ANALYSIS OF DELAMINATION IN DRILLING OF CIRCULAR PLATE COMPOSITE MATERIALS WITH A MULTI-FACET DRILL BIT

A Thesis by

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ANALYSIS OF DELAMINATION IN DRILLING OF COMPOSITE MATERIALS
WITH A MULTI-FACET DRILL BIT

I 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.

______________________________
Behnam Bahr, Committee Chair

We have read this thesis
and recommend its acceptance:

______________________________
Hamid M. Lankarani, Committee Member

______________________________
S. Hossein Cheraghi, Committee Member
DEDICATION

To my family and friends
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ABSTRACT

Delamination is recognized as one of the most critical defects that can result from the machining of composites. Delamination has been a major form of failure in drilled composite materials due to the composite’s lack of strength in the direction of drilling, which results in poor surface finish, reduction in bearing strength, reduction in structural integrity, and ultimately poor performance of the composite. Delamination due to drilling has been a major research interest for many years, and a considerable amount of work has been done to reduce it.

This thesis work involved deriving a formula to determine what applied thrust force would cause delamination in a particular drill bit, the multi-facet drill bit. To achieve that goal, a formula was developed. The conditions and the drill bit used were altered. The thrust force at which delamination occurred was dependent on the thickness and the composition of the material being used.

Experimental validation of the physical model involved calculating the thrust force that would cause delamination, using the formula, and drilling at the calculated thrust force. The thrust force was applied as a correlation of feed rate and spindle speed.
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<tr>
<td>MFD</td>
<td>Multi-Facet Drill Bit</td>
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<td>GFRP</td>
<td>Glass Fabric Reinforced Plastic</td>
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<tr>
<td>SIF</td>
<td>Stress Intensity Factor</td>
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<td>CNC</td>
<td>Computer Numerical Control</td>
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LIST OF SYMBOLS

\( G \) \quad \text{Strain energy release rate}
\( \mu \) \quad \text{Micron}
\( \circ \) \quad \text{Degree}
\([x^\circ]_{16}\) \quad \text{Stack orientation and number of plies}
\( X \) \quad \text{Angle}
\( U \) \quad \text{Stored strain energy}
\( dU \) \quad \text{Infinitesimal strain energy}
\( \pi \) \quad \text{Pi}
\( D \) \quad \text{Flexural rigidity}
\( r \) \quad \text{Any distance from the center of the plate}
\( \nu \) \quad \text{Poisson’s ratio}
\( a \) \quad \text{Radius of the circular plate}
\( P \) \quad \text{Thrust force}
\( w \) \quad \text{Deflection of the plate when thrust force } P \text{ is applied}
\( dw \) \quad \text{Work done during drilling when a thrust force } P \text{ is applied}
\( dA \) \quad \text{Increase in the area of the delamination crack}
\( G_{IC} \) \quad \text{Strain energy release rate}
\( K \) \quad \text{Stress intensity factor}
CHAPTER 1
INTRODUCTION

1.1 Composite Materials

Materials are often chosen to fulfill certain structural or load requirements. Not all materials have all the necessary properties, and not all the necessary properties are present in one material. To make optimum use of the properties needed and the materials used, two or more materials can be combined to give desired properties. Earlier metals were combined to yield alloys, which had suitable properties. But as requirements became more and more demanding, it was found that the necessary properties could be obtained by combining chemically different materials to create a new material with the desired properties. Thus began the use of composite materials, also known as composites, their components being either metallic or non-metallic.

Composites are used for many reasons: A single large part made of composites can replace many metal parts. Composite materials can be embedded with sensors, which can monitor fatigue and performance. They have a high stiffness to density ratio thereby providing greater strength at lighter weights. The use of lighter-weight materials means an increase in the fuel efficiency of automobiles and airplanes. Also the endurance limit of some composites, shown in Table 1, is higher than that of aluminum and steel; most composites are made of plastics or resins and hence provide a high level of resistance to corrosion, while aluminum and iron need special treatments like alloying to protect them from corrosion. Composites have a low co-efficient of thermal expansion, which can help to provide dimensional stability when required. Manufacturing composite material takes less time, and the part can be made to be a particular shape or size, not requiring further
machining. Complex parts with special shapes and contours can be directly fabricated with composites, which would be impossible to do with metals. The fabrication of complex parts means fewer number of parts to assemble and more production time saved. Composites show better impact properties compared to metals; they are good dampers and can reduce vibration and noise, which makes them useful in various applications in automobiles, aircraft, tennis racquets and golf clubs.

