and the importance of the difference on the desired performance. While it is a fact that all types of defects cause adverse and unfavorable effects on performance, the type and size of defect to be recognized can be set for any application according to the results of mechanical destructive tests and it is a necessity to precisely know how such defects grow and if they grow at all in the future service environment. This process determines the criteria of acceptance for production and in-service defects. It is beyond the scope of this article to address the issue of defects in depth but it needs to emphasize that an assessment of defect significance is necessary before meaningful acceptance and rejection criteria can be established. Since the glass fibers in this study are artificial and man-made, naturally, they had some defects inside the texture of material in the form of bubble.

3.3 Cutting Tools

The used tools in this experiment are the conventional drill and end-mill tool with 8^{mm} diameters produced by the company Ultra Tools. The tools are labeled HSS which means they have high speed machining applications as well.

Figure 2: (8^{mm}) End Mill Tool

Figure 3: (8^{mm}) Drill Tool

3.4 Machine Setup Procedure

The machine used for this experiment is a Dugard ECO 760 3-axis CNC manufactured by Timesavers. Specifications of the machine are given as follows:

Table 2: CNC Machine Specification

Spindle Speed Type	Air cooled, quick change
Spindle Speed	8000rpm (opt 10000rpm)
Feed Rate (X-Y-Z)	24 m/min
CNC controller	Fanuc 0iMD
X-axis Travel Distance	760
Y- axis Travel Distance	430
Z- axis Travel Distance	460

3.5 Clamping

In metalworking, a jig is what commonly referred to as an especially made tool for the purpose of controlling the motion and movement of another tool. The main purpose behind a jig is ensuring precision and repeatability in manufacturing and making of products. The jig vase was made in exactly the same size as specimen with the difference that the height was half its size as it was more convenient for take out and put in.

Figure 4: Jig

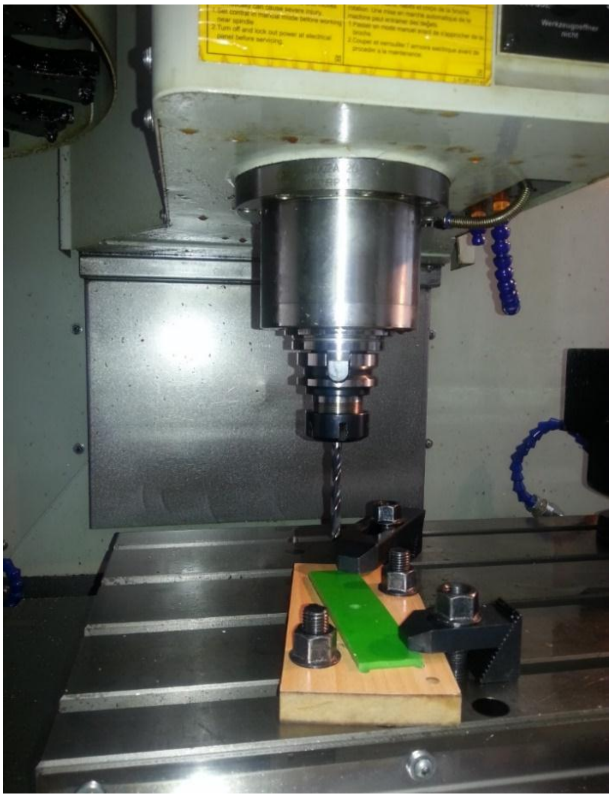


Figure 5: Clamping

The holes were made with the help two types of tools, namely end-mill and drill, while observing the designed spindle speed and feed rates by Design Expert.

3.5 Surface Quality

The evaluation of machined surfaces is possible through a variety of methods which of course have their own unique characteristics relevant to the desired quality. Mechanical performance of homogenous materials induced the material and surface topography which are a result of their dependence on residual stress. As FRP does not develop residual stress during machining, to appraise the machined FRP quality, surface profilometry and visual techniques are considered.

Two principal aspects of machined GFRP's quality are surface topography and machine damage which are characterized by surface roughness and delamination in order. Surface of a machined GFRP mostly is comprised of little holes, fiber cracks, fiber chipping and blur of matrix material.

Furthermore, there are also other factors at play in surface roughness such as tool wear, feed rate and temperature. The parameters characterizing a machined surface are of two categories of roughness parameters (R_a, R_q, R_z, R_t) an statistical parameters like skewedness, kurtosis and frequency height distributions. Various roughness is subcategorized as arithmetic average height (R_a), root-mean square height (R_q), peak to valley height (R_t), valley to mean height (R_v) and ten-point average height (R_z). Of these subcategories, R_a and R_q are reported to have displayed restricted variation and change in their values with respect to fiber orientation. As a result, the parameters of interest to represent the surface features of composites are peak to valley height (R_t) and ten-point average height (R_z), which are the average of five peak points and five valley points.

The aforementioned roughness parameters serve the purpose of appraising the surface produced by a machining process and quantifying the machining damage amount for various process parameters like cutting speed, feed rate and cut depth. It has been revealed that as the value of surface roughness goes down, the quality of machined surface improves. Roughness values also point out to changes in mechanical properties of machined FRP. Relevant literature shows that an increase in roughness results in decrease in fatigue strength and impact strength (Arola & Ramulu, 1995). Roughness was measured on a mechanical surface with the help of the commonly used stylus profilometer instrument. Roughness value is provided by the vertical displacement of a diamond stylus tip which moves along the machined surface. As fiber direction changes from layer to layer, roughness measurement results are highly linked to the stylus path. A yet better way of measuring roughness is keeping the stylus in one layer and recording readings at different locations of this layer or taking readings at different locations for different layers and calculate the average. Yet another important thing worthy of consideration in obtaining roughness measurements of a composite surface is the fact that matrix smearing, fiber protruding and fiber clinging to the stylus tip will play havoc with reading and will not yield a precise enough description of the surface. To compensate for this shortcoming, profilometer reading should be accompanied by visual inspection to quantify surface topography.

3.5.1 Roughness Measurement

After each process of machining whether the drill tool is user or the end mill, roughness was measured by a device named Surface roughness tester TR 200.Besides, all the data was entered in Design Expert software as responses.

Figure 6: TR 200 Roughness Tester

Table 3: TR200 Roughness Tester's Specifications

Roughness parameters	Ra, Rz, Ry, Rq, Rt, Rp,Rmax, Rv, R3z, RS,RSm, RSk, Rmr,
Measuring system	Metric, English
Display resolution	0.01μm
Measuring Range	20 μm , 40 μm, 80 μm
Tolerance	±10%

Roughness data is collected for the end mill tool with consideration range of $\pm 80\mu m$.Probe of roughness test device is located inside the hole with repetition of five times. Whole provided figures are average of measurements after several times. Repetition is a cause for attainment of more precise outcomes. On the first step, roughness of holes were made by End mill tool were measured.

Table 4: Roughness Parameters

Samples	R_a	R_q	R_z	R_t	R_p	R_v
1	2.921	3.726	16.62	26.65	8.507	8.112
2	6.184	8.269	38.01	52.79	17.28	20.72
3	1.948	2.433	11.47	18.6	5.832	5.639
4	1.643	2.084	9.992	13.11	4.656	5.335
5	2.308	2.308	13.78	26.47	5.932	7.852
6	6.454	7.738	29.78	35.09	13.03	16.74
7	3.749	4.77	21.41	38.56	10.32	11.08
8	5.836	7.183	29.95	44.27	13.97	15.98
9	3.994	4.821	19.79	27.36	9.352	10.43
10	2.943	3.764	18.27	29.13	7.547	10.72
11	3.896	4.873	22.55	31	12.8	9.76

Afterwards, samples those hole machined by 8^{mm} Drill tool were admeasured. On the subject of, quality of material surface finishing, although mostly specimens were processed by Drill tool were out of range.

3.5.2 What Is Tensile All About?

The tensile testing is performed with the help of exerting longitudinal or axial load at a certain extension rate to a standard tensile specimen which has known dimensions (gauge length and cross sectional area perpendicular to the load direction) until it fails. To the purpose of calculating stress and strain, the exerted tensile load and extension rate are taken note of. There are a range of standards made available by professional societies like American Society of Testing and Materials (ASTM), British standard, JIS standard and DIN standard from which the tests can be chosen relevant to the desired uses. Every standard may be comprised of diverse test standards appropriate for different materials, dimensions and fabrication history.

Depending on the standard applied, a standard specimen is made ready in a round or square section along the respective gauge length. Both ends of the specimens are required to have enough length and surface condition in such a way that they are securely gripped while being tested. The initial gauge length Lo is consistent and standardized in many countries and changes with the diameter (D_0) or the cross-sectional area (A_0) of the specimen. The reason is that the gauge length is very lengthy and in this case it is possible that the elongation percentage might be estimated less than it really is. The possible heat treatments should be performed on the specimen prior to machining so as to make the ultimate specimen ready for testing. The underlying reason is that oxide scales that might play the role of stress concentration which in turn may have an impact on the ultimate tensile properties as a result of premature failure. Exceptions such as surface hardening or surface coating on the materials are imaginable. To achieve the tensile properties results which contain the actual specimen surface conditions, it is a good idea to employ these processes after specimen machining.

