ORTHOGONAL MACHINING OF UNI-DIRECTIONAL CARBON FIBER
REINFORCED POLYMER COMPOSITES

A Thesis by

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ORTHOGONAL MACHINING OF UNI-DIRECTIONAL CARBON FIBER REINFORCED POLYMER COMPOSITES (UD-CFRP)

The following faculty members have examined the final copy of this thesis for form and content, and recommend that it be accepted in partial fulfillment of the requirement for the degree of Master of Science with a major in Mechanical Engineering.

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DEDICATION

To my mother C Vanitha, my family, and my dear friends
I owe my deepest gratitude and sincere thanks to my adviser, Behnam Bahr, for his exceptional knowledge, guidance and support both academically and financially throughout my research. I want to thank my co adviser Krishna Krishnan for his guidance and valuable support lately. Thanks are also due to Hamid Lankarani for his guidance and to be a committee member.

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ABSTRACT

This research basically deals with Orthogonal Machining of Unidirectional Carbon Fiber Reinforced Polymer (FRP) Composites as secondary operations like machining is a very important process in composites manufacturing. Even though composites are manufactured to near net shape, machining operations becomes obvious to attain dimensional accuracy and surface finish for further assembly operations. The machining of FRP’s is different and more complicated to that of metals because of their anisotropic and inhomogeneous nature, along with the chip formation mode for its brittle behavior. Fibers are very abrasive in nature and cause extreme tool wear making it difficult for cutting and when combined with matrix which is comparatively weak produce fluctuating force on the tool to augment for the tool wear. It will be very helpful to study their behavior for optimizing the machining condition and to minimize the above mentioned drawbacks.

This work will be basically dealing on the experimental study and numerical prediction of machining quality during orthogonal machining on various fiber orientation and cutting conditions. Orthogonal machining was performed using 3-axis miniMILL for experimental work and commercially available simulation software ABAQUS 6.9-2 for numerical study. The numerical findings are presented to supplement experimental work for predicting delamination which is very important for its service life along with some interesting observation which is discussed in this report.
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CHAPTER I
INTRODUCTION

1.1 Composite Material

Composites in general are combination of two or more materials and their technology dates back few centuries early when straws was first used in clay to form composite brick. As time evolved their definition was refined and now, it’s defined as the combination of two or more materials which differ in their physical and chemical form, where their constituents can be easily differentiated. The ability to tailor these materials to the specific needs and their superior properties are the driving force behind this increased utilization. Composite materials have high strength to weight ratio know as the specific strength as compared to conventional materials, hence used a lot in aerospace industry.

1.2 Constituent Materials

It has been stated before that composite consist of two or more distinctly different materials. In most cases, the composite is made of matrix and reinforcement materials that are mixed in certain proportions depending on the requirement. Each constituent materials have their own properties which when combined properly will provide desired results, which is the most important aspect of composite due to its tailor ability. Fibers have great strength and stiffness which when combined with weaker matrix will result in a composite with lesser properties than the actual fibers, but the overall composite properties in general will have considerable difference to that of conventional materials.
1.2.1 Reinforcement

Reinforcements are used to provide the strength to composites and take most of the loading. Reinforcement materials are used in the form of continuous fibers, short fibers, particulates, and whiskers. Continuous fibers are materials that have one very long axis with a very high length to diameter/thickness ratio and are often circular or near circular in shape. Fibers have significantly higher strength and stiffness in the length direction than in the other directions. This limits their use in a stand-alone form and underscores the need for a tough matrix in the composite structure. Thus fibers are most commonly used for the reinforcement of a softer matrix. The most commonly used composite fibers are discussed below.

1.2.1.1 Glass Fiber

Glass is by far the most widely used fiber, because of the combination of low cost, corrosion resistance, and in many cases efficient manufacturing potential. It has relatively low stiffness, high elongation, and moderate strength and weight, and generally lower cost relative to other fibers their use is limited in high- performance applications because of their relatively low stiffness, low fatigue endurance, and rapid degradation in properties with exposure to moisture.

1.2.1.2 Carbon Fiber

The high stiffness and strength combined with low density and intermediate cost has made carbon fiber second only to glass fiber in use. Carbon fibers are widely used for advanced composites in aerospace and some sporting goods applications, taking advantage of the relatively high stiffness-to-weight and high strength-to weight ratios of these fibers. Carbon fibers vary in strength and stiffness with the processing variables, so that different grades are available such as
high modulus (HM), intermediate modulus (IM), or high strength (HS), with the trade-off being between high modulus and high strength

1.2.1.3 Aramid Fiber

Aramid fibers are the acronym of aromatic polyamides sold under the trade name Kevlar are organic fibers. Aramid fibers offer higher strength and stiffness relative to glass coupled with lightweight, high tensile strength, but lower compressive strength. Aramid also exhibits an outstanding toughness and damage tolerance. It tends to respond under impact in a ductile manner, as opposed to carbon fiber, which tends to fail in a more brittle manner.

1.2.2 Matrix

The matrix material is used to bind the reinforcements so as to provide the shape to composites and transfer the loads to fibers and to protect them from abrasion and adverse environmental conditions. The matrix dilutes the properties to some degree, but even so very high specific (weight-adjusted) properties are available from these materials. Matrix may be made from metals, ceramics, or polymers. It may be pure, or mixed with other materials (additives) to enhance its properties. The reinforcement may also be treated to enhance bonding to the matrix. Most commonly used matrix materials are discussed below.

1.2.2.1 Metal Matrix

Aluminum and its alloys have received by far the most attention. Metal matrices are reinforced with continuous fibers, particulates, and whiskers that are made from metals (stainless steel, boron, carbon) or ceramics (SiC, Al2O3). Aluminum metal matrix composites are used in a
vast number of applications where strength and stiffness are required. This includes structural members in aerospace applications and automotive engine components

1.2.2.2 Ceramic Matrix

Ceramic matrix composites mostly use ceramics for both the matrix phase and the reinforcement phase. Because of the excellent thermal stability and high stiffness of ceramics, their composites are attractive for applications where high strength and high stiffness are required at high temperatures.

1.2.2.3 Polymer Matrix

Polymer matrices by far are most widely used in composites applications. The wide range of properties that result from their different molecular configurations, their low price and ease of processing make the perfect material for binding and enclosing reinforcement. Polymer matrices are normally reinforced with glass, carbon, and aramid fibers. Polymer matrix composites have found a wide range of applications in sports, domestic, transportation, and aerospace industries

Composites are broadly classified according to the type of matrix material

- Metal matrix composites
- Ceramic matrix composites
- Polymer matrix composites

It is further classified according to the reinforcement form and arrangement

- Particulate reinforced (random, preferred orientation)
- Fiber reinforced (continuous, discontinuous, aligned, random)

Figure 1.1 Schematic of different reinforcement arrangements in composites [7]

Further it can be classified based on the type of fiber material

- Glass fiber reinforced polymer composites (GFRP)
- Carbon fiber reinforced polymer composites (CFRP)
- Graphite epoxy polymer composites (Gr-EP)
- Aramid fiber reinforced polymer composites (AFRP)

Composites are classified as conventional (used in low end application) and advanced (used in high end application, particularly in aerospace industry) composite materials based on their constituents and properties.
Advanced composites are superior in properties and generally use continuous fibers to achieve the desired properties in required direction, like, high specific strength (most basic requirement for an aircraft) and stiffness. Continuous fibers are those which have very high length to diameter ratio and often incorporated into a composite in desired orientation.

Fiber Reinforced Polymers (FRP’s) are a class of advanced composites which uses fibers as the reinforcement which provides strength to the composite and polymers as the matrix which bonds to the fibers, providing shape and transferring load to the fibers.

These materials are characterized by their high specific strength and high specific stiffness. They are also excellent corrosion resistance materials and provide better resistance to fatigue loading. This makes them suitable for various applications in the chemical, marine, transportation, and aerospace industries. In addition, they find wide applications in the sporting and leisure industries.

1.3 Composite Properties

Properties of composites, particularly continuous-fiber reinforced, are different from those of metals in that they are highly directional. A material is called anisotropic when its properties at a point vary with direction. The orientation of the reinforcement within the matrix affects the state of isotropy of the material.

Properties of composites are also described with respect to the scale at which the material is analyzed. Consider a composite lamina, which is the simplest possible form of a composite consisting of an assembly of anisotropic fibers in an isotropic matrix. At the microscopic scale,
analysis is conducted at the fiber diameter level. This is called micromechanics analysis and it deals with relationships between stress and deformation in the fibers, matrix and fiber–matrix interface. Micromechanics analysis allows for the prediction of the average lamina properties as a function of the properties of the constituents and their relative amounts in the structure. At the macroscopic level, the lamina is treated as a whole and the material is considered as homogeneous and anisotropic. Lamina average properties are used to study the overall lamina behavior under applied loads. Macromechanics is also concerned with analysis of the behavior of laminates consisting of multiple laminas stacked in a certain sequence based on the average properties of the lamina.

1.3.1 Density

Consider a composite consisting of matrix and reinforcement phases of known densities. The weight of the composite, \( w_c \) is given by the sum of the weights of its constituents, \( w_f \) and \( w_m \)

\[
w_c = w_f + w_m,
\]

(1.1)

Where, the subscripts \( f \) and \( m \) refer to the reinforcement and the matrix, respectively. Substituting for \( w \) by \( \rho \) \( v \), above can also be written as

\[
\rho_c v_c = \rho_f v_f + \rho_m v_m,
\]

(1.2)

Where \( v_c \), \( v_f \), and \( v_m \) denote the volume of the composite, reinforcement, and matrix, respectively. Dividing (1.2) by \( v_c \) it becomes

\[
\rho_c = \rho_f V_f + \rho_m V_m,
\]

(1.3)
Where $V_f$ and $V_m$ denote the volume fractions of the constituents, $v_f/v_c$ and $v_m/v_c$, respectively. Equation (1.3) is known as the law of mixtures and it shows that the density of a composite is given by the volume fraction adjusted sum of the densities of the constituents.