Composites can be tailor made to suit specifications by varying fiber orientation, the type of fiber used, or the matrix material. Glass-reinforced and aramid-reinforced composites have low toxicity and low smoke. This property makes composites a good material to be used in plane and automobile interiors, galley ways, etc. The pressure and temperature for processing of composites is much less than that required for metals, thereby providing flexibility in the way composites are processed, in turn providing flexibility in production.

### Table 1

Properties of Fibers and Conventional Materials [1]

<table>
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<tr>
<th>Material</th>
<th>Diameter (μm)</th>
<th>Density (g/cm³)</th>
<th>Tensile Modulus (E) (GPa)</th>
<th>Tensile Strength (σ) (GPa)</th>
<th>Specific Modulus (E/ρ)</th>
<th>Specific Strength</th>
<th>Melting Point (°C)</th>
<th>% Elongation at Break</th>
<th>Relative Cost</th>
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<tr>
<td>Fibers</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E-glass</td>
<td>7</td>
<td>2.54</td>
<td>70</td>
<td>3.45</td>
<td>27</td>
<td>1.35</td>
<td>1540</td>
<td>4.8</td>
<td>Low</td>
</tr>
<tr>
<td>S-glass</td>
<td>15</td>
<td>2.50</td>
<td>86</td>
<td>4.50</td>
<td>34.5</td>
<td>1.8</td>
<td>1540</td>
<td>5.7</td>
<td>Moderate</td>
</tr>
<tr>
<td>Graphite, high modulus</td>
<td>7.5</td>
<td>1.9</td>
<td>400</td>
<td>1.8</td>
<td>200</td>
<td>0.9</td>
<td>&gt;3500</td>
<td>1.5</td>
<td>High</td>
</tr>
<tr>
<td>Graphite, high strength</td>
<td>7.5</td>
<td>1.7</td>
<td>240</td>
<td>2.6</td>
<td>140</td>
<td>1.5</td>
<td>&gt;3500</td>
<td>0.8</td>
<td>High</td>
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<td>Boron</td>
<td>130</td>
<td>2.6</td>
<td>400</td>
<td>3.5</td>
<td>155</td>
<td>1.3</td>
<td>2300</td>
<td>—</td>
<td>High</td>
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<td>80</td>
<td>2.8</td>
<td>55.5</td>
<td>1.9</td>
<td>500(D)</td>
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<td>1.45</td>
<td>130</td>
<td>2.8</td>
<td>89.5</td>
<td>1.9</td>
<td>500(D)</td>
<td>2.5</td>
<td>Moderate</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steel</td>
<td>7.8</td>
<td>208</td>
<td>0.34–2.1</td>
<td>27</td>
<td>0.04–0.27</td>
<td>1480</td>
<td>5–25</td>
<td>&lt;Low</td>
<td></td>
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<td>0.14–0.62</td>
<td>26</td>
<td>0.05–0.23</td>
<td>600</td>
<td>8–16</td>
<td>Low</td>
<td></td>
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</table>
A composite is a heterogeneous material created by the synthetic assembly of two or more components, one a selected filler of reinforcing material and the other a compatible matrix binder, in order to obtain specific characteristics and performance. The binder and the filler have two very different properties but when combined together form a material with properties that are not found in either of the individual materials. The simplest explanation of a composite material can be seen in Figure 1.

![Figure 1. Formation of composite material using fibers and resins [1].](image)

The matrix keeps the reinforcement material together, giving it shape and preserving it from external forces, including environmental effects. The matrix is responsible for the surface finish of composite materials and how long they last. Its main function is to bind the reinforcement together and act as a medium to distribute any applied stress that is transmitted to the reinforcement. The matrix also should separate the layers, prevent crack propagation and protect the reinforcement from damage due to mechanical abrasion.