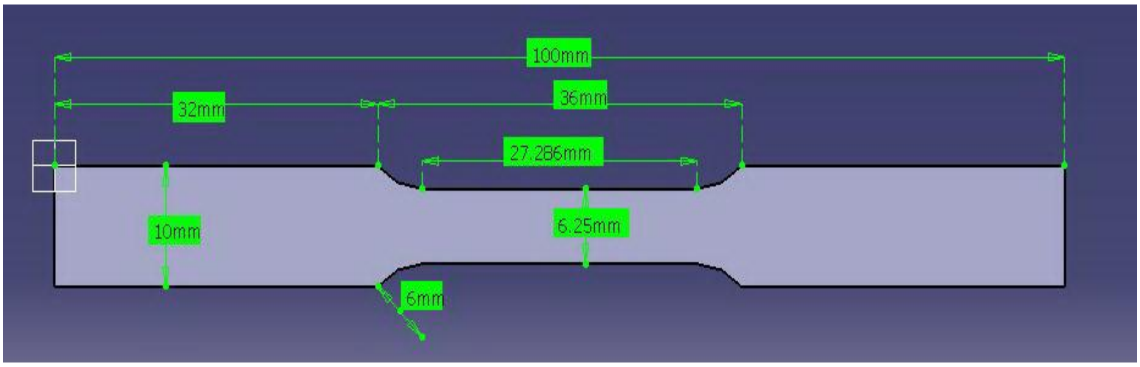


Figure 7: Dimension of Tensile Test Specimen

As noted earlier, the tensile test serves the purpose of obtaining information used later in the design calculations or to make sure the compliance of a material with the necessities of desired specification. Hence, it may be either a quantitative or qualitative test.

The process of this test can be described as gripping the ends of a properly prepared standardized piece in a tensile test machine followed by exerting a load which keeps increasing until the time failure happens.

The applied equipment for tensile testing comes in a range of simple to intricate controlled systems. However, the alleged universal testing machines, which are driven by mechanical screw or hydraulic systems, are the most commonly used. General techniques used for the measurement of loads and displacements benefit from sensors which provide electrical signals. Moreover, while load cells are made used of to measure the exerted load, strain gauges are utilized for measuring strains.

Any change in a linear dimension is equivalent to an electrical voltage change of the strain gauge placed on the specimen.

This method of testing aims at being used in testing resin-compatible sized glass fiber materials which are especially designed to be used with specific generic types of plastics. The application of a resin impregnant compatible with the tested reinforcement material provides results which very well represent the actual strength available in the material when it is used as needed in an end product. There is a possibility for premature reinforcement failure if the resin system is elongated less than the tested reinforcement. This necessity may confine the application of certain resin systems in this procedure. There could be unreliable results if glass fiber materials are tested sans complete resin impregnation of the fiber when an incompatible resin is utilized for impregnation.

While tensile properties may give us beneficial data for plastics engineering and design purposes, due to the highly sensitivity displayed by many plastics to rate od straining and environmental conditions, the collected data in such a way cannot possibly be deemed as valid for uses where there are load-time scales or environments hugely vary from those peculiar to this test method. When such differences are perceived, it is impossible to estimate the cut-off point of usefulness for most of plastics. Such sensitivity to rate of straining dictates testing over a broad load-time scale including impact and creep and scope of environmental conditions should tensile properties are intended to be enough for engineering design purposes.

3.5.2.1 Tensile Test Procedure

The device used for tensile test is Instron 3385 H that electromechanical load frames are designed to apply a load to a test specimen via the moving crosshead. The drive system moves the crosshead up to apply a tensile load on the specimen, or down to apply a compressive load on the specimen.

A load transducer or load cell, which is place in series with the specimen, quantifies the applied load. The load cell which is in position of converting the load into an electrical signal that the system, and hence all the collection and analysis will be done through a software program.

A jog control panel, which is used to carry the crosshead into the initial position when setting up the test, is placed on the load frame. It is possible to change load cells with others of various capacities, yielding a scope of load measuring capabilities confined only by the highest capacity of the load frame. Also, it is feasible to use strain transducers (extensometers) on such systems to quantify strain. The testing system is controlled with an Instron proprietary software program especially developed to test materials.

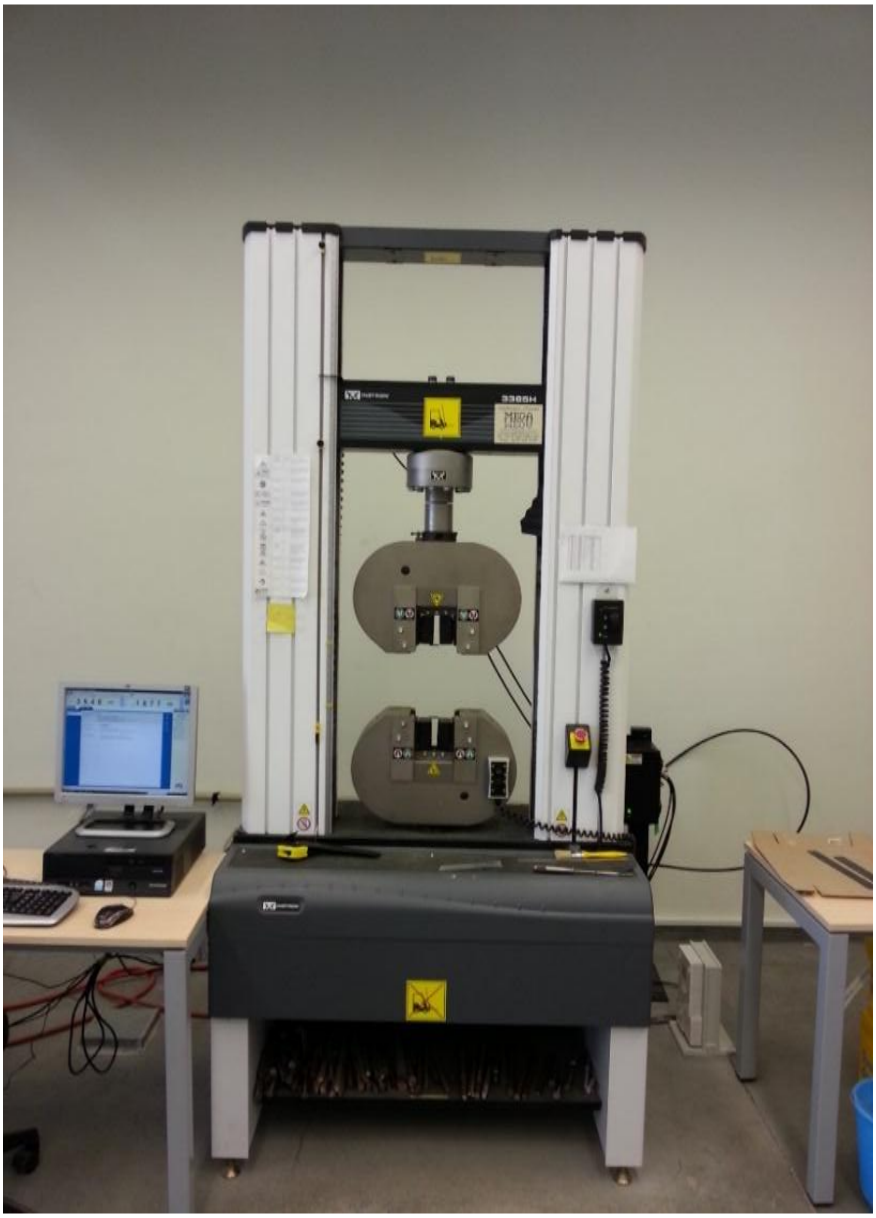


Figure 8: Instron 3385 H

Once the specimen was located between the gripper, the test was commenced. The initial distance between two grippers was a wide as 31 mm which had to be admeasured by hand. A uniaxial force commenced the test. The specimen's dimensions are brought in Figure 7. Practically, the fracture was positioned somewhere in gauge length for area reduction. Subsequently, once the reinforcement failed, it was followed by specimen fracture. The pertaining data are as follows:

Table 5: Tensile Test Outcomes

Yield Tensile Stress	(MPa)	62,46899
Yield Tensile Elongation	(mm)	3,89995
Drawing Tensile Stress Resistance	(MPa)	57,81136
Tensile Strain Resistance	(mm/mm)	0,11452
Tensile Elongation at Resistance	(mm)	3,55
Drawing Fracture Stress	(MPa)	6,09596
Elongation at Break	(mm)	4,08332
Tensile Elongation Resistance	(mm)	3,55
Load Tensile Strength	(N)	2289,33
Modulus (Automatic)	(MPa)	574,642

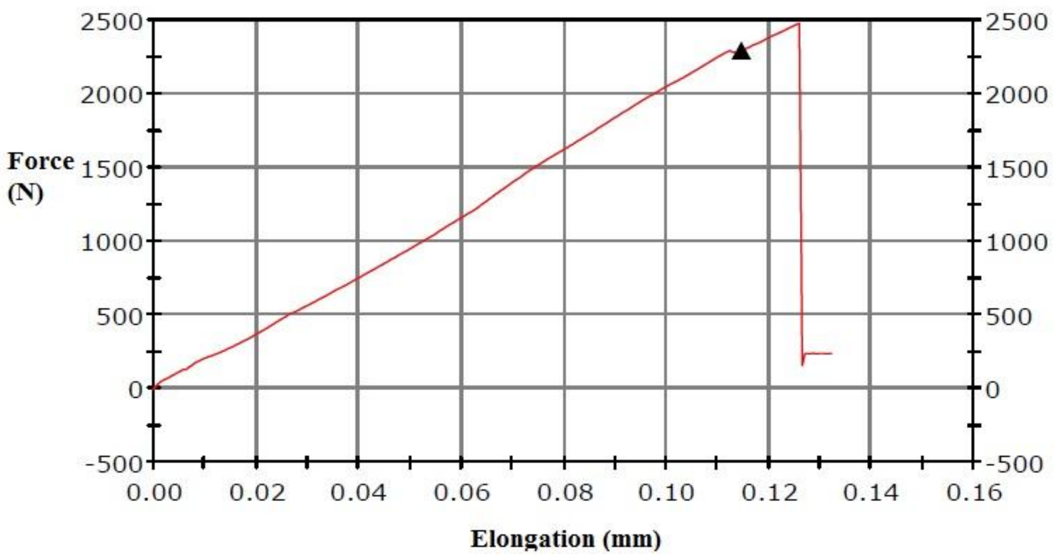


Figure 9: Force to Elongation

After the material’s fracture the given chart was supplied. The Increasing trend of the applied force continues to the point of 2300 (N) which is namely the Yield point that stated by a rectangle, Also, it goes on to the Ultimate point which in that point all the glass fıbers are torn apart. On the other hand, the only resistant factor is resin. On the further stage can be realized that the inclination sharply declined due to the mentioned cause. Plainly could be figured out that the fracture takes place in Elongation of 0.134 ^{mm}.