1.3.2 Elastic Properties

The composite lamina is assumed to be macroscopically homogeneous and linearly elastic. The matrix and the fibers are assumed to be linearly elastic and homogeneous, with the fibers being also anisotropic (transversely isotropic). The interface is completely bonded and both the fiber and matrix are free of voids. The response of the lamina under load can be analyzed using a parallel model or a series model. In the parallel model (also called Voigt model and equal strain model), it is assumed that the fiber and the matrix undergo equal and uniform strain. This leads to the following expression for stiffness in the longitudinal direction

$$E_1 = V_f E_{1f} + V_m E_m.$$  (1.4)

Figure 1.2 Principal material orientation of composite laminate [7]

Here the subscripts $1f$ refer to the longitudinal direction of the fibers. Note that (1.7) is similar to (1.3) and it gives the elastic modulus as the weighted mean of the fibers and the matrix
modulus. In a series model (also called Ruess model), it is assumed that the fibers and the matrix are under equal and uniform stress. This leads to the following expression for compliance along the longitudinal direction

\[ C_1 = V_f C_1 f + V_m C_m. \]  

(1.5)

Knowing that \( C = 1/E \), (1.5) is rewritten as

\[ E_1 = E_1 f E_m / (V_f E_m + V_m E_1 f) \]  

(1.6)

In similar manners, the remaining equations for the major Poisson ratio and in plane shear modulus are determined using the equations

\[ \nu_{12} = V_f \nu_{12} f + V_m \nu_m, \]  

(1.7)

\[ G_{12} = G_{12} f G_m / (V_f G_m + V_m G_{12} f). \]  

(1.8)

1.4 Research Objective

By considering the above it is clear that composites are totally different to that of metals so does their machinability and also there is little research conducted on composites, hence it will be useful to investigate the machinability of composites. The objective of this research is to study both experimentally and numerically the effect of two most important machining parameters, fiber orientation and rake angle on surface quality in particular delamination/debonding, the delamination is a series issue affecting the structural integrity and service life. This will lead to better understanding of machinability of composites, their by leading to better design of materials, tooling and cutting conditions.
CHAPTER II
LITERATURE REVIEW

Everstine and Rogers [8] were the first to submit their theoretical work based on continuum mechanics approach to predict the minimum cutting force required to machine $0^\circ$ fiber orientation. Koplev et al [1] were one of the first to experimentally study the machining process of FRP’s, which set the foundation for future research and publications.

According to their findings the chip formation in orthogonal machining was highly dependent on fiber orientation and consisting of series of fractures each creating a chip, the study was performed for fibers both parallel and perpendicular to the feed direction. Many have studied the effect of tool geometry, cutting conditions and material properties on cutting forces, chip formation, tool wear and surface quality to observe the machining kinematics of composites.

Takeyama and Iijima [14] developed a model to predict cutting forces independent of fiber orientation, also concluding the chip formation for most fiber angled composites to be similar to that of metals. One of the major findings in the literature indicate the in-plane shear strength for FRP’s plays an important role while machining, at the same time there were no universally accepted standard test to come up with the shear strength of FRP’s. It was later found that Iosipescu Shear Test can be used with some modification to simulate the orthogonal machining at very low cutting speeds [15].
In general, results from machining of FRP’s can be obtained either experimentally or numerically depending on the facilities available. Numerical simulations are usually used to support the experimental findings and to further apply to obtain new findings where the experimental investigations become difficult and expensive.

2.1 Machining Models

2.1.1 Everstine and Rogers Model

Everstine and Rogers [8] had proposed a theory on machining of FRP composites. The model predicts the minimum cutting force required for machining parallel unidirectional fibers based on a continuum mechanics approach [9]. They proposed a displacement field for the chip region analogous to the thick-zone model in cutting of metals that was proposed by Palmer and Oxley [10]. They explained the formation of wrinkle ahead of tool tip owing to tensile loading from the chip separation. Plastic deformations are determined kinematically, the deformation is found by using suitable displacement boundary condition and constraint conditions [12]. They proposed an estimate for the principle cutting force, \( F_c \) in terms of the tool geometry, material properties and the proposed deformation. The schematic diagram of their cutting mechanism is shown in Figure 2.1.
2.1.2 Koplev model

Koplev et al. [1] studied the chip formation process and surface quality of machined surface while machining the unidirectional CFRP material with a single edged tool. The tests were carried out for 0 and 90 deg fiber orientation. The chip formation process was investigated with a quick stop device. The advantage of this study was to make use of macrochip method to study many small chips produced during machining process. In this method, the workpiece surface is coated with a thin layer of rubber-based adhesive. After machining, the chips remain stick to the adhesive. The chips on the adhesive are then examined [13]. A schematic diagram of macrochip method is shown in following figure.
Koplev et al. [1] found that the fiber orientation is the major parameter in controlling the surface quality of machined surface. Smother finish was achieved while machining parallel to the fiber orientation. The fibers showed tensile failure because friction force caused the tool to press down on them. Greater value of surface roughness was observed while machining 90 deg fiber orientations, this is due to a layer of disturbed materials on the surface consisting both matrix and small pieces of fibers. The cracks were developed below the cutting plane, with cracks propagating both parallel to and perpendicular to surface. Inoue and Ido [6] proposed that the depth of this damaged zone is related to the cutting edge radius of the tool and the fiber orientation angle.

The study of macrochips revealed no presence of plastic deformation, an indication of brittle failure of both matrix and fibers. While machining perpendicular to the fibers, the forward
movement of the chip presses the composite in front of it, causing the composite to bend and fracture to form chips. At the same time, the cracks are formed due to the downward pressure on the composite below the tool. While machining parallel to the fibers, the pressure on the specimen causes formation of chips. A crack appears in front of tool leading to the start of next chip. The two machining mechanisms are shown in figure below

![Figure 2.3: Chip formations at 90° and 0° fiber orientation [1]](image)

2.1.3 Takeyama and Iijima

Takeyama and Iijima [14] predicted cutting force model by using Merchant”s minimum energy theory. They studied the chip formation process when cutting continuous fiber reinforced plastics at various fiber orientations. Figure 2.4 shows the schematic diagram of orthogonal cutting process for finer reinforced composite material.
Takeyama et al. [14] predicted the cutting force and surface finish as a function of fiber angle. They stated that, at 0° fiber angle cracking occurred in the direction of fibers, whereas at 90° fiber angle, blocky chips were produced due to fracture. At intermediate angles they observed the chip formation close to that of the metal cutting process with the angle of shear plane being bound by that of fiber. Based on Merchant’s theory, the cutting power \( P \) is calculated by

\[
P = V \cdot R \cdot \cos(\beta - \alpha) = \frac{b \cdot t \cdot \tau(\theta) \cdot V \cdot \cos(\beta - \alpha)}{\sin \phi \cdot \cos(\phi + \beta - \alpha)}
\]  

(2.1)

Where \( \phi \) shear angle, \( \beta \) friction angle, \( \alpha \) rake angle, \( \theta \) fiber orientation, \( \theta' \) shear fiber angle

Shear angle is determined in such a way that the shearing in chip formation occurs in the direction so as to minimize the cutting energy, such as
\[
\frac{\partial P}{\partial \phi} = \frac{\partial \tau(\theta)}{\partial \phi} \sin \phi \cos(\phi + \beta - \alpha) - \tau(\theta) \cos(2\phi + \beta - \alpha) = 0
\] (2.2)

Where \( \tau(\theta) \) is the experimental model for simple shear test.

Based on the Merchant’s minimum energy theory and experimental results of \( \tau(\theta) \), the principal and thrust cutting forces are determined as

\[
F_p = \frac{bt \tau(\theta) \cos(\beta - \alpha)}{\cos(\phi + \beta - \alpha) \sin \phi}
\] (2.3)

\[
F_t = \frac{bt \tau(\theta) \sin(\beta - \alpha)}{\cos(\phi + \beta - \alpha) \sin \phi}
\] (2.4)

Although the cutting forces predicted from this method are similar to those determined experimentally. The model failed to explain the phenomenon of the chip formation when reversing the machining direction, i.e. the model is not valid for materials with fiber orientations greater than 90\(^0\). The model also lacked the detailed description of shear test procedure to find the shear phenomenon and shear strength. For FRP materials, there are no standard techniques to measure the shear plane angle. Since the chips are generally very small and mostly in the powder form, it is extremely difficult to measure the chip thickness and so to calculate shear plane angle as in case of metals. Even the model failed to explain the phenomenon of mean angle of friction between tool and chip for all the fiber angles.
2.1.4 Bhatnagar et al. model

Bhatnagar et al. [2] studied the orthogonal cutting process of unidirectional carbon fiber composites for different fiber orientations. From their experimental studies, they concluded that shear strength of the material is an important factor while machining composites. They overcome the drawbacks of the previous Takayama and Iijima [14] models by proposing a method to obtain accurate values for the shear strength of composites. Since there was no standard method to determine the shear strength of the material for any given fiber orientation, they used Iosipescu shear test method to evaluate the shear strength of material accurately. Based on this method, they were able to plot the variation of in-plane shear strength with fiber angle.

On machining negative fiber orientation, they found the chip formation to be similar to that of Koplev et al. The fibers were bent and the chips were formed by delamination of material. For positive fiber orientation, they found a blocky chip formed by fracture. On further examinations they found the existence of a plane along which the macrocrack propagated leading to the formation of chips. This plane also corresponds to that found during Iosipescu shear test.

For machining positive fiber orientations, they concluded that

1. Fibers break in tension to produce the machined surface.
2. Chips are produced ahead of the cutting edge of the tool by shearing of the matrix in a plane along the fiber orientation.

From the experimental results it was found that the cutting forces were higher for fiber orientations less than 90°. The forces were maximum for fiber orientations between 30 and 60° and minimum between 120 and 150°.
In their model, they were able to predict the effect of fiber orientation on cutting forces by resolving these forces parallel and perpendicular to the fibers. They schematically showed the fracture of the fibers separately for negative and positive fiber orientation. This is shown in figure 2.4.