The matrix material can be a metal, polymer, or ceramic. Depending on the matrix material, composites are classified into metal matrix composites, polymer matrix
composites and ceramic matrix composites. The filler or reinforcement materials also differ. They can be natural fibers, carbon fibers, glass fibers or polymers.

The function of reinforcement in composite materials is primarily to increase the load bearing capacity of the material. It is also responsible for the tensile strength, stiffness, and tensile modulus of composites. It also determines the overall cost and performance of composites. The mechanical properties of the composite material are determined by what kind of fiber is chosen for reinforcement, since the mechanical properties of almost all reinforcing fibers are better than the mechanical properties of unreinforced resin systems. The four ways in which the fiber can contribute to a composite material are as follows:

- Mechanical properties of the fiber itself.
- Interaction between the fiber and the resin.
- Amount of fiber in the composite (also known as fiber volume fraction).
- Orientation of the fibers.

Like most materials, composites properties are also identified by terms such as yield strength, ultimate strength, stiffness, etc. One of the main reasons for using aluminum has been its light weight. However compared to a carbon composite, the carbon composite has a lower density and hence is lighter. It also has a higher strength compared to aluminum. Its only drawback is that it does not elongate like aluminum and therefore will not stretch before it breaks.

Carbon fiber reinforced materials are mainly used for structural purposes since they provide a high strength-to-weight ratio. They also have high stiffness and low density. Carbon composites are now widely used in the automotive industry and
aerospace industry where low weight and high stiffness are necessary. Carbon fibers are one of the stronger and more abrasive reinforcement materials available. Machining of such composites is usually difficult because they quickly wear down the tool.

Composites are not new. One of the first known composite materials used was the reinforcement of mud bricks with straws. Mud bricks were known for the load that they could hold but were seen to break when tensile forces were applied on them. Straw, on the other hand, had good tensile properties but would crumble as soon as it was bent. When a mud brick was reinforced with straw, it yielded a brick that could withstand tensile and compressive loads.

Another example of an often-used composite material is concrete beams. Aggregate (stones or gravel) is held together by cement. Concrete has good strength under compression and it can be made stronger under tension by adding metal rods, wires, mesh, or cables, thereby creating reinforced concrete.

Composite materials are fast replacing the use of metals and their alloys in many areas. This is due to the tailor-made properties that can be obtained in a composite material. They can be manufactured such that more strength is provided toward the direction or area that has higher load acting on it than the rest of the region. Another reason for the shift toward composites has been due to their light weight and the fact that they do not corrode.

Corrosion has been one of the major disadvantages of metals. The arrival of composite materials which were lighter than metals as well as corrosion resistant meant that they soon started replacing metals. Some of the major industries to use composite materials have been the automobile industry, aerospace industry, and the space industry.
Although there are many advantages for using composite materials, there are some drawbacks that need to be taken into consideration. Some of the disadvantages are mentioned here. Composite materials are more expensive to obtain than steel and aluminum. Earlier methods of fabricating composites were slow and tedious which meant low volumes of composite materials produced. Earlier design processes involved reference of data handbooks for material properties and other needs. A lack of such a database for composites is sometimes a disadvantage. The temperature resistance of composites is dependent on the matrix material used for binding the fibers. Most matrix materials are polymer based hence they have a lesser maximum working temperature than metals do. Solvent and environment resistance of composites are polymer/matrix dependent. Composites absorb moisture which affects the way they behave. Recycling of composites poses a major problem. Despite many drawbacks composite materials have been more advantageous than metals. Composites are replacing metals in most parts as they are much lighter than metals. The weight reduction that composites bring about has been a major advantage. Most of the drawbacks can be controlled or composites can be used in places or environments which don’t affect them. An indication of the increased usage of composites is shown in Figures 2 and 3.

Figure 2. Composite components in commercial aircraft industry [2].
The increased use of composites has meant there is a demand for joining of some of the parts together. Adhesive bonding is the method used most often for joining most composites, but it has its disadvantages. Some of the disadvantages are as listed below.