The Stress-Strain graph is one the most vital elements in illustration of mechanical properties of material after tensile test. Load results and the extension results that are measured subsequently are transformed to stress-strain values that are described as (load/specimen area) and (extension/gauge length) and the results are plotted on a graph. The stress levels resulting from this test are nominal or practical engineering values. Due to the fact that tensile test does not provide any information as to the strength of a beneath high cyclic loadings, so the resistance of the material to shock loading.

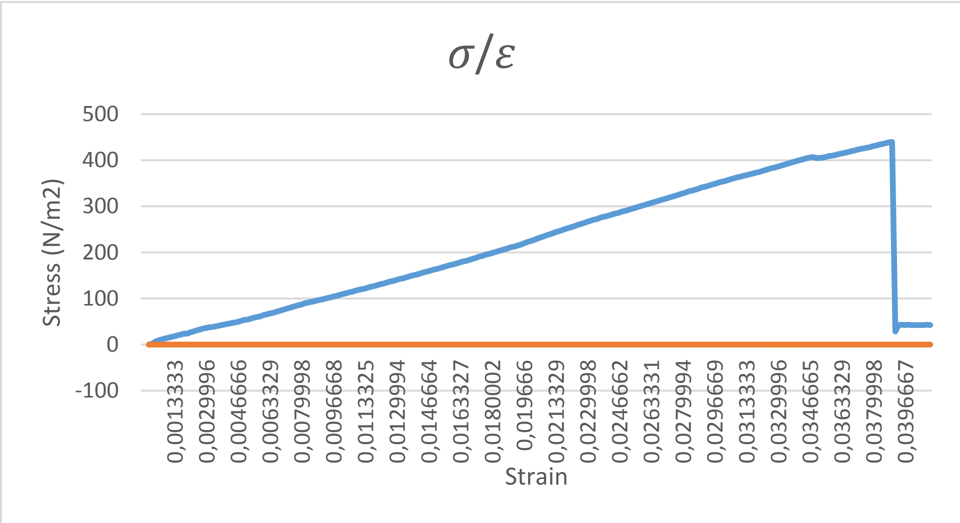


Figure 10: Stress-Strain Graph

After that, all the open hole samples were located into the grippers and were put under the uniaxial force once more. The same procedure as it was done for the raw materials specimen.

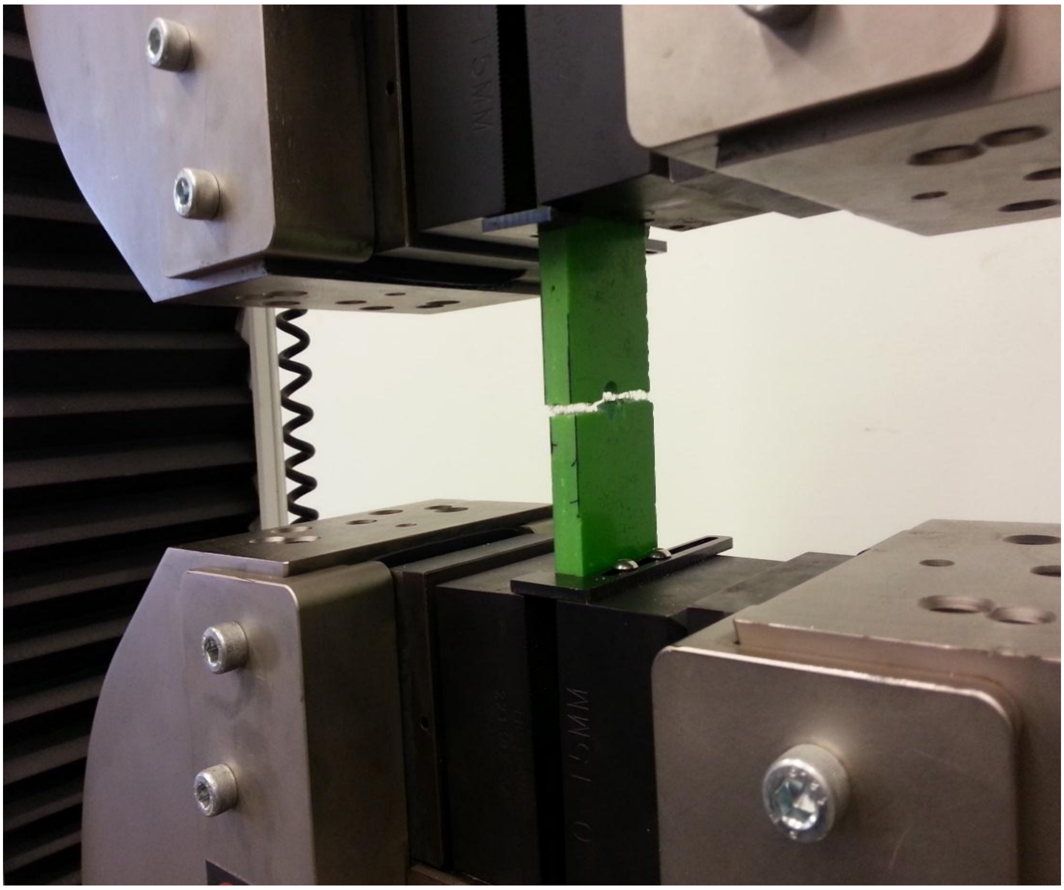


Figure 11: Open Hole Tensile Test

3.5.3 Microscope Observations

The last stage was determination of materials behavior under the optical microscope with 2.54x magnification.

Chapter 4

RESULTS AND DISCUSSION

4.1 Surface Quality of Holes Machined by Milling Process

In this section, the surface quality and strength of samples machined by milling process is discussed.

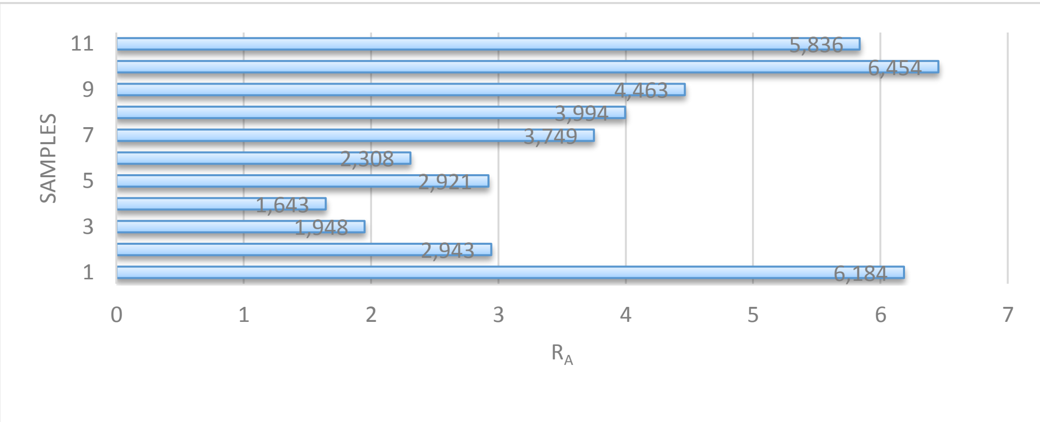


Figure 12: R_a Measurement

4.1.1 Average Roughness (R_a)

Figure 12 presents the R_a (average roughness) results obtained from 11 tests. Test 4 offers the lowest R_a which equals to the value of 1.643μm and test 6 provides the highest value equivalent to 6.454 μm (Table 4). ANOVA (analysis of variance) was performed in order to know the significance of parameters on R_a. It can be seen from ANOVA (Table 6) that the chosen quadratuc model is significant. There is only a

1.34% chance that the model F-Value of 9,5 could occur due to noise. The value of "Prob > F" less than 0.0500 indicate that the model terms are significant. Thus, according to ANOVA, the individual effect of parameters (ω, f) is not important, rather their combination $(\omega * f)$ is significant.