![Figure 2.4: Cutting mechanism of CFRP from Bhatnagar et al. [2]](image)

For negative fiber orientation materials, the progress of the tool causes the fiber to experience compression and bending. The fibers are pushed upward by the tool and are broken by shearing. For positive fiber orientation materials, the fibers tend to tilt by the cutting force and are subjected to tension and bending as well as compression by the tool rake face. They also observed affects of tensile to shear strength ratio of fibers on the cutting force.

For positive fiber orientation materials, they modeled the cutting process similar to that proposed by Takeyama and Iijima [14]. They assumed the chip formation along a shear plane and applied the minimum energy principle. The further assumptions they made are as follows

1. Existence of crack propagation plane along the fiber direction at which matrix shears.
2. The cutting force is dependent on the in-plane shear strength of the fiber angle.
3. The cutting is orthogonal and the fiber angles are in between 0 and $90^0$.  

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4. The coefficient of friction between the tool and chip interface is assumed to vary for each fiber orientation and the effect of temperature is neglected.

5. Chip formation takes place in a manner to minimize the cutting energy.

6. The matrix shear plane angle is independent of the tool rake angle.

Bhatnagar et al. [2] predicted the cutting forces by substituting the fiber angle instead of shear plane angle in that of Merchant’s model. The cutting forces are

\[
F_c = \frac{\tau a \cos(\beta - \alpha)}{\sin \theta \cos(\theta + \beta - \alpha)} \quad (2.5)
\]

\[
F_r = \frac{\tau a \sin(\beta - \alpha)}{\sin \theta \cos(\theta + \beta - \alpha)} \quad (2.6)
\]

Where, \(\tau\) in-plane shear strength of the material for a given fiber angle, \(a\) area of the shear plane, \(\theta\) fiber angle, \(\alpha\) rake angle, \(\beta\) friction angle.

The friction angle was calculated from the Merchant’s circle after taking the force measurements. This, in turn allowed determining the shear strength \(\tau\). The results were in good agreement with the Iosipescu shear test up to 60° fiber angle.
CHAPTER III
MACHINING

Machining is a material removal process to remove unwanted material from the work piece to meet dimensional tolerance and surface finish for further assembly operations.

Machining FRP’s are different to that of metals because of its inhomogeneous and anisotropic nature due to the presence of different constituent phases. As the fibers which are mostly strong and brittle that may have poor thermal conductivity as seen in kevlar fibers, contrarily, the matrix is weak and ductile. Hence, machining of FRP’s is characterized by uncontrolled fracture which is not seen in case metal machining. Also, the machining forces will be oscillating due to the subsequent cutting of constituents and its machinability is determined by their physical and mechanical properties. It is also observed to have excessive tool wear while machining FRP’s along with fiber pullout and debonding/delamination. This paper will analyze the cutting forces and surface quality while machining uni-directional FRP’s.

Machining of metals has been taking place for a very long time and there is extensive literature on that. Even though, composite materials are totally different to that of metals but their kinematics remains the same and have been used with proper modifications to cutting tool geometry, cutting speed and feed rate.

Machining is broadly classified as conventional and non-conventional based on the machining kinematics.
3.1 Conventional Machining

3.1.1 Turning

Turning is used to make cylindrical objects using a single point cutting tool. The workpiece is rotated through its axis while the cutting tool is fed parallel to its axis of rotation. As the cutting tool engages with the workpiece, a new surface of revolution is produced by removing a layer of material whose thickness is equal to the depth of cut. A typical machine tool for this kind of operation is an engine lathe.

3.1.2 Milling and Trimming

In milling, the rotating cutter that may have one or more cutting edges removes the material from the workpiece. Most common types of machining FRPs are peripheral milling or profiling and end milling. Peripheral milling has the cutting edges on the periphery of the tool. The machined surface is parallel to the cutter axis rotation and the engagement into the workpiece is in the radial direction as shown in figure 3.1. Peripheral milling is more appropriately called edge trimming because of smaller diameter tools and the axial engagement encompasses the entire thickness of the workpiece. End milling is similar to peripheral milling, except that the axial engagement will be less than the actual thickness of the part and a slot will be produced.
End milling and edge trimming operations are further classified into conventional or up milling and climb or down milling, depending on how the cutting edge approaches the workpiece as shown in figure 3.2. In up milling, the workpiece feed direction is opposite to the direction of speed vector at engagement. In down milling, the workpiece feed direction is same to the direction of speed vector at engagement. The resulting chip shape in both cases is a “comma” and the length of the chip is described by a torchoid that results from the superposition of peripheral motion and feed motion. In up milling, the cutting edge begins engaging the chip at the thin section of the comma shape. This generates low engagement forces and in lifting up of the workpiece. In down milling, the cutting edge engages the chip at the thick section of the comma shape. This generates higher forces result in pushing the workpiece against the work holding surface. Cutting forces during milling are not continuous. In up milling, the forces gradually increase from zero at the start of tool engagement to a maximum when the cutting edge is about to leave the workpiece. Forces drop to zero again once the cutting edge leaves the workpiece.
3.1.3 Drilling

Drilling is the most common material removal operation in metals and composites machining. It is used for producing holes required for assembly. Drilling is done on conventional upright drilling machines, milling machines, and other specialized machines. In drilling on a vertical drill press, the spindle provides the primary rotational motion to the drill bit and the feed into the workpiece is provided through the spindle axis. A two flute twist drill has two major cutting edges that form the drill point angle.

3.1.4 Abrasive Cutting

A abrasive wheels are commonly used in finishing operations of metals and ceramics where higher surface finish is required. Abrasive cutters are also used in machining FRPs because they provide less mechanical damage and good surface finish than traditional cutting tools.
In abrasive cutters, many diamond particles are brazed or bonded to the tool shank or body and act as multiple cutting points. Abrasive cutters are mainly classified by the size of the abrasive particle and the method by which the particles are bonded to the tool body. The size of abrasive particles is identified by grit number, which is a function of sieve size. The greater the sieve size, the smaller the grit number.

3.2 Non Conventional Machining

As the demand on high performance composites increases, stronger, stiffer, and harder reinforcement materials are introduced into modern advanced composite structures. This makes the secondary machining of these materials increasingly difficult. Traditional machining of composites is difficult because of its heterogeneity, anisotropy, low thermal conductivity, heat sensitivity, and high abrasiveness. The stacked nature of most fiber-reinforced composites makes them also susceptible to debonding between the individual plies as well as within the same ply, under such conditions it might be efficient using nontraditional machining process.

Nontraditional machining processes include waterjet (WJ), abrasive waterjet (AWJ), abrasive suspension jet (ASJ), laser and laser-assisted machining, ultrasonic machining, and electrical discharge machining (EDM). Among this wide range of processes, only AWJ, laser, and EDM of FRP composites have received considerable attention in the Literature

3.2.1 Abrasive Water Jet machining

High-velocity waterjets have been used since the early 1970s in cutting a variety of materials, including corrugated board, paper, cloth, foam, rubber, wood, and granite. Abrasive
waterjets expand the capabilities of high-velocity waterjets by introducing abrasive particles as the cutting medium

Currently AWJs are used to cut a wide range of engineering materials including ceramics, metal alloys, and composites. There are many distinct advantages of AWJ cutting which makes it desirable over other traditional and nontraditional machining processes. AWJ can virtually cut any material without any significant heat damage or distortion. Because the cutting forces are very small and no cutting tools are required, the setup time is shorter than traditional machining processes and fixturing requirements are either very minimal or not required at all

3.2.2 Laser Machining

Laser machining of FRP composites offers many advantages over traditional machining processes. There is no contact between the tool and the workpiece, and hence there are no cutting forces, no tool wear, and no part distortion because of mechanical loading. Laser cutting is a thermal process and is not influenced by the strength and the hardness of the work material. Therefore it is best suited for cutting heterogeneous materials composed of different phases with contrasting mechanical properties. It provides high machining rates, thin kerf width, and flexibility to cut complex contoured shapes

Drawbacks of laser cutting include material changes and strength reduction due to the formation of a HAZ, the formation of kerf taper and a decrease in cutting efficiency as thickness of workpiece increases
Even though nontraditional machining have their own advantages and disadvantages but their use is determined by the final outcome of the process, for e.g., if the process requires higher production rate then Non-Traditional process (e.g. AWJ) is shown that cutting speeds as high as 2,400 m/min may be used to cut effectively CFRP and GFRP thin parts (6mm thick). This represents tremendous productivity gains over traditional trimming methods.

If the process requires good surface quality then traditional machining process is used, the dimensional tolerances and surface finishes also depend on thickness and cutting speed. The tolerance range that can be held on small parts is about ±0.025mm and on large parts is about ±0.125mm. Tighter tolerances are possible with tighter control of the machine axes and nozzle motion. Nevertheless, these tolerances do not compare with the tolerance ranges of traditional machining processes (e.g. ±0.002mm for rough milling and ±0.001mm for finishing).

### 3.3 Orthogonal Machining

In particular, orthogonal machining is defined as the material removal process in which the cutting edge is perpendicular to the feed direction and assumed as a 2-dimensional process as the deformation is mostly confined to a single plane. The surface generated is a plane parallel to the original work surface. A carpenter’s plane cuts orthogonally, as does a band saw. Rotary peeling of veneer approximates orthogonal cutting.

It was found that tool material and rake angle have significant effect on the process output. Figure 3.3 (a) different forces acting during orthogonal machining developed by Merchant known as Merchant”s theory of metal cutting. Figure 3.3 (b) shows the schematic of orthogonal cutting of uni-directional FRP”s, fiber orientation angle is measured clockwise.
between feed direction and fiber axis, rake angle is measured between the vertical line and rake face facilitating the chip flow, clearance angle is measured between the clearance face and the machined surface which contribute to the thrust force measured perpendicular to the cutting direction. The intersection of the rake face and the clearance face constitute the cutting edge responsible for the cutting force measured along the cutting direction.