Adhesive bonding requires surface preparation of the materials before they can be joined. Heat and pressure may be required for curing purposes during adhesive bonding. Adhesives are chemicals used to join composites together. Depending on the adhesive chosen, the cure time of composites might be low or very high. Due to the chemicals used, safety and health might be at risk. Bonded joints are difficult to inspect for faults or in general. Adhesive bonding needs specialized people to work on it and also requires more attention toward the process than needed for mechanical joints. Adhesive bonding is a permanent bond which means that parts cannot be broken down and assembled again. On the other hand, mechanical joints can be assembled and disassembled as many times as wanted. Surface preparation is not required for creating mechanical joints. They also
offer the ability to check the quality of joints created and inspecting them from time to
time. The widespread use of composites and the need for joining them has meant that
there is an increasing demand for machining of composites. The characteristics of the
material determine how they behave during machining. There are various new methods
for machining of composites, such as water jet machining and laser machining. The high
cost of such processes means that drilling is still used widely as a major secondary
machining process, due to the need for structural joining of composite materials.

Machining of composites brings with it some major problems, including rapid
tool wear due to the abrasiveness of composites, fiber fracture, and matrix breaking.
Another known nuisance has been delamination, or the breaking of material fibers, which
creates a bad surface finish and causes stress concentrations at such regions. The low
thermal conductivity of composite materials also has posed many challenges during the
drilling process which requires a large amount of coolant.

1.2 Machining of Composites

Machining involves the removal of any extra or unwanted material. Some of the
most common machining processes are drilling, turning, and milling. Earlier composites
machined like metals. But poor surface finish and faster tool wear led to the further study
of composite machining. Unlike metals, composites need separate tools and working
conditions. Although tools used for machining of metals can still be used for composites,
care must be taken to maintain optimum levels of, feed rate, thrust force, and other
factors. Metal tools tend to wear out faster when used for machining of non-metals.

One of the main advantages of composites has been the fact that an entire part
can be manufactured. This minimizes the machining of composites. However with “part
integration,” sometimes composites need to be joined to form a larger part, which means that a certain amount of machining needs to be done for composites too. “A typical aircraft wing might have as many as 5,000 holes [1].” Hence, machining is a cost factor in the production of composites. A composite might have to go through all or some of the machining processes like milling, drilling, cutting, etc.

In his book Mazumdar[1] lists the various purposes of machining of composites:

- To create features that cannot be created during manufacturing. Such features can be holes, slots, etc.
- To maintain tolerance levels in manufactured parts at desired/given values.
- To remove any remaining materials from the surface of the composite after machining so that the finished surface can then be used for painting, adhesion, or any other operation as required.
- To obtain a smooth surface.
- To make smaller pieces of larger material for test purposes.

The machining of composites seems to be as simple as machining of metals, but it has its own set of problems. Some of these challenges faced during machining include the following:

- Most composites are reinforced with fibers. Machining of composites makes the fibers discontinuous, which affects performance of the composite part.
- Dimensional accuracy during machining of composites is very hard to predict since the reinforcement and the matrix material have different coefficients of thermal expansion.
• During machining, the matrix material and the reinforced material are removed, thereby exposing the reinforced material to nature and also to other chemicals, thus making them susceptible to chemical reactions and moisture.

• For thermoset composites, the cutting temperature cannot be higher than its cure temperature, since a higher temperature can cause disintegration of the material or local stress zones.

• Thermoplastic resin-based composites can have very low melting points. While machining, if the temperature at the cutting point is higher than the melting point, then the tool can become clogged as the resin melts.

• Most composites are very poor thermal conductors. During machining, heat can build up at the cutting edge of the tool. In order to reduce the heat and protect the composite and the tool, a suitable coolant is needed during machining.

• Usage of coolants is necessary while machining, but the selection of the coolant is also very important since the coolant might react chemically with the composite. Hence, a coolant must be chosen with care.

• Obtaining smooth edges after cutting/machining is sometimes difficult, because the fibers are tough and can easily absorb the cutting energy. Hence, when machined, the edges might not be smooth and might have burr surfaces or other surface defects.