Table 6: ANOVA for Response Surface R_a Quadratic Model

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	
Model	26,37631	5	5,275263	9,577177	0.0134	significant
ω	1,438661	1	1,438661	2,611871	0.1670	
f	0,188455	1	0,188455	0,342137	0.5840	Insignificant
ω^2	1,076156	1	1,076156	1,953749	0.2210	Insignificant
f^2	1,672087	1	1,672087	3,035654	0.1419	Insignificant
$\omega * f$	15,35918	1	15,35918	27,88441	0.0032	significant
Residual	2,75408	5	0,550816			
Lack of Fit	2,328721	2	1,164361	8,212079	0.0607	Insignificant
Pure Error	0,425359	3	0,141786			
Cor Total	29,13039	10				

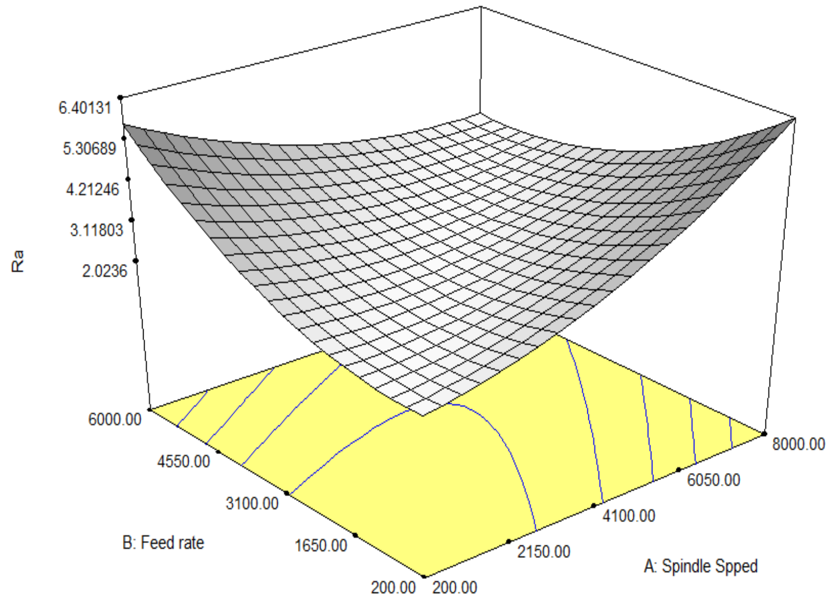


Figure 13:Interaction of Effective Parameters on Ra

Figure 13, which is a 3D response surface, shows the interactive effect of feed rate and spindle speed on R_a As can be seen, the combination of low spindle speed (200 rev/min) and low feed rate (200 mm/min) (i.e., $\frac{\omega}{f}$ =1) and the combination of high spindle speed (8000 rev/min) and high feed rate (6000) (i.e., $\frac{\omega}{f}$= 1.33) provide low R_a On the other hand, the combination of high spindle speed (8000 rev/min) and low feed rate (200 mm/min) (i.e., $\frac{\omega}{f}$ = 40) or the combination of low spindle speed (200 rev/min) and high feed rate (6000 mm/min) (i.e., $\frac{\omega}{f}$ = 0.033) yields high R_a It follows that both very low and very high $\frac{\omega}{f}$ ratios are not appropriate to employ to produce good quality holes, because in the former case the glass fibers most probably melts due to excessive heat generated by large spindle speeds relative to feed rate. Whereas, in the latter case, the tool don't find adequate time to cut the material and thus the tool instead of cutting pushes the material. This means in order to control surface quality of in terms of R_a, one should control the $\frac{\omega}{f}$ ratio which according to the shown response surface (RS) is around 1.

The empirical model for R_a, in terms of parameters under investigation, is as follows:

Equation 1: The Quadratic Model for the R_a Based on Real Factors

$$R_a = +1.99604 + 2.01153E\text{-}004 * \omega - 5.71364E - 005 * f + 4.75284E - 008 * \omega^2 + 1.16889E - 007 * f^2 - 1.49384E - 007 * \omega * f$$

The R-squared value (multiple correlation factor) for the model (Eq. 1) is 0.9055, which means the model well fits to the datum points. In order to further verify the robustness of above proposed model, the normal distribution of residuals (another criterion for testing soundness of an empirical model) is examined in Figure 14. As can be seen from the figure, the residuals follow normal distribution. Based on the results of these two tests, it can be said that the model is accurate can be used to navigate the design space. Therefore, the above model can be employed to predict surafce roughness of holes to be milled.

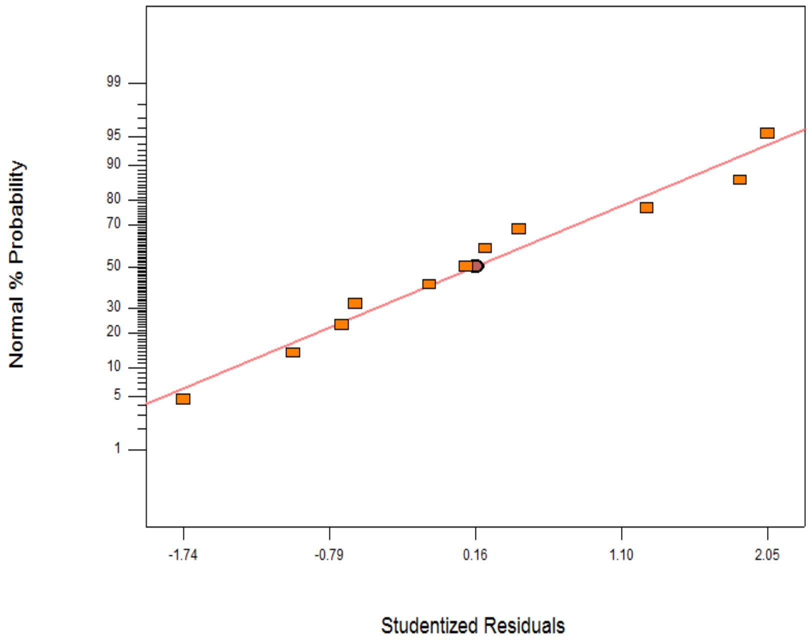


Figure 14: Normal Plot of Residual for R_a

4.1.2 Peak Roughness (R_P)

The same procedure is followed for the further responses. As it is presented in Table.4 R_p results obtained from 11 tests. Test of number 4 supplies the lowest R_p which equals to the value of 4,656μm, and the test number 2 presents the highest value equivalent to 17,28 μm.

Table 7: ANOVA for Response Surface R_p Quadratic Model

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	
Model	118,15	5	23,63	3,043	0.1237	Insignificant
ω	0,881644	1	0,881644	0,113543	0.7498	insignificant

f	6,110513	1	6,110513	0,786945	0.4157	insignificant
ω^2	3,030146	1	3,030146	0,390239	0.5596	insignificant
f^2	11,70699	1	11,70699	1,507691	0.2741	insignificant
$\omega * f$	76,95999	1	76,95999	9,91133	0.0254	significant
Residual	38,82425	5	7,76485			
Lack of Fit	34,37565	2	17,18783	11,59094	0.388	insignificant
Pure Error	4,448601	3	1,482867			
Cor Total	156,9735	10				

Based on the above table, the Model F-value of 3.04 implies the model is significant. There is only a 12.37% chance that a "Model F-Value" this large could occur due to noise. Moreover, the interaction between ω and f is significant.

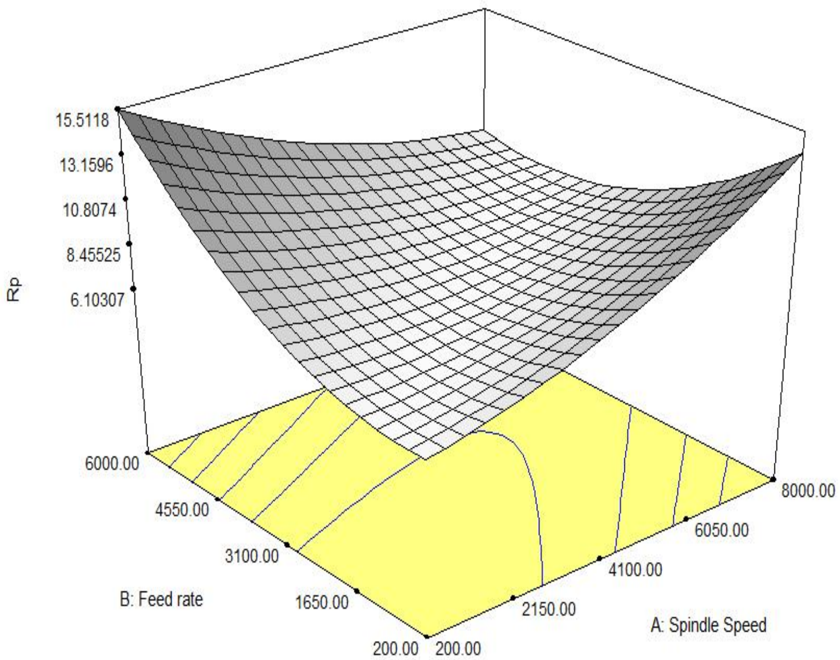


Figure 15: Interaction of Effective Parameters on R_p

In Figure 15, again which is response surface in 3D, demonstration of the interactive effect of on R_p can be seen. It is obvious that, whether the combination of high values of spindle speed and feed rate are used or low values seemingly provides low R_p. On the other hand, the combination of high spindle speed (8000 rev/min) and low feed rate (200 mm/min) (i.e., $\frac{\omega}{f}$= 40) or the combination of low spindle speed (200 rev/min) and high feed rate (6000 mm/min) (i.e., $\frac{\omega}{f}$= 0.033) yields high R_p. It is conspicuous that both very low and very high $\frac{\omega}{f}$ ratios are not suitable to employ to produce good quality holes, due to the fact that in the past case the glass fibers with high probability melting due to extreme heat generated by large spindle speeds relative to feed rate. Whereas, in the latter case, the tool does not find adequate time to cut the material and thus the tool instead of cutting pushes the material. This means in order to control surface quality of in terms of R_p, one should control the $\frac{\omega}{f}$ ratio which according to the shown RS is around 1.

The quadratic model for the R_p, in terms of parameters under investigation, is as follows:

Equation 2: The Quadratic Model for the R_p Based on Real Factors

$$R_p = + 6.07595 + 4.82675E\text{-}004 * \omega - 2.32847E\text{-}004 * f + 7.97530E\text{-}008 * \omega^2 + 3.09291E\text{-}007 * f - 3.34390E\text{-}007 * \omega * f$$

The R-squared value for the model (Eq. 2) is 0.7527, which means the model well fits to the datum points. In order to further verify the robustness of above proposed model, the normal distribution of residuals is examined in Figure 16. The lower figure give a picture of residuals trail normal distribution. Based on the results of these two tests, it can be said that the model is accurate can be used to navigate the design space. Therefore, the above model can be employed to predict surafce roughness of holes to be milled.