![Figure 3.3: Schematic of orthogonal cutting (a) Metals (b) UD-FRP (0 < θ < 90) [2]](image)

### 3.4 Chip Formation Modes

The process of chip formation in orthogonal machining of unidirectional fiber reinforced composites was studied by several researchers. Koplev et al. [8] were among the first to study this phenomena using the quick stop device and macro chip methods. The quick stop device is widely used in the study of metal machining, and is well documented in the metal cutting literature [2] and thus will not be discussed here.

The chip formation process in machining unidirectional FRPs is categorized into five different types, depending on fiber orientation and cutting edge rake angle. Figure 3.4 schematically shows the different modes of chip formation when machining FRPs with a sharp cutting edge (nose radius in the order of a few micrometers) and the resulting chip types.
Delamination type chip formation (Type I) occurs for the 0° fiber orientation and positive rake angles as shown in figure 3.4 (a). Mode I fracture and loading occur as the tool advances into the work material. A crack initiates at the tool point and propagates along the fiber–matrix interface. As the tool advances into the workpiece, the peeled layer slides up the rake face, causing it to bend like a cantilever beam. Bending-induced fracture occurs ahead of the cutting edge and perpendicular to the fiber direction. A small distinct chip segment is thus formed and the process repeats itself again. The fractured chip flattens out upon separation and returns to its original shape because of the absence of plastic deformation. The cutting forces widely fluctuate with the repeated cycles of delamination, bending, and fracture. The machined surface microstructure reveals fibers partly impeded in the epoxy resin matrix because of elastic recovery and the fracture patterns of the matrix suggest that it was stretched in Mode I loading before fracture. Fibers on the machined surface are fractured perpendicular to their direction as a result of micro buckling and compression of the cutting edge against the surface. Figure 3.4 (a) shows an example of the machined surface for delamination type chip formation [14].

Fiber buckling type of chip (Type II) occurs when machining 0° fiber orientation with 0° or negative rake angles as shown in figure 3.4 (b). In this case, the fibers are subjected to compressive loading along their direction, which causes them to buckle. Continuous advancement of the cutting tool causes Mode II loading (sliding) or in-plane shearing and fracture at the fiber–matrix interface. Successive buckling finally causes the fibers to fracture in a direction perpendicular to their length. This fracture occurs in the immediate vicinity of the cutting edge and results in small discontinuous chips.
The cutting forces fluctuation in this case is smaller than that for the delamination type (Type I) chip formation process. The machined surface for the buckling type chip is also similar to that of the delamination type chip machined surface. Fiber cutting type chip formation occurs when machining fiber orientations greater than 0deg and less than 90deg, and for all rake angles as shown in figure. 3.4 (c–e). The chip formation mechanism consists of fracture from compression-induced shear across the fiber axes followed by interlaminar shear fracture along the fiber–matrix interface during the cutting tool advancement. During the compression stage of the chip formation process, cracks are generated in the fibers above and below the cutting plane. The cracks below the cutting plane remain in the machined surface and are visible when examined under microscope. Chip flow in machining all positive fiber angles up to 90◦ thus occurs on a plane parallel to fiber orientation. This makes this particular type of chip formation similar in appearance to the chip formation in metal cutting where material is deformed by plastic shear as it passes across a shear plane. An important distinction, however, is the absence of plastic deformation in the case of machining FRPs. Material removal in these cases appears to be governed by the in-plane shear properties of the unidirectional composite material.
3.5 Machining Tools

Machining of fiber-reinforced polymers (FRPs) is a challenging process from the point of cutting tool requirements. Unlike metal cutting where plastic deformation is the predominant cause of chip formation, the cutting of FRPs takes place by compression shearing and fracture of the fiber reinforcement and matrix. This puts stringent requirements on the cutting edge geometry and material. A sharp cutting edge and large positive rake angle are often required to facilitate clean shaving of the fibers, and a tool material with high hardness and toughness is
required to resist the abrasiveness of the fibers and the intermittent loads generated by their fracture

A wide range of cutting tool materials is available for machining applications. These materials are generally classified into three main groups according to their hardness, strength, and toughness, as shown in figure 3.5, which also demonstrates the opposing relationship between hardness and toughness. The three groups are high-speed steels (HSS), cemented carbides, and ceramics/super hard materials. Each group has its own characteristic mechanical and thermal properties, which makes its application more suitable for certain machining operations.

![Figure 3.5: Interrelations between toughness and hardness for the tool materials [7]](image-url)
3.6 Tool Geometry

A cutting tool has one or more sharp cutting edges. The cutting edges separate the chips from the workpiece. A cutting tool is selected to suit a particular machining operation.

Rake face directs the flow of the newly formed chip, is oriented at a certain angle called the rake angle. Range mostly +5° to -5°; some +10° to -10°; a few +20° to -20°.

Flank face, which provides a clearance between the tool and the newly generated work surface, and is oriented at an angle called the clearance angle and ranges positive 2°-10°

Chip Breakers are frequently used with single-point tools to force the chips to curl more tightly than they would naturally be inclined to do, thus causing them to fracture.

A single-point tool has a main cutting edge and a tool point from which the name of this cutting tool is derived.

A Multiple edge cutting tool has more than one cutting edge and usually achieves their motion relative to the work part by rotating.

3.7 Tool Wear

Tool wear is defined as the unwanted removal of tool material from the cutting edge or the permanent deformation of the cutting edge leading to undesirable changes in the cutting edge geometry. Once the initial cutting geometry is altered, the cutting tool becomes less effective in performing its principal functions, which are material removal and generating good quality machined surface. Tool wear leads to undesirable consequences such as reduction in cutting edge
strength, increased tool forces and power consumption, increased cutting temperatures, degradation in surface finish, loss of part dimensional accuracy, and eventually loss of productivity. Therefore, it is extremely desirable that tool wear is considerably minimized and controlled.

3.7.1 Types of Tool Wear

- Flank wear in which the portion of the cutting tool at contact with the finished part is worn out and can be used in tool life expectancy equation.
- Crater wear is on the rake face as the flowing chips erodes away some of the face. This type of tool wear is common, and does not seriously affect the use of a tool until it becomes larger enough to cause a cutting edge failure. It can be caused by very low spindle speed or very high feed rate. In orthogonal machining this typically occurs where the tool temperature is highest.
- Built-up edge in which workpiece material sticks on to the cutting edge. Some materials (copper and aluminum) have the tendency to anneal themselves to the cutting tool edges. It occurs frequently while machining softer metals that has low melting point. It can be prevented by good lubrication and increasing cutting speeds.
- Edge wear refers to wear on the outer edges of a drill bit around the cutting face caused due to excess cutting speed.
3.8 Tool life

Tool life is defined as the cutting time required for reaching an amount of wear as specified by a tool-life criterion. A tool-life criterion is defined by a machining objective such as predetermined acceptable levels of cutting forces, surface quality, dimensional stability, or production rate.

3.9 Machining Forces

In orthogonal cutting, the tool edge is perpendicular to the direction of the cutting speed vector, \( v \). Orthogonal cutting represents a two-dimensional problem, and hence, it lends itself well to research work. In orthogonal cutting, all forces, motions, and deformations are in the plane formed by the cutting velocity vector and the direction normal to the following assumptions are made to further simplify the analysis:

- The tool cutting edge is perfectly sharp and straight, cuts perpendicular to the direction of motion, and has a width greater than that of the workpiece.
- The cutting edge generates a plane surface, at constant depth of cut as the work moves past it with a uniform velocity.
- The chip does not flow to either side, since it has the same width as the workpiece.
- A continuous chip is produced without a built-up edge.
- The shear surface is a plane extending upward from the cutting edge.
- There is no contact between the workpiece and the clearance surface of the tool.
The cutting ratio \( r \) is defined by \( ac / ao \). The relationship between \( r \) and \( \phi \) can be obtained from Figure 3.6 as follows:

\[
\sin \phi = \frac{a_c}{AB} \\
\frac{r}{1-r \sin \phi} = \frac{a_c}{a_o} = \frac{AB \sin \phi}{(AB \cos (\phi - \alpha_o))} \\
= \sin \phi / \cos (\phi - \alpha_o) \\
tan \phi = \frac{r \cos \alpha_o}{1-r \sin \alpha_o}
\]  

The force \( F_f \) represents the frictional resistance met by the chip as it slides over the rake face of the tool, \( F_n \) is known as the normal force from figure 3.6. The ratio of \( F_f \) to \( F_n \) is the mean coefficient of friction, \( \mu \). Forces on the rake face are

\[
F_f = F_c \sin \alpha_o + F_c \cos \alpha_o = R \cos (90 - \beta) \\
F_n = F_c \cos \alpha_o - F_c \sin \alpha_o = R \sin (90 - \beta)
\]
\[
\mu = \tan \beta = \frac{F_f}{F_n} = \frac{[F_c \sin \alpha + F_c \cos \alpha]}{[F_c \cos \alpha - F_c \sin \alpha]}
\] (3.5)

The cutting force, \( F_c \), in the direction of the relative motion between the tool and workpiece determines the amount of work required to remove material. The thrust force, \( F_t \), is normal to the relative motion between the tool and workpiece and does no work. Thus, the machining power is defined as
\[
P_m = F_c v. \tag{3.6}
\]

The specific cutting energy also called the specific cutting pressure is the machining power per unit volume removed per unit time
\[
P_s = \frac{F_c v}{v A_c} = \frac{F_c}{A_c} \tag{3.7}
\]

A high degree of fluctuation in the cutting forces is exhibited when machining FRPs. The fluctuations in the principal or cutting force are observed to be higher than those in the thrust force. The degree of fluctuation depends primarily on fiber orientation and it correlates to a large extent with the mode of chip formation prevalent in cutting the particular fiber orientation as explained in Figure. 3.4. For cutting parallel to the fibers with positive rake angle, the force fluctuations are indicative of the peeling and bending/fracture action of the fibers occurring on the rake face. For cutting positive fiber orientations, the principal force reflects changes in the process of shearing and fracture of the fiber and matrix materials with changes in fiber orientation. The thrust force reflects the interaction between the machined surface and the clearance face of the tool.
3.10 Surface Quality

In any machining operations, a specific surface geometry is produced as a result of the prescribed machine tool kinematics. This surface geometry is called an ideal or theoretical surface geometry, which follows a repeated pattern. In real life, however, the actual machined surface deviates from the ideal surface because of tool wear, machine vibrations, material inhomogeneity, and other factors not related to machine tool kinematics. The actual machined surface may not have a regular geometry which is called natural surface finish.