• Composites might be abrasive and thus might reduce the tool life.

• The sequence in a lay-up composite and the orientation are very important factors during machining. Knowing these might help reduce delamination at edges.
during machining. This is mostly observed in, but not limited to, continuous fiber composites.

During the machining of composites, the behavior of the tool or the material cannot be predicted, since each composite material has different characteristics. Some general behaviors observed during machining of composites include the following:

- Some reinforcing materials are brittle, while others are ductile. During machining of aramid fibers, a common mode of failure is the axial splitting of the fiber in the direction transversal to the fiber due to weak molecular bonds.
- Weaker molecular bonds mean that they have lower compressive strength, which in turn means that special tools are needed for machining aramid fibers.
- Ductile materials absorb energy while machining, which results in poor surface quality.
- Fibers with lower compressive strengths tend to recede into the matrix during machining, which causes burr and fiber kinking during machining.

1.3 Drilling

Drilling involves the removal of material from a workpiece such that a hole is obtained. The holes created are used primarily for fastening one component to another, for passing coolants, and for wiring purposes. It is a common process for removing unwanted material. Drilling has been widely used to make holes in metals, but due to its availability, it is now being used to remove materials from composites as well.

Drilling is widely used because it is a more cost-effective process than laser beam cutting and because there are not many other processes that produce a deep circular hole. Drilling is often used in the machining of composites, because of readily available
machinery and because it is simply more cost effective than the more advanced method of laser beam cutting.

Although composites are not metals, industries previously cut them like metals. This resulted in tool wear, and poor surface finish. Many researchers then studied the reasons for this. Although similar to metal drilling, composite drilling requires special drill bits, which are usually coated with tungsten carbide or titanium nitride.

Some of the major factors that determine tool wear are feed rate, geometry of the drill bit, and many other factors. As research was conducted and papers were published, a new villain was found on the drilling horizon, delamination of composites. It was observed that most poor surface finishes were handled by varying the feed rate; however delamination was still observed in many composites.

Delamination can be avoided by using a more pointed drill bit, or by using a positive rake angle so that the fibers are cut within the material. Both steps, however, make the tool sensitive and fragile. The schematic of a rake angle is shown in Figure 4.

Figure 4. Schematic of rake angle [13].
Negative as well as neutral rake angles must be avoided as much as possible, since they tend to push the fibers outwards, thereby causing smaller and poorly finished holes. A negative rake angle also uses more force toward cutting and, hence, increases the pressure being applied. This increase in pressure causes a heat build-up which causes tools to clog.

One of the most popular drill bits has been the twist drill, widely used in the drilling of metals but lately also used in drilling composites. Hocheng and Tsao [4] have done a lot of work towards minimizing delamination during drilling. Their successful work includes studying various drill bits and developing mathematical equations to reduce delamination.

The most common defect observed in a hole drilled in composite material is delamination, which occurs at both entry and exit points. At the point of entry, delamination is usually known as the peel up of the material. At the exit point, delamination occurs when the drill bit tries to push through the material. One of the methods that was used to reduce delamination at the point of exit was with a back-up plate. Hocheng and Tsao [4] and Lachaud et al. [5] have successfully managed to drill holes without delamination, without back up at the exit, by clamping the plates and developing equations for the thrust force applied.

The major differences between drilling of composites and metals are listed in Table 2, although conventional drilling is cost effective it has many drawbacks, the most important one being delamination.
Table 2
Comparison Between Drilling of Metals and Drilling of Composites

<table>
<thead>
<tr>
<th>Drilling of Metals</th>
<th>Drilling of Composites</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drill tips are designed to heat up so as to provide for the plastic flow of cut metal</td>
<td>Designed to generate as little heat as possible to avoid degradation of material</td>
</tr>
<tr>
<td>Chips formed are usually long</td>
<td>Chips formed are short and easy to remove</td>
</tr>
</tbody>
</table>

1.4 Delamination

Delamination is defined in the MIL 17 Handbook for Composite Materials [6] as