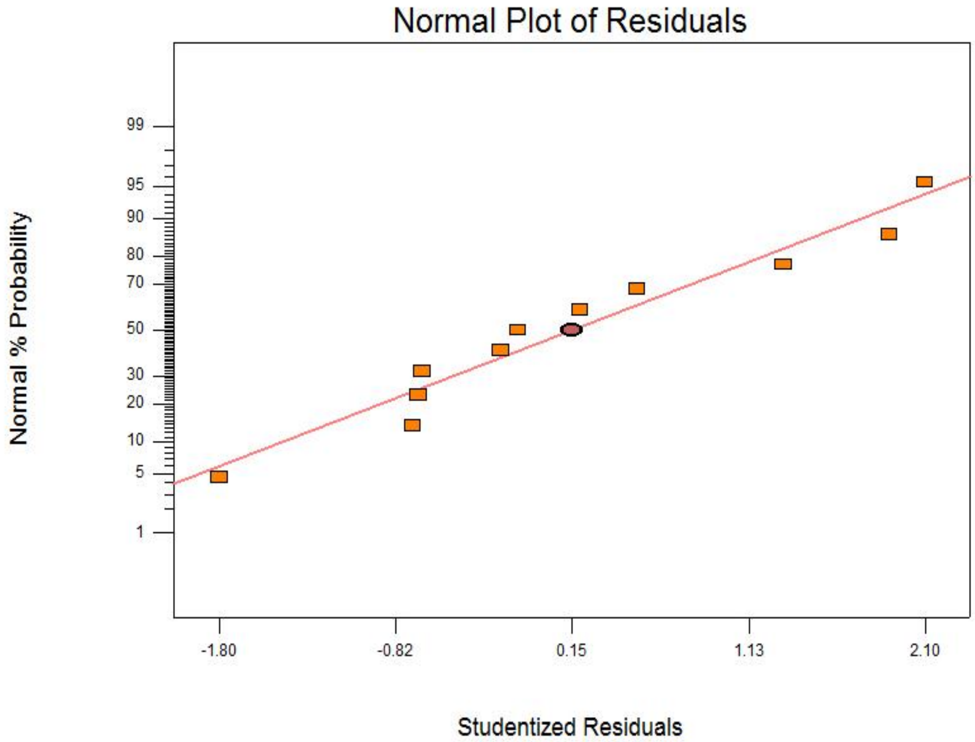


Figure 16: Normal Plot of Residual for R_p

4.1.3 Valley Roughness (R_V)

The same procedure is followed for the further responses. As it is presented in Table.4 R_v results obtained from 11 tests. Test of number 4 supplies the lowest R_v which equals to the value of 5,535μm, and the test number 2 presents the highest value equivalent to 20,72 μm.

Table 8: ANOVA for Response Surface R_v Quadratic Model

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	
Model	226,5469	5	45,30939	34,64221	0.0007	significant
ω	0,336466	1	0,336466	0,257252	0.6336	insignificant
f	27,32816	1	27,32816	20,8943	0.0060	significant
ω^2	15,51364	1	15,51364	11,86127	0.0184	significant
f^2	11,84581	1	11,84581	9,056956	0.0298	significant
$\omega * f$	142,7446	1	142,7446	109,1383	0.0001	significant
Residual	6,539621	5	1,307924			
Lack of Fit	6,170813	2	3,085407	25,09767	0.06	insignificant

Pure Error	0,368808	3	0,122936			
Cor Total	233,0866	10				

Based on the above table, the Model F-value of 34.64 implies the model is significant. There is only a 0.07% chance that a "Model F-Value" this large could occur due to noise. Further, f,ω^2, f^2 and interaction between ω and f are significant model terms.

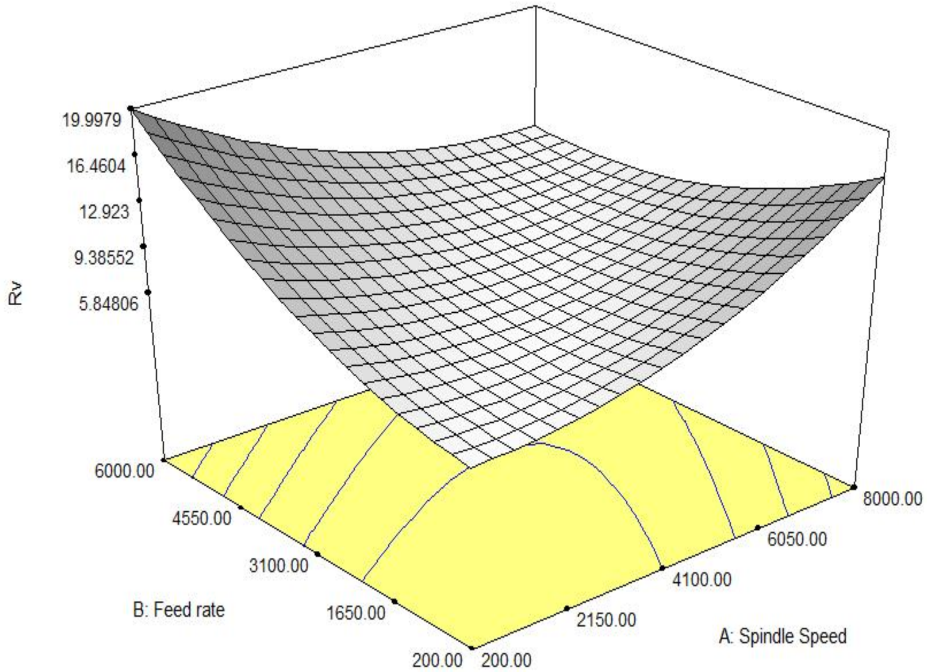


Figure 17: Interaction of Effective Parameters on R_v

Figure 17 shows the interactive effect of parameters on R_V As evident, small combinations of both ω and f offers low R_V From the other points of view, the combination of high spindle speed (8000 rev/min) and low feed rate (200 mm/min) (i.e., $\frac{\omega}{f}$= 40) or unlikely, the combination of low spindle speed (200 rev/min) and high feed rate (6000 mm/min) yields high R_v. These results reveal that both large and small ratios are not appropriate, because of the reason detailed above for R_a. This means in order to control surface quality of in terms of R_a, one should control the $\frac{\omega}{f}$ ratio which according to the shown RS is around 1.

The empirical model for R_V, in terms of parameters under investigation, is as follows:

Equation 3: The Quadratic Model for the R_v Based on Real Factors

$$R_v = +5.72750 - 6.17701E-006 * \omega + 6.01765E-004 * f + 1.80456E-007 * \omega^2$$

$$+3.11119E-007 * f^2 - 4.55407E-007 * \omega * f$$

The R-squared value for above equation 3 is 0.9719, which means the model well fits to the datum points. In Figure 18, to further verify the correctness of above proposed model, yet again normal distribution of residuals is examined. The residuals track the normal scattering as represented from the figure. Relying on both test outcomes, it shows the model's accuracy is adequate and therefore the mdoel can be used to navigate the design space. As a result, the proposed model can be applied to R_a of holes to be milled.

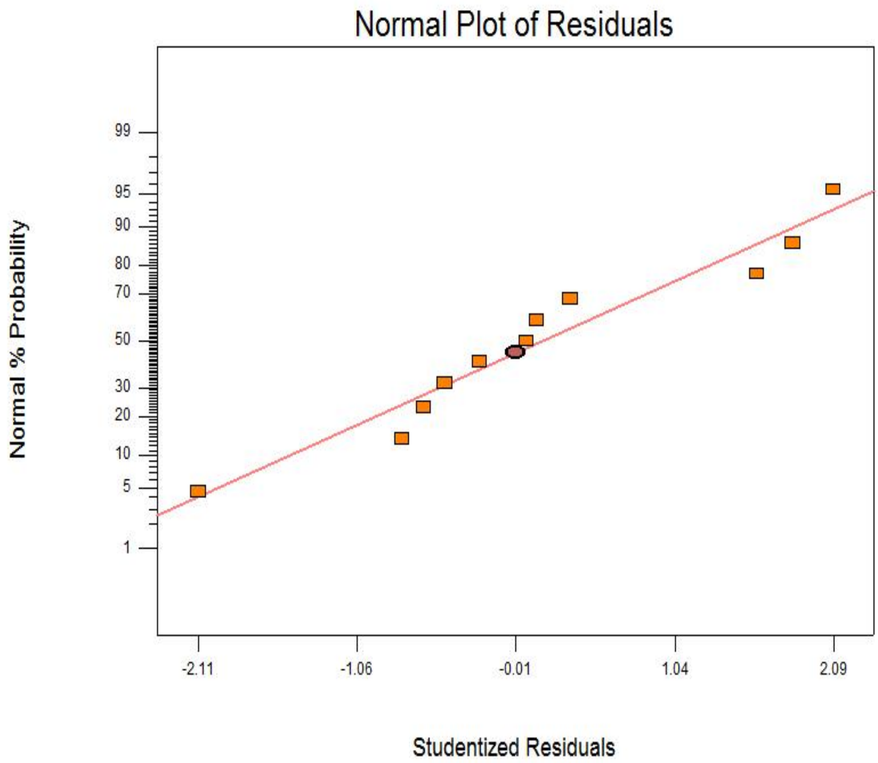


Figure 18: Normal Plot of Residual for R_v

It is noticeable from that all considered responses are not extremely in relation with individual effect of parameters (ω, f), but their combination. R_p and R_v will be affected by the R_a due to the fact that they could be mentioned as a coefficient of R_a, for that reason, direct correlation of the these parameters cannot be overlooked. Subsequently, the closer the R_a gets to the optimum value the nearer R_p, R_v values will follow the same trend.