Surface roughness is most often used to characterize machined surfaces. It is measured by statistical parameters such as the arithmetic mean value $R_a$, maximum peak to valley height $R_t$, maximum peak to mean height $R_p$, mean to valley height $R_v$, and ten point average height $R_z$. Machined surface profile is most usually measured by a stylus surface profilometer. Modern profilometers trace the machined surface over a prescribed sampling distance and automatically compute the statistical parameters for the user.

![Figure 3.7: Schematic representation of machined surface [7]](image-url)
Machined surface quality is often characterized by surface morphology or texture and surface integrity. Surface morphology is concerned with the geometrical features of the generated surface. It is a function of the tool geometry, kinematics of the machining process, and machine tool rigidity. Surface integrity describes the physical and chemical changes of the surface layer after machining. This includes fiber pullout, fiber breakage, delamination, matrix removal, and matrix melting or decomposition. Both surface morphology and integrity depend on process and workpiece characteristics such as cutting speed, feed rate, fiber type and content, fiber orientation, and matrix type and content.

The reliability of machined components, especially of high strength applications, is critically dependent on the quality of the surfaces produced by machining. The condition of the surface layer of the machined edge may drastically affect the strength and the chemical resistance of the component. It is necessary, therefore, to characterize and quantify the quality of the machined surface and the effect of process parameters on surface quality.
CHAPTER IV

EXPERIMENTAL SETUP AND PROCESS PARAMETERS

A 2.5 in or 1.15 in wide uni-directional carbon composite panel was used for machining experiments in this research. The panels were securely fixed to the swivel based vise to attain desired fiber orientation during the machining process just by rotating the vise to desired angle. The vise was attached to a KISTLER 9272 dynamometer using an adaptor. A HAAS 3-axis vertical minimill CNC machine was used for all the experiments under dry cutting conditions.

![Orthogonal machining setup](image)

Figure 4.1: Orthogonal machining setup

The dynamometer readings were transferred to a National Instruments (NI) data acquisition (DAQ) card after being amplified by 5010B KISTLER dual-mode amplifiers. VILogger LabVIEW 8.0 registered the received signals with a frequency of 500 Hz. The DAQ card used was NI–6023E. Before using the DAQ card for the experiments, it was calibrated. The calibration was done using two steps, one with calibrating the voltage readings and the other is to
convert the voltage to the desired physical quantity. The X and Y forces of the dynamometer which corresponds to the cutting and thrust forces respectively were calibrated with standard weights and hanging scale, respectively, and the torque was calibrated with a precise torque wrench. Figure 4.1 shows the setup used for the experiments. The orientation of the cutting and thrust forces with respect to the dynamometer coordinate system is shown in figure 4.2.

![Dynamometer setup](image)

Figure 4.2: Dynamometer to capture cutting forces

### 4.1 Methodology

All the experiments were performed using 4-edged orthogonal cutting tool with all four edges having the same geometry with desired rake and relief angles is shown in figure 4.3. The tools were attached to the spindle holder which in-turn was attached to spindle head. Since in orthogonal cutting the cutting edge should be perpendicular to the work piece and should remain in the position throughout the cutting process the spindle head was rigidly fixed in the desired position using the spindle orient option or the M19 code. This code provides feedback control for the spindle in order to keep it stationary. It also reorients the spindle in the same direction any time the code is run. Hence, maintains the desired rake and relief angles relative to the cutting direction, the tool should be fit in the tool holder with the correct orientation.
Another important factor was to maintain a constant depth of cut (DOC) and width of cut (WOC) as it is proven that varying these parameters will significantly affect the cutting forces. All the experiments were performed with a constant through-the-thickness WOC of 1mm and in-plane DOC of 0.1mm so as to be consistent with prior work, and a constant feed of 5.9mm/sec was achieved through the horizontal movement of the vise while the cutting tool was fixed. A dial indicator was used to check the flatness of the work piece because a slight variation in the position will alter the through-the-thickness WOC and might result in inaccurate data, before each orthogonal cut the work piece was polished to remove any damage from previous cut and this action makes sure that the material is flat in the direction of the feed hence allowing to maintain the constant in-plane DOC through-out the experiment. Also it is assumed that the nose radius was unchanged as the DOC were sufficiently small and also different cutting edges were used out of the four edges available, also, microscopic images were periodically taken to check for any damage in tool and found out to be in good shape.
Machining Forces and Surface Quality
(for orthogonal cutting of unidirectional material)

Tool Geometry
- Rake Angle
- Tool Tip Radius

Material Properties
- Fiber Orientation
- Young Modulus of Fiber
- Fiber Volume Fraction
- Fiber Diameter
- Shear Modulus of Fiber
- Shear Modulus of Matrix
- Tensile Strength of Fiber
- Matrix Shear Strain at Fracture

Machining Condition
- Depth of Cut
- Feed Rate

Figure 4.4: Cutting tool geometry

Figure 4.5: Factors affecting machining forces and surface quality
Figure 4.4 shows the cutting tool geometry and the measurement of rake and relief angles used in this study, while figure 4.5 shows the machining parameters that affect the machining forces and surface quality.

Table 4.1: Orthogonal cutting experiments matrices

<table>
<thead>
<tr>
<th>Fiber Orientation (°)</th>
<th>Tool Rake Angle (γ)</th>
<th>Fiber Orientation (°)</th>
<th>Tool Rake Angle (γ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>5</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>40</td>
<td>5</td>
<td>40</td>
<td>15</td>
</tr>
<tr>
<td>60</td>
<td>5</td>
<td>60</td>
<td>15</td>
</tr>
<tr>
<td>80</td>
<td>5</td>
<td>80</td>
<td>15</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>40</td>
<td>10</td>
<td>40</td>
<td>20</td>
</tr>
<tr>
<td>60</td>
<td>10</td>
<td>60</td>
<td>20</td>
</tr>
<tr>
<td>80</td>
<td>10</td>
<td>80</td>
<td>20</td>
</tr>
</tbody>
</table>

Table 1.1 shows the different fiber orientation and rake angles used in this study while keeping a constant clearance angle of 6deg and DOC 0.1mm.

4.2 Machining Forces

The experiments were conducted for fiber orientations less than 90° for both Hexply and Newport materials. Tables 4.2 to 4.5 show the measured machining forces for both Hexply and Newport unidirectional materials. The V I logger system attached to the dynamometer picks up the signal during machining and stores in an excel format for future viewing and analyzing, figure 4.6 shows one such data of cutting force during machining CFRP, similarly the thrust force will be acquired for all machining conditions.
Figure 4.6: Acquired experimental cutting force for CFRP

Table 4.2: Cutting force values from the experiments on Hexplymaterial. All forces (lbf)

<table>
<thead>
<tr>
<th>Rake Angle Orientation</th>
<th>5°</th>
<th>10°</th>
<th>15°</th>
<th>20°</th>
</tr>
</thead>
<tbody>
<tr>
<td>10°</td>
<td>2.2, 5.2, 4.4</td>
<td>4.1, 3.6, 4.2</td>
<td>3.1, 5.5, 4.5</td>
<td>4.5, 2.8, 4.3</td>
</tr>
<tr>
<td>40°</td>
<td>1.4, 3.5, 3.8</td>
<td>5.6, 6.3, 5.3</td>
<td>4.3, 5.6, 6.4</td>
<td>2.2, 3.1, 3.2</td>
</tr>
<tr>
<td>60°</td>
<td>10.6, 8.6, 8.6</td>
<td>5.0, 4.0, 2.2</td>
<td>2.0, 2.6, 2.9</td>
<td>2.8, 3.6, 1.4</td>
</tr>
<tr>
<td>80°</td>
<td>6.7, 3.10, 9.34</td>
<td>4.8, 7.0, 10.0</td>
<td>3.3, 3.8, 3.1</td>
<td>6.8, 6.0, 5.2</td>
</tr>
</tbody>
</table>

Table 4.3: Thrust force values from the experiments on Hexplymaterial. All forces (lbf)

<table>
<thead>
<tr>
<th>Rake Angle Orientation</th>
<th>5°</th>
<th>10°</th>
<th>15°</th>
<th>20°</th>
</tr>
</thead>
<tbody>
<tr>
<td>10°</td>
<td>2.9, 5.2, 5.3</td>
<td>5.0, 5.1, 5.8</td>
<td>3.3, 6.0, 6.3</td>
<td>7.8, 5.8, 7.8</td>
</tr>
<tr>
<td>40°</td>
<td>1.4, 3.1, 3.6</td>
<td>6.5, 5.4, 5.4</td>
<td>7.7, 9.0, 9.8</td>
<td>3.2, 4.2, 5.1</td>
</tr>
<tr>
<td>60°</td>
<td>9.7, 8.8, 10.0</td>
<td>5.7, 5.6, 2.9</td>
<td>3.9, 5.0, 4.9</td>
<td>4.7, 3.5, 1.7</td>
</tr>
<tr>
<td>80°</td>
<td>5.0, 6.4, 4.7</td>
<td>2.8, 4.0, 4.7</td>
<td>3.0, 3.8, 3.6</td>
<td>8.3, 9.3, 8.5</td>
</tr>
</tbody>
</table>
Table 4.4: Cutting force values from the experiments on Newport material. All forces (lbf)

<table>
<thead>
<tr>
<th>Rake Angle</th>
<th>Orientation</th>
<th>5°</th>
<th>10°</th>
<th>15°</th>
<th>20°</th>
</tr>
</thead>
<tbody>
<tr>
<td>10°</td>
<td>3.2, 5.0, 5.32</td>
<td>4.1, 5.1, 2.6</td>
<td>2.2, 1.8, 3.5</td>
<td>1.7, 0.9, 2.4</td>
<td></td>
</tr>
<tr>
<td>40°</td>
<td>3.8, 3.5, 3.3</td>
<td>2.7, 2.7, 2.9</td>
<td>3.5, 2.4, 3.0</td>
<td>2.4, 2.4, 1.8</td>
<td></td>
</tr>
<tr>
<td>60°</td>
<td>7.2, 6.8, 2.4</td>
<td>3.5, 4.7, 5.5</td>
<td>3.2, 4.1, 3.1</td>
<td>1.9, 1.7, 1.5</td>
<td></td>
</tr>
<tr>
<td>80°</td>
<td>8.6, 7.0, 6.9</td>
<td>6.2, 5.4, 7.1</td>
<td>8.2, 4.2, 5.5</td>
<td>1.6, 1.6, 3.2</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.5: Thrust force values from the experiments on Newport material. All forces are in (lbf)

<table>
<thead>
<tr>
<th>Rake Angle</th>
<th>Orientation</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>2.1, 3.4, 2.2</td>
<td>5.0, 2.6, 1.7</td>
<td>2.1, 1.5, 2.4</td>
<td>3.0, 1.3, 3.9</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>2.2, 2.3, 2.2</td>
<td>1.5, 1.9, 2.1</td>
<td>2.4, 2.6, 2.2</td>
<td>4.2, 4.3, 4.9</td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>2.5, 2.6, 2.2</td>
<td>2.5, 3.1, 3.4</td>
<td>3.0, 3.4, 3.2</td>
<td>2.4, 2.3, 2.4</td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>5.0, 5.3, 3.8</td>
<td>1.9, 1.8, 2.2</td>
<td>1.3, 2.0, 1.5</td>
<td>1.6, 2.1, 3.8</td>
<td></td>
</tr>
</tbody>
</table>

4.3 Surface quality

Figure 4.6 shows the damage length along fiber orientation. If L is greater than $-a_c/\sin \theta$, the composite edge will be damaged after material removal and the damage residue exists. However, if L is smaller than $-a_c/\sin \theta$, the broken fibers will be completely removed from the workpiece and the surface quality will be very good without any major or minor defects. In this research the delamination length (DL) is measured from the numerical software at different time frames and the maximum value out of these and presented as the delamination length for that particular fiber orientation and this process is repeated for all fiber orientations and rake angles considered in this study.
Figures 4.8 to 4.38 shows the microscopic images for fiber orientations 10, 40, 60, and 80deg, rake angles 5, 10, 15, and 20deg for both NPT and Hexply materials, keeping the relief angle and depth of cut constant at 6deg and 0.100mm respectively. All the images were analyzed with OLYMPUS compact inverted metallurgical microscope GX 41 which in turn is connected to soft imaging system for acquisition and processing. The images were taken at three different locations on the machined surface for each sample and this process was repeated for all the machined samples. These images were imported to CorelDRAW software were it is been processed to clearly analyze the machining damage.
Figure 4.8- Microstructure in the subsurface (fiber-orientation = 10°, depth of cut = 0.100mm, rake angle = 5°, relief angle=6°)

Figure 4.9- Microstructure in the subsurface (fiber-orientation = 10°, depth of cut = 0.100mm, rake angle =10°,relief angle=6°)

Figure 4.10- Microstructure in the subsurface (fiber-orientation = 10°, depth of cut = 0.100mm, rake angle =15°,relief angle=6°)

Figure 4.11- Microstructure in the subsurface (fiber-orientation = 10°, depth of cut = 0.100mm, rake angle =20°,relief angle=6°)

Figure 4.12- Microstructure in the subsurface (fiber-orientation = 40°, depth of cut = 0.100mm, rake angle = 5°, relief angle=6°)

Figure 4.13- Microstructure in the subsurface (fiber-orientation = 40°, depth of cut = 0.100mm, rake angle =10°,relief angle=6°)
Figure 4.14- Microstructure in the subsurface (fiber-orientation = 40°, depth of cut = 0.100mm, rake angle = 15°, relief angle=6°)

Figure 4.15- Microstructure in the subsurface (fiber-orientation = 40°, depth of cut = 0.100mm, rake angle = 20°, relief angle=6°)

Figure 4.16- Microstructure in the subsurface (fiber-orientation = 60°, depth of cut = 0.100mm, rake angle = 5°, relief angle=6°)

Figure 4.17- Microstructure in the subsurface (fiber-orientation = 60°, depth of cut = 0.100mm, rake angle = 10°, relief angle=6°)

Figure 4.18- Microstructure in the subsurface (fiber-orientation = 60°, depth of cut = 0.100mm, rake angle = 15°, relief angle=6°)

Figure 4.19- Microstructure in the subsurface (fiber-orientation = 60°, depth of cut = 0.100mm, rake angle = 20°, relief angle=6°)
Figures 4.8 to 4.23 are the microscopic of NPT material and it can be seen that a better surface quality is obtained for 10 and 40deg fiber orientation and it gets worse for 60 and 80deg fiber orientation. Also, the effect of rake angles on surface quality is greater for higher fiber orientation.
Figure 4.24- Microstructure in the subsurface (fiber-orientation = 10°, depth of cut = 0.100mm, rake angle = 5°, relief angle = 6°)

Figure 4.25- Microstructure in the subsurface (fiber-orientation = 10°, depth of cut = 0.100mm, rake angle = 10°, relief angle = 6°)

Figure 4.26- Microstructure in the subsurface (fiber-orientation = 10°, depth of cut = 0.100mm, rake angle = 15°, relief angle = 6°)

Figure 4.27- Microstructure in the subsurface (fiber-orientation = 10°, depth of cut = 0.100mm, rake angle = 20°, relief angle = 6°)

Figure 4.28- Microstructure in the subsurface (fiber-orientation = 40°, depth of cut = 0.100mm, rake angle = 5°, relief angle = 6°)

Figure 4.29- Microstructure in the subsurface (fiber-orientation = 40°, depth of cut = 0.100mm, rake angle = 10°, relief angle = 6°)
Figure 4.30 - Microstructure in the subsurface (fiber-orientation = 40°, depth of cut = 0.100mm, rake angle = 15°, relief angle = 6°)

Figure 4.31 - Microstructure in the subsurface (fiber-orientation = 40°, depth of cut = 0.100mm, rake angle = 20°, relief angle = 6°)

Figure 4.32 - Microstructure in the subsurface (fiber-orientation = 60°, depth of cut = 0.100mm, rake angle = 5°, relief angle = 6°)

Figure 4.33 - Microstructure in the subsurface (fiber-orientation = 60°, depth of cut = 0.100mm, rake angle = 10°, relief angle = 6°)

Figure 4.34 - Microstructure in the subsurface (fiber-orientation = 60°, depth of cut = 0.100mm, rake angle = 15°, relief angle = 6°)

Figure 4.35 - Microstructure in the subsurface (fiber-orientation = 60°, depth of cut = 0.100mm, rake angle = 20°, relief angle = 6°)
Figures 4.24 to 4.39 are the microscopic images of Hexply composite materials and it is seen that a similar trend to that of NPT material is obtained and is also consistent with the literature regarding the chip formation mechanism for different fiber orientation and associated surface quality.
CHAPTER V
NUMERICAL SIMULATION

Most of the research on machining of composites is experimental, which is tedious and expensive. However, a good amount of knowledge has been obtained by experimental studies on the orthogonal machining of unidirectional FRPs which can be used to validate other cheaper and faster analysis techniques. One such technique is FEA. The use of FEA provides immense opportunities to study the effect of variables like tool geometry, laminate stacking sequence, bonding strength between fiber and matrix, operating conditions etc. on cutting forces, chip formation, surface roughness and the extent of sub-surface damage. An experimental test matrix to study the effects of the above variables on the cutting forces and chip formation modes would involve a considerable amount of time and effort.

Simulation of machining of composites is achieved by utilizing the “chip formation criteria”, which are generally commonly used composite failure criteria such as maximum stress criterion, Tsai-Hill criterion, Hoffman criterion, etc. These models are developed either by considering the composite to be an Equivalent Orthotropic Homogeneous Material (EOHM) or by considering the composite to be a two-phase material consisting of a fiber phase and a matrix phase. Finite Element Analysis (FEA) of the machining of composites saves a lot of experimental effort in the determination of machining parameters such as cutting forces, chip formation mechanism and other workpiece responses to machining. Comparison of experimental results with those obtained by FEA yields a good correlation between cutting forces and chip formation modes. The variations of machining parameters with machining conditions are also discussed for different finite element modeling approaches.
The literature available on the FEA of machining of unidirectional FRPs is not very exhaustive. Arola and Ramulu [18] were the first to simulate the orthogonal cutting of UD-CFRP composites using finite elements. They considered the work material to be an EOHM and studied the case where the chip release occurs in the fiber direction. Chip formation was divided into two stages, (1) primary fracture, involving nodal debonding in front of the tool tip and (2) secondary fracture, when an appropriate failure criterion (Maximum stress or Tsai-Hill failure criteria in their study) was satisfied to cause failure at the free-edge. A good correlation was obtained between the experimental and (FEA) predicted principal cutting force, but large differences were observed in the thrust force.

Nayak et al. were the first to develop a micromechanical approach to model the workpiece material, which consisted of a fiber phase and a matrix phase. The separation of the two phases during machining was achieved by using the DEBOND and FRACTURE CRITERION options in ABAQUS. With such an approach, both the principal and the thrust force values agreed well with the experimental results. Another side study was the analysis of the chip formation. In [27], the macro-mechanical approach made it difficult to identify the chip formation modes.