4.1.4 Tensile Strength

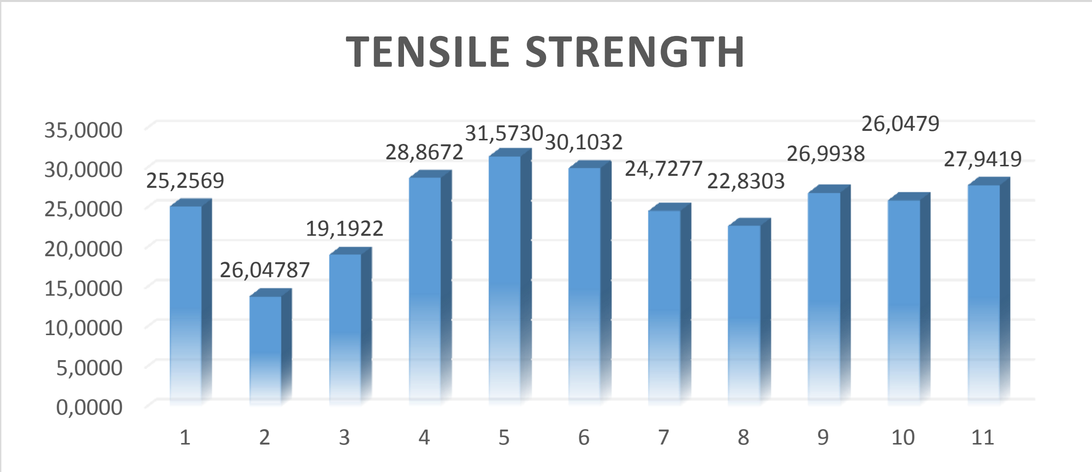


Figure 19: Tensile Strength

Figure 19 displays the tensile strength results, obtained from the experiments. To know the significance of operating parameters on strength of machines parts, ANOVA was carried out, the results of which are shown in Table 9.

Table 9: ANOVA for Tensile Strength Quadratic Model

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	
Model	158.7676	5	31.75353	1.602678	0.3087	insignificant
ω	62.49808	1	62.49808	3.154431	0.1359	insignificant
f	42.84248	1	42.84248	2.162365	0.2014	insignificant
ω^2	43.11769	1	43.11769	2.176255	0.2002	insignificant
f^2	3.075552	1	3.075552	0.155231	0.7098	insignificant
$\omega * f$	23.21851	1	23.21851	1.171895	0.3284	insignificant
Residual	99.06394	5	19.81279			
Lack of Fit	5.866565	2	2.933282	0.094422	0.9125	insignificant
Pure Error	93.19737	3	31.06579			
Cor Total	257.8316	10				

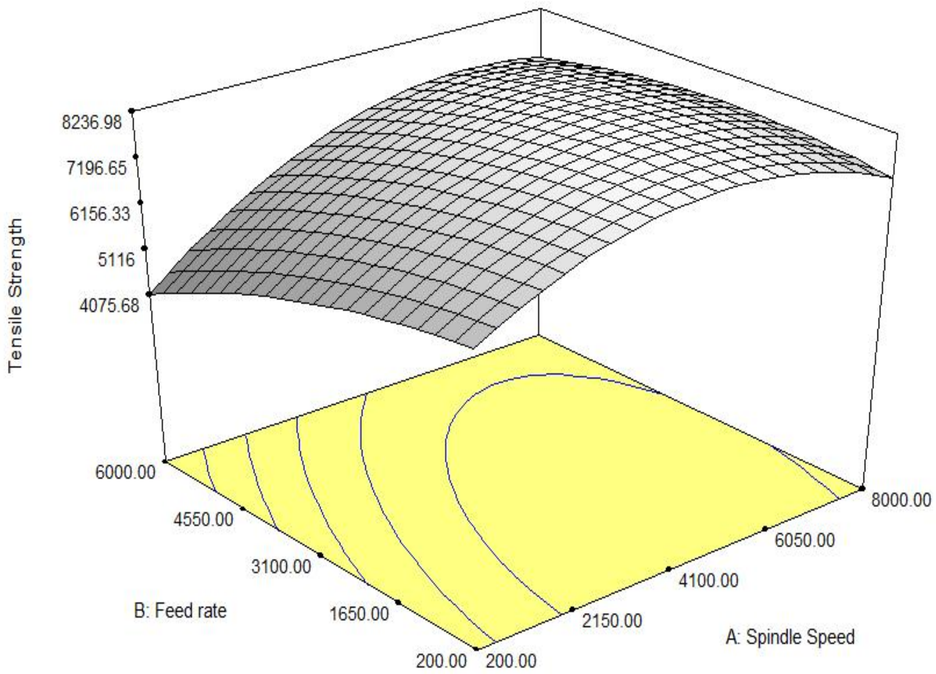


Figure 20: Interaction of Effective Parameters on Tensile Strength

The above figure generally depicts the intermediate values of ω & f leads to higher tensile strength. It follows that both low and very high values of parameters are not useful. It could be due to the fact that the material could break at low spindle speed and high feed rates with low feeds and melting of glass fiber could have taken place at high speeds.

4.1.5 Optimization

In the last phase, optimization is done. The goal of optimization was set as given in Table 10.

Table 10: Optimization Setup

Parameter	Goal	Importance
ω	in range	3
f	in range	3
R_a	minimize	5

R_p	minimize	3
R_v	minimize	3
Tensile strength	maximize	3

The following solution was suggested by DX-7 software:

Table 11: An Optimized Solution

ω	f	R_a	R_p	R_v	Tensile strength	Desirability
1034.04	430.38	2.18544	6.46859	6.02801	25.5525	0,853168

4.2 R_a in Hole Drilling

As mentioned in section 3.5.1 tests (same as designed for milling process) were executed using drilling process. The surface quality due to fiber pull out was found to be very poor. Due this reason, R_a of holes was too high (more than capacity, $80\mu m$, of instrument) to measure in most of the tests. Therefore, an empirical model cannot be developed. However, some results which could be measured are presented in Table 12, and these are compared with those of milled holes, to be discussed in coming section.

Table 12: Roughness Parameters of Drilled Hole

Sample	R_a	R_q	R_z	R_t	R_p	R_v
3	3,228	3,854	16,28	22,87	7,295	8,984
7	5,07	6,488	27,44	37,95	15,56	11,87
10	6,953	8,187	30,71	39,31	15,64	15,07

4.3 Comparison of R_a in Hole Milling and Hole Drilling

Figure 21, for some runs (3, 7, 10), depicts comparison between R_a of drilled and milled holes. As can be seen, the R_a for milled holes is smaller for each of the milled hole than that of the drilled hole. In fact, this is due to the fact that fiber pull out occurs in drilling where as such a phenomenon was not observed during hole milling, as can be seen from micrographs of hole shown in Figure 22.

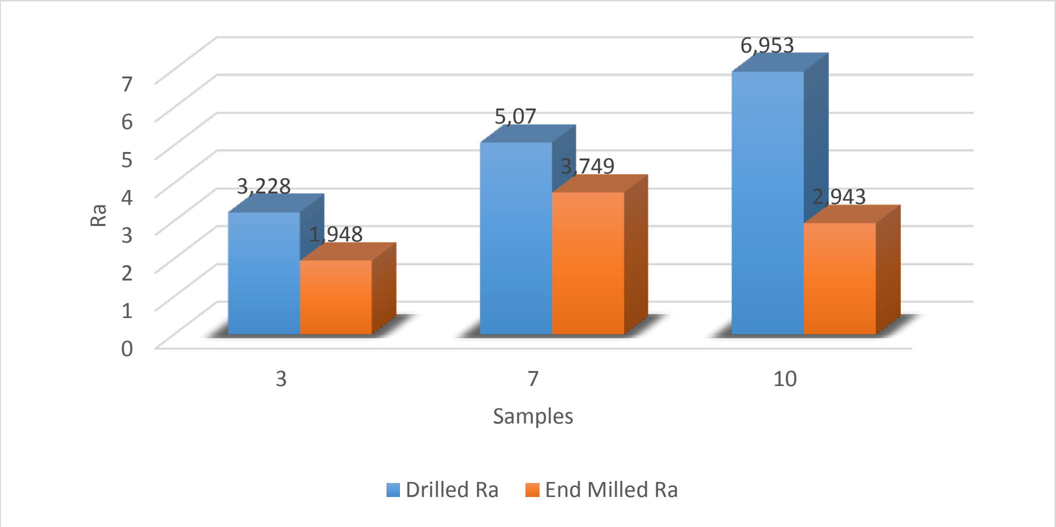
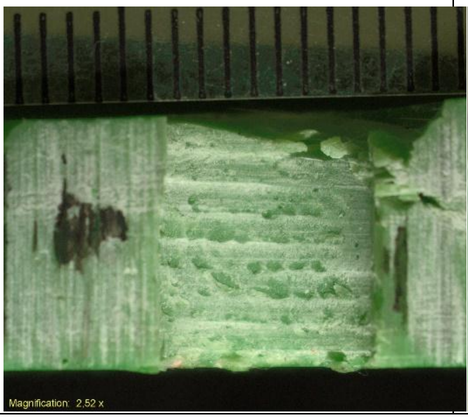
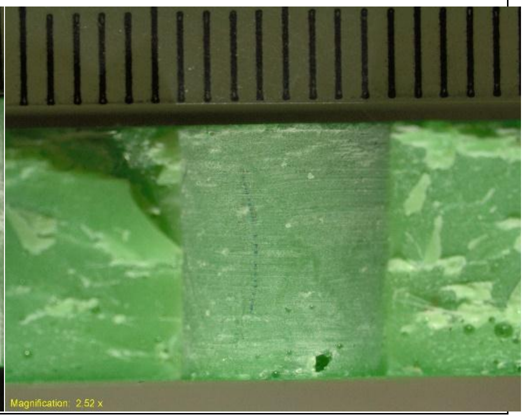