Venu Gopala Rao et al. [15] extended the work of Nayak et al. by including some new features in their micro-mechanical model, including the isotropic hardening of the matrix, stiffness degradation of the matrix once the yield stress has been reached, and using cohesive zone model (CZM) for debonding at the fiber-matrix interface, in which the fracture energies for Mode I and Mode II fractures are used to simulate debonding.
In general, the EHM approach gives good estimates of global properties such as cutting forces but cannot be used to study chip formation mode and geometry. The micro-mechanical approach provides better accuracy, but both these approaches consider the machining process to be 2-dimentional which is not the case in actual machining which might be the cause of variation. Hence in order to overcome these discrepancies and to model a more realistic simulation a 3-dimentional approach has been used in this study using a special option available in ABAQUS 6.9-2.

Table 5.1: CFRP composite material properties

<table>
<thead>
<tr>
<th></th>
<th>Room Temperature Data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B-Basis (US Units)</td>
</tr>
<tr>
<td>( X_t )</td>
<td>251.40 (ksi)</td>
</tr>
<tr>
<td>( E_1^t )</td>
<td>--</td>
</tr>
<tr>
<td>( \nu_{12} )</td>
<td>--</td>
</tr>
<tr>
<td>( Y_t )</td>
<td>5.95 (ksi)</td>
</tr>
<tr>
<td>( E_2^t )</td>
<td>--</td>
</tr>
<tr>
<td>( X_c )</td>
<td>139.20 (ksi)</td>
</tr>
<tr>
<td>( E_1^c )</td>
<td>--</td>
</tr>
<tr>
<td>( Y_c )</td>
<td>28.30 (ksi)</td>
</tr>
<tr>
<td>( E_2^c )</td>
<td>--</td>
</tr>
<tr>
<td>( S_{12} )</td>
<td>19.76 (ksi)</td>
</tr>
<tr>
<td>( G_{12} )</td>
<td>--</td>
</tr>
<tr>
<td>( S_{13} )</td>
<td>12.59 (ksi)</td>
</tr>
</tbody>
</table>

Table 5.1 shows the mechanical properties of CFRP at room temperature for 0 and 90 deg fiber orientation used in both experimental and numerical study which is NCT 321/G150
(NASS) Unitape, the panels were prepared at National Institute of Aviation Research (NIAR) facility.

Most of the material properties listed in table 5.1 are not readily available as individual properties of each of the constituents and should be calculated from the mechanical properties of the composite in whole. Fiber volume fraction is one such essential parameter that must be known ahead or can be found looking through the cross section of the composite under microscope in order to calculate the mechanical properties of the components. The properties from table 5.1 can be used to calculate the individual material properties necessary for the study.

The other individual material mechanical properties can be calculated as shown from the following equations known as rule of mixtures, using the data provided by Newport Adhesives and Composites, Inc.

\[ E_1 = v_f E_f + v_m E_m \]  \hspace{1cm} (5-1)
\[ E'_m = \frac{E_m}{1 - v_m^2} \]  \hspace{1cm} (5-2)

From the mechanics of material, it is known that

\[ G_f = \frac{E_f}{2(1 + v)} \]  \hspace{1cm} (5-3)

Similarly \( G_m \) can also be calculated using the rule of the mixtures

To find the fiber and matrix strength, the rule of mixtures can be used as

\[ X_t = v_f F_b + v_m \bar{\sigma}_m \]  \hspace{1cm} (5.4)
The individual fiber strength is much higher than the fiber bundle, especially when the fiber length is very small. This is because of very few imperfections in fiber that are smaller in length. In this research, the fiber flexural strength is assumed to be at least 2.5 times the fiber bundle strength. The matrix shear strength is estimated to be the same as the composite shear strength, since it can be assumed that the fiber does not shear.

5.1 Finite Element Modeling

Finite element analysis (FEA) was conducted to measure the fiber-matrix debonding length. The material was modeled at the microscopic level to better understand the delamination mechanisms. Fiber and matrix were modeled separately, bonded together using cohesive elements. Abaqus provides a type of element, which is primarily intended for bonded interfaces where the bonding properties is defined in the interaction section. The response of these interactions can be directly expressed in terms of traction versus separation. In the case of cohesive element and availability of the macroscopic properties of the adhesive material, it may be more appropriate to model the response using the conventional material model. For the purpose of this study, the cohesive properties for the interface with the traction-separation response were used. Cohesive behavior, defined in terms of the traction-separation law is advisable to predict delamination response.

5.2 Fiber and Matrix Modeling

Fiber was modeled as transversely orthotropic and matrix material was modeled as isotropic with elastic-plastic behavior and shear damage failure criterion.
5.3 Simulation Procedure

Conventionally, in the 2-dimensional machining of homogeneous material, a plane strain analysis is used, but due to out-of-plane displacements of FRPs during machining, 3D stress analysis should be used.

Finite element analysis was studied using Abaqus/Explicit. The tool was modeled as a 3D analytical rigid. The workpiece was modeled with three different zones fiber, matrix, and equivalent homogeneous material (EHM). The objective of this analysis was to find the fiber-matrix debonding length when the tool is cutting the material. The workpiece dimensions were 400μm × 200μm with nine fibers. There was a matrix layer between each fiber. The rest of the workpiece was modeled as EHM by an equivalent transversely isotropic homogeneous single-phase material with properties \((E_{11}, E_{22}, G_{12}, \text{and} \nu_{12})\), determined from the rule of mixtures from equations 5.5 to 5.8. Figure 5.1 shows a schematic finite element model used for the numerical simulation.

\[
E_{11} = v_f E_f + v_m E_m
\]  
(5.5)

\[
E_{22} = \frac{E_f E'_m}{v_f E'_m + v_m E_f}
\]  
(5.6)

\[
E'_m = \frac{E_m}{1 - \nu_m^2}
\]

\[
G_{12} = \frac{G_f G_m}{v_f G_m + v_m G_f}
\]  
(5.7)

\[
\nu_{12} = v_f \nu_f + v_m \nu_m
\]  
(5.8)
Carbon fiber was modeled with orthotropic material properties, also EHM zones are not isotropic, material orientation should be defined for each zone to assign material properties in their local material orientation. Since orthotropic model is used for carbon fibers and EHM, they can share the same coordinate system. The bottom of the work piece is constrained in all directions along with left and right sides; the cutting of composites is done by moving the cutting tool against the workpiece with the desired velocity. Figure 5.2 shows the exaggerated view of the cutting zone where the mesh density is very high and gradually decreases away from the zone to accurately capture the machining response.
5.4 Element Selection

The Abaqus/Explicit solid element library includes first-order (linear) interpolation elements and modified second-order interpolation elements in two or three dimensions. Triangular and quadrilateral first-order elements are available in 2D and tetrahedral, triangular prism, and hexahedral (brick) first-order elements are available in 3D.

In Abaqus/Explicit you can choose between full or reduced integration for hexahedral (brick) elements. Only first-order elements with reduced integration are available for quadrilateral elements in Abaqus/Explicit; the elements with reduced integration are generally referred to as centroid strain or uniform strain elements with hourglass control. Triangular and tetrahedral elements are geometrically versatile and are commonly used in many automatic meshing algorithms. It is convenient to mesh complex shapes with tetrahedral or triangular
elements, and the second-order and modified triangular and tetrahedral elements (CPE6, CPE6M, C3D10, C3D10M, etc.) in Abaqus and is suitable for general purpose applications. However, a good mesh of hexahedral elements usually provides a solution with better accuracy at less cost. Quadrilaterals and hexahedra have good convergence rate than triangles and tetrahedral, and their sensitivity to mesh orientation in regular meshes is not an issue.

An 8-node linear brick element with reduced integration and hourglass control is used for all the simulations with second order accuracy. Distortion control and element deletion option is used to form chips during and improve convergence because machining involves large deformations and are sensitive to element deletion.

5.5 Interactions

In Abaqus, there are two ways to define adhesive interaction during simulation either defining cohesive elements or Surface based cohesive behavior. Cohesive element requires creating a zone to define traction separation properties. Surface-based cohesive can define the interaction between two surfaces, these two surfaces are paired and given a cohesive property, one of them is defined as the master surface and other the slave surface.

Surface-based cohesive behavior and cohesive element are very similar in terms of their function, but surface-based cohesive behavior is simple to use since it is not necessary to create additional elements, and can be used in a many applications, such as two sticky surfaces coming into contact during an analysis. Surface-based cohesive behavior is applicable for situations in which the interface thickness is negligibly small. If the interface adhesive layer has a finite thickness and macroscopic properties (such as stiffness and strength) of the adhesive material are
to be included, it will be more appropriate to model the response using conventional cohesive elements.

In this research, there is no separate region for cohesive elements; hence it is more appropriate to model the work piece using surface-based cohesive behavior because it can significantly reduce computational cost.

5.6 Analysis Type

The direct-integration dynamic procedure available in Abaqus/Standard offers a choice of implicit operation for integration of the equations of motion, whereas Abaqus/Explicit uses the central-difference operation. In implicit dynamic analysis the integration operator matrix must be inverted and a set of nonlinear equilibrium equations must be solved at each increment of time step. In an explicit dynamic analysis displacements and velocities are calculated in terms of quantities that are known at the beginning of an increment step, therefore, the global mass and stiffness matrices need not be formed and inverted, which means that each increment is considerably inexpensive compared to that in an implicit integration scheme. The size of the time increment in an explicit dynamic analysis is limited, however, because the central-difference operator is only conditionally stable.

Abaqus/Explicit offers fewer element types than compared to Abaqus/Standard. For example, only first-order, displacement method elements (4-node quadrilaterals, 8-node bricks, etc.) and modified second-order elements are used, and all degrees of freedom in the model must have mass or rotary inertia associated with it. However, the method provided in Abaqus/Explicit has some important advantages as shown below and hence used as the analysis type for all models.
The analysis cost rises only linearly with problem size, whereas the cost of solving the nonlinear equations in case of implicit integration rises very rapidly than linearly with problem size. Therefore, Abaqus/Explicit is very suitable for large problems.

The explicit integration method is more often efficient than the implicit integration method for solving extremely discontinuous short-term events or processes.

Problems involving stress wave propagation can be far more efficient computationally in Abaqus/Explicit to that of Abaqus/Standard.

Is computationally efficient for the analysis of large models with relatively short dynamic response times and for the analysis of extremely discontinuous events or processes;

Allows for very general contact definition

Uses a consistent, large-deformation theory in which models can undergo large rotations and large deformation;

Can use a geometrically linear deformation theory in which strains and rotations are assumed to be small

Can be used to perform an adiabatic stress analysis if inelastic dissipation is expected to generate heat in the material

Can be used to perform quasi-static analyses with complicated contact conditions

Allows for either fixed or automatic time incrementation to be used, Abaqus/Explicit uses automatic time incrementation with the global time estimator.

5.6 Validation

The chip formation process in orthogonal machining of unidirectional fiber reinforced polymer composites has been studied by several researchers. Koplev et al. [1] were among the
first to study this phenomena using the quick stop device and macrochip methods. Later, many researchers have studied this phenomenon using various techniques and finally Wang et al. came up with the chip formation modes for different fiber orientation and rake angles which is discussed in detail in chapter II. The numerical simulation obtained for different fiber orientations with positive rake angle is compared with the literature of Wang et al. and found to be in good agreement with the modes of chip formation. Although, there are few results available in literature about the chip formation modes but are mostly experimental findings and could not predict delamination during machining.

![Figure 5.3: Comparison of numerical results with Wang et al. (0 or 180deg fiber orientation)](image)

![Figure 5.4: Comparison of numerical results with Wang et al. (45deg fiber orientation)](image)
Figure 5.5: Comparison of numerical results with Wang et al. (90deg fiber orientation)

The cutting forces were measured for the experimental machining process as explained in previous chapter and similarly the cutting forces were measured for the numerical simulation by activating the contact force between cutting tool and work piece. The numerical cutting forces were compared with the experimental cutting forces which in turn were compared with literature and were found to be in good agreement. Fig 5.6 shows the experimental and numerical cutting force comparison for 20deg rake angle which shows similar trend for different fiber orientations. For all the experiments three set of readings were taken and shown below and the variations in the cutting forces is attributed to human errors in maintaining a constant depth and width of cut, along with the inbuilt variance of the machine, even though after each cut the machined surface is thoroughly polished their exist some damage in the material which will be inconsistent for each polish. Also, the material properties are not the same all the way through its length. From figure 5.6 it can seen that the cutting forces gradually increases as the fiber orientation increases as observed in the literature due to change in chip formation modes as shown in figures 5.3 to 5.5 and explained in previous chapter.
In any numerical simulation it is required to input material properties to simulate the actual process and these properties greatly affect the outcome of the simulation process. It is always necessary to include all the properties and specify correctly to model the simulation as close as possible to the actual physical system which is complex and extensive. In fact, modeling of composites is more complex because of its anisotropic and heterogeneous nature which needs to be taken care, and this situation is even more complex when performing a micro-mechanical analysis which studies local defects such as delamination for which the interface properties needs to be specified. All these properties are neither readily available in literature nor provided by the manufacturer hence the numerical model involves some level of approximation which results in variation from the experimental work. From figure 5.6 it can be seen there is difference in cutting forces for experimental and numerical simulation and the maximum variation is found to be 33% that can be observed for 80deg fiber orientation.

Figure 5.6: Experimental and numerical comparison of the cutting forces for rake 15
5.7 Delamination length

The finite element analysis was run on a unidirectional material with mechanical properties given in table 5.1 and the delamination lengths for different fiber orientation are shown in figure 5.7 to 5.10. Once the cutting is done the fibers will spring back to its original position due to elastic recovery and looks very normal without delamination but, there still exists delamination which has to be clearly investigated by going back and checking at different time frames.

Since composites are widely used in aviation industry, delamination causes a serious threat for its service life. The delamination zone provides an opportunity for impurities to sneak through, particularly moisture which at room temperature doesn’t cause a serious problem but when the aircraft is flying at high altitudes during service, water freezes to form ice and due to volumetric expansion the separation between fibers and matrix increase thereby causing severe delamination issue during its operation and deteriorating its structural integrity.

Figure 5.7: Delamination damage for 80deg fiber orientation
Figure 5.8: Delamination damage for 60deg fiber orientation

Figure 5.9: Delamination damage for 40deg fiber orientation
Figures 5.7 to 5.10 clearly shows the delamination for 80, 60, 40 and 10deg respectively, the delamination lengths is measured by selecting a node on the desired fiber along the trim plane and selecting another node along fiber axis up to the point of maximum separation for which the software measures the shortest distance measuring delamination length.
CHAPTER VI
RESULTS AND DISCUSSION

The orthogonal experimental and numerical cutting forces with respect to fiber orientations on NPT material is plotted for different rake angles. Figure 6.1 to 6.4 represent the cutting force for 5, 10, 15 and 20deg respectively with other parameters kept constant.

![Rake 5](image)

Figure 6.1: Experimental and numerical cutting forces for rake 5deg on NPT material

From figure 6.1 it can be seen that the cutting forces increases both in experiments and numerical simulations as the fiber orientation increases and this is because the failure mode changes from mode I to mode III as explained in chapter three. Even though there is a large variation in certain experimental and numerical values but follows the same trend indicating the correctness of the numerical model, the larger experimental cutting forces might be attributed to tool wear.
Figure 6.2: Experimental and numerical cutting forces for rake 10deg on NPT material

Figure 6.2 and 6.3 shows the experimental and numerical cutting forces for 10 and 15deg rake angles respectively and we can see clearly see the increasing trend for both rake angles.

Figure 6.3: Experimental and numerical cutting forces for rake 15deg on NPT material
Figure 6.4: Experimental and numerical cutting forces for rake 20deg on NPT material

Figure 6.4 shows the experimental and numerical cutting forces for 20deg rake angle for different fiber orientations, the cutting forces are important in orthogonal machining process because all the work required for cutting and generating chips is due to cutting tool movement contributing to cutting force, and thrust does no work, once the actual cutting is done the rake face slides against the machined surface contributing for thrust force. Generally, thrust forces have lot of variations in orthogonal machining and in particular machining composites, as the fracture takes place and chips are formed and because of its brittle nature tiny chips are formed which carries away sliding through the rake face of the tool, however few particles gets in-between the cutting tool rake face and machined surface causing the thrust force fluctuation.

Figure 6.5 to 6.8 shows the experimental and numerical thrust force on NPT materials, as already discussed the effect of thrust force on sub-surface damage is very minimal as compared to principal cutting force along with variations in thrust force values.
Figure 6.5: Experimental and numerical thrust forces for rake 5deg on NPT material

Figure 6.6: Experimental and numerical thrust forces for rake 10deg on NPT material

Figure 6.6 and 6.7 shows the plot of thrust force and fiber orientations for 5 and 10deg respectively, the thrust forces doesn”t follow any particular trend a values were randomly distributed which is normal and observed in prior literature.
Figures 6.7 and 6.8 shows the plot of thrust forces and fiber orientations for 15 and 20deg respectively, from all the figures it can be seen that thrust force value for 80deg fiber orientation for is lesser clearly indicating that the thrust force has minimum effect on delamination.
Delamination lengths are measured for different fiber orientations and rake angles as shown in table 6.1. Measuring delamination lengths experimentally is very difficult and also to get the exact values is practically feasible as the delamination seen microscopically is not the true representation because of the spring back action of the composites.

Table 6.1: Numerical simulation delamination lengths (µm)

<table>
<thead>
<tr>
<th>Rake Angle Orientation</th>
<th>5°</th>
<th>10°</th>
<th>15°</th>
<th>20°</th>
</tr>
</thead>
<tbody>
<tr>
<td>10°</td>
<td>80</td>
<td>80</td>
<td>70</td>
<td>50</td>
</tr>
<tr>
<td>40°</td>
<td>90</td>
<td>52</td>
<td>48</td>
<td>62</td>
</tr>
<tr>
<td>60°</td>
<td>119</td>
<td>58</td>
<td>77</td>
<td>64</td>
</tr>
<tr>
<td>80°</td>
<td>117</td>
<td>70</td>
<td>118</td>
<td>74</td>
</tr>
</tbody>
</table>

Figure 6.9: Numerical simulation delamination lengths (µm)

Figure 6.9 shows the delamination lengths and fiber orientations for 5, 10, 15 and 20 deg rake angles, it can be seen that the delamination lengths increase as the fiber orientation increases which was observed in microscopic images, also following the same trend observed to that for cutting forces.
7.1 Conclusion

Orthogonal machining was experimentally conducted for different positive fiber orientations and rake angles and compared with numerical simulation and found to be in good agreement.

A new modeling technique to predict delamination is presented here that specifies surface based cohesive behavior for interactions between 3D fibers and matrix without actually creating a layer for cohesive zone used in prior literature, thereby creating a more realistic model to predict delamination and also accounting for accurate volume ratios.

The surface quality does not always decrease with increasing positive fiber orientation and was found the better quality is obtained for 0 and 40deg fiber orientation. Also, the effect of rake angle is high for fiber orientation 60 and 80deg, where as it is negligible for 10 and 40deg. The surface quality rapidly decreases for 60deg when compared to 40deg fiber orientation due to chip formation mechanisms.

Delamination lengths were measured from numerical simulations and found to have the most damage for 80deg fiber orientation indicating a good agreement with experimental machining.
### 7.2 Future Work

In the future, each lamina can also be modeled using two phase system of fiber and matrix in the depth direction, so that each fiber will be completely surrounded by matrix representing actual composite panel, but will drastically increase the contacts defined and computational time.

Also a full factorial study can be conducted to investigate the effect of machining conditions and cutting tool parameters on delamination depth to study their behavior and come up with optimized process parameters.

Frictional forces vary with fiber orientation and increases with increasing fiber orientation. Numerical simulations can be performed with different friction coefficients depending on fiber orientations to investigate their effects on delamination damage and cutting forces.
REFERENCES