Figure 21: R_a's Comparison In Drilled and End Milled Holes

Sample	Drilled Samples	Milled Samples
#3 ω =200 f = 200		

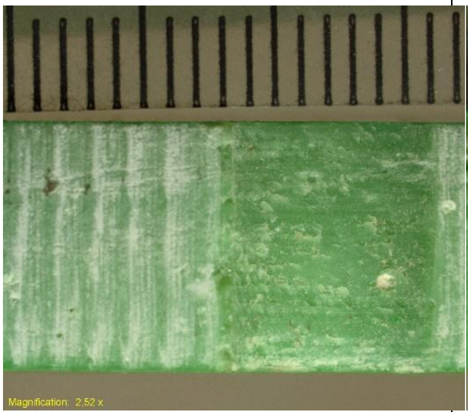
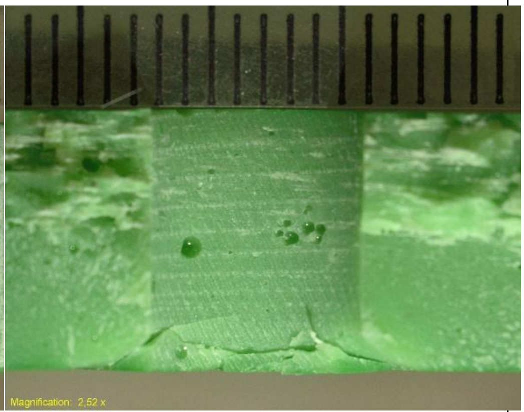
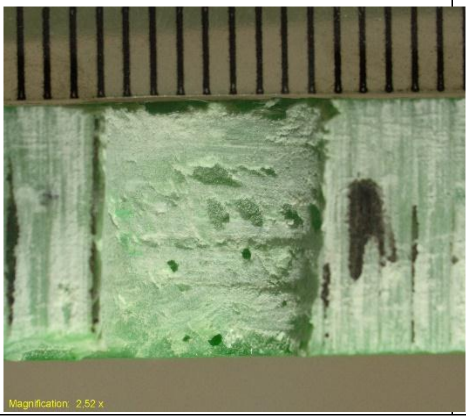
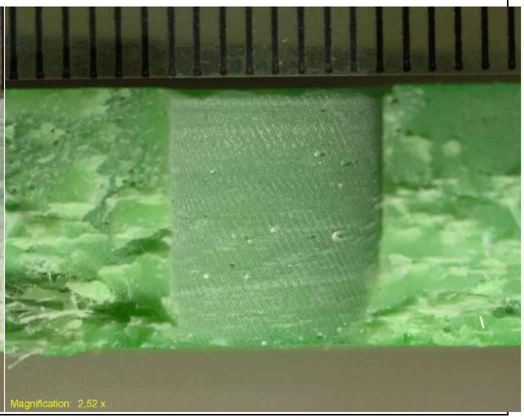
#7 ω =8000 f =6000		
#10 ω =4100 f =6000		

Figure 22: Internal Micrographs of Holes

4.4 Microscope Observations: Delamination and Internal Cracking

Figure. 23, 24, 25 and 26 exhibits inside micrographs of holes made through milling and drilling processes. As can be seen from the pictures that delamination in milled holes is much higher in drilled holes than in milled holes. Also, cracking occurs in drilled holes which are detrimental to structural integrity of the components under service. Therefore, it can be said that milling, as compared to drilling, is a better process to produce holes in FRPC. Also, as found from tests and shown qualitatively in Figures below, $\frac{\omega}{f}$ should be kept between 0.033 and 1in order to control delamination.

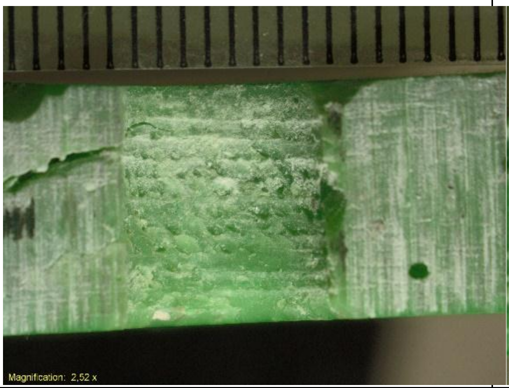
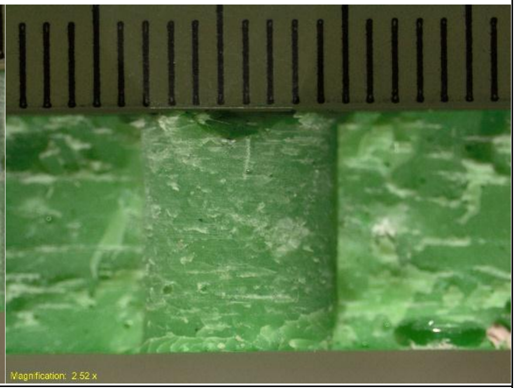
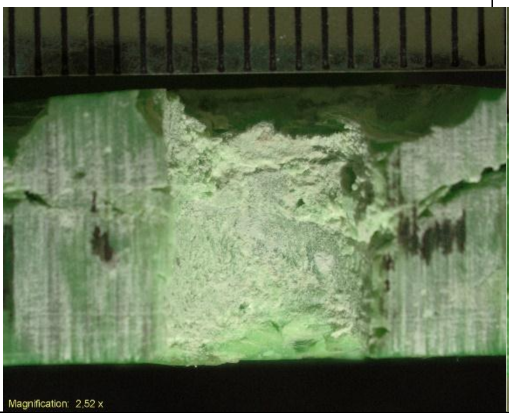
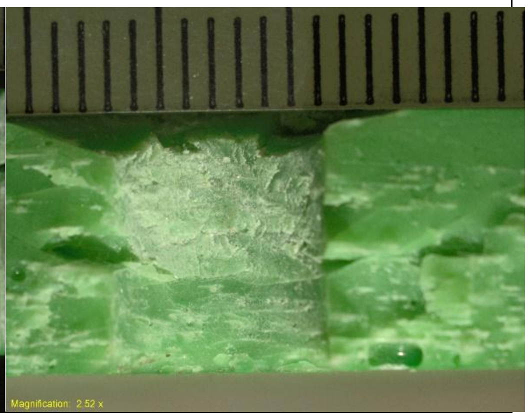
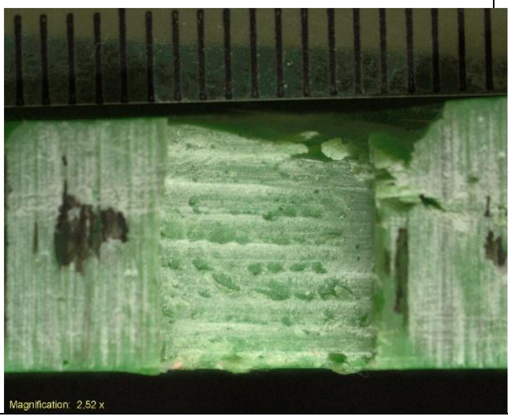
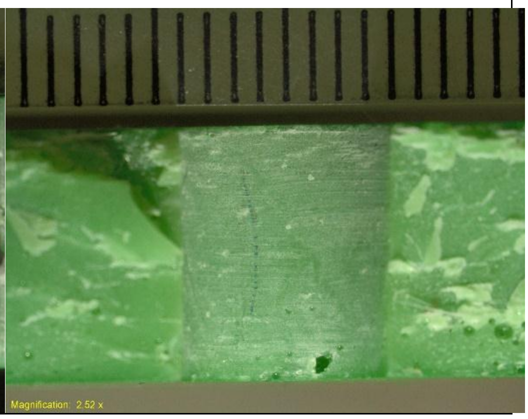
	Hole Machining by Drill	Hole Machining by End mill
#1		
#2		
#3		

Figure 23. Qualitative Comparison of Delamination and Internal Cracking in Milling and Drilling Processes

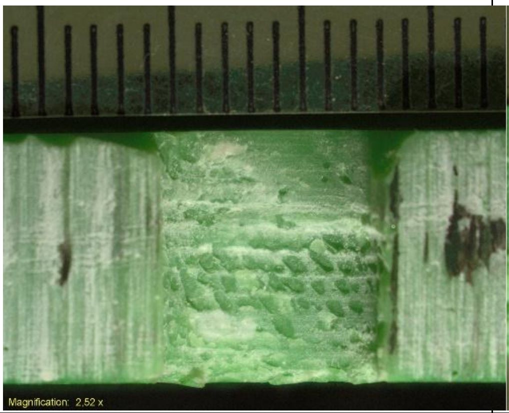
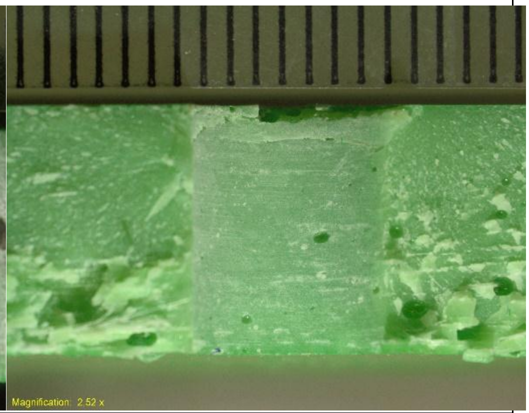
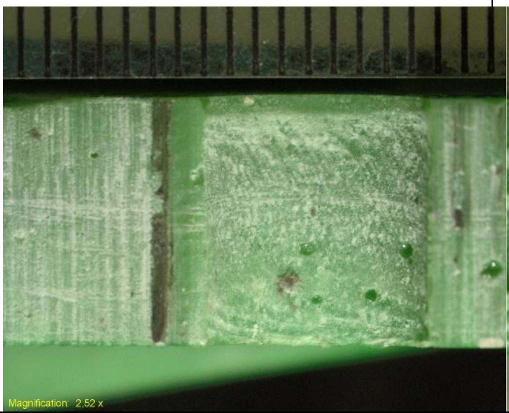
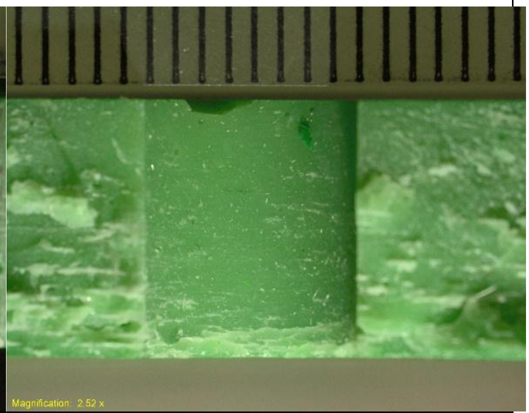
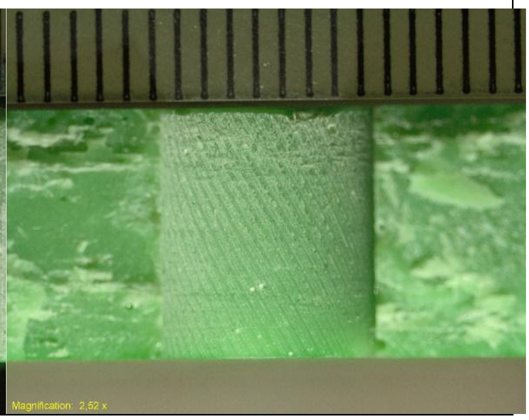
#4		
#5		
#6		

Figure 24: Qualitative Comparison of Delamination and Internal Cracking in Milling and Drilling Processes

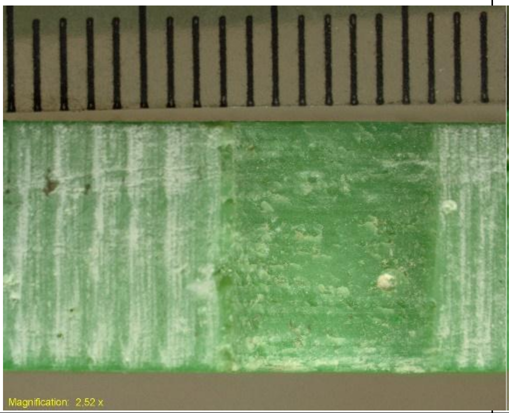
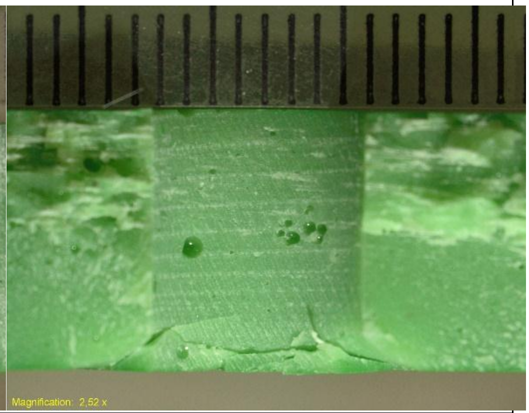
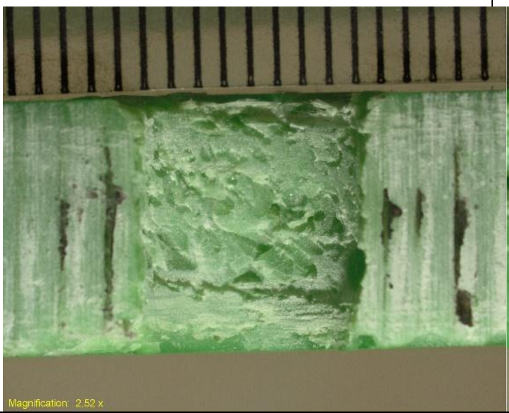
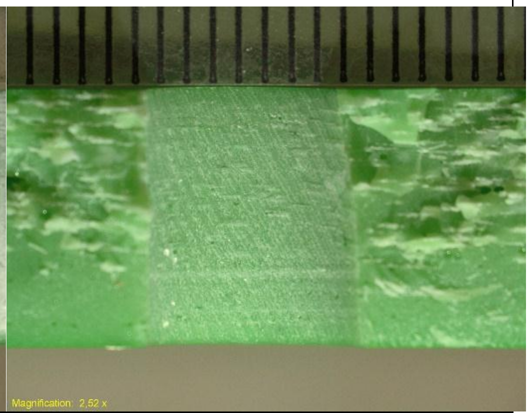
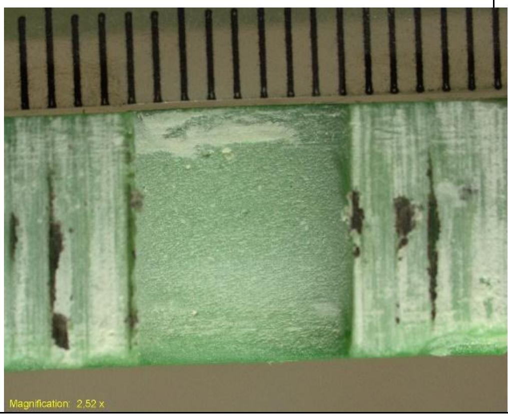
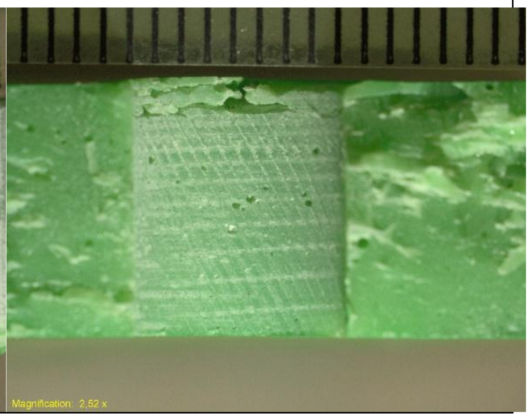
#7		
#8		
#9		

Figure 25: Qualitative Comparison of Delamination and Internal Cracking in Milling and Drilling Processes

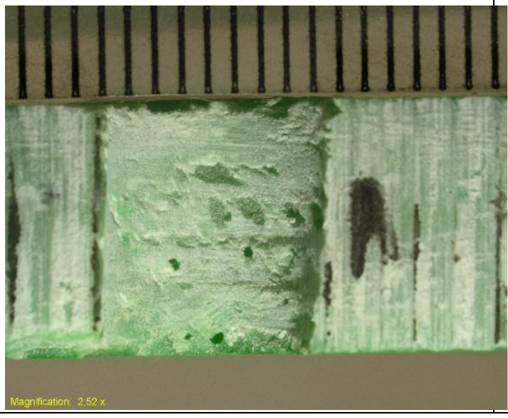
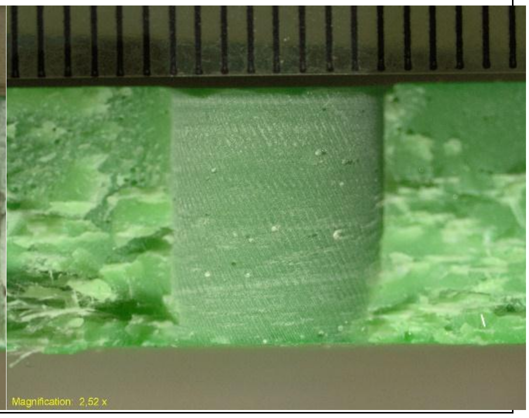
#10		

Figure 26: Qualitative Comparison of Delamination and Internal Cracking in Milling and Drilling Processes

Chapter 5

CONCLUSIONS AND FUTURE WORK

In this study, the effect of two important process parameters, namely rotational speed of spindle and feed rate, was investigated on hole machining of glass fiber reinforced polymer composites (GFRPC). The holes were cut using two machining processes, milling and drilling. The following conclusions are drawn from the study:

1. Milling is a better process to machine holes in GFRPC because it offers low R_a and low delamination as compared with drilling.

2. The individual effect of parameters is not significant, rather their interaction is important. Therefore, to achieve good surface quality (roughness) in milling, the ratio of rotational speed to feed rate ($\frac{\omega}{f}$) needs to be controlled. The optimal value of this ratio has been found to be around 1. Since the ratio is important, one should opt for large speeds and feeds to enhance productivity of process.

3. In order to minimize delamination, the $\frac{\omega}{f}$ ratio should be maintained around 1, same as found for controlling roughness.

4. Very low and very large feeds and speeds cause reduction in strength of machined samples; therefore intermediate values of these parameters (e.g. ω =4100rpm and f=3100mm/min) should be chosen where strength of component is primary objective.

5. Empirical model to predict roughness for given set of parameters has been proposed, which within the investigated range of parameters can be used to optimize parameters to produce high quality holes using milling processes.

The number of flutes of end mill cutter might influence surface quality of holes. This work is proposed as a future task.

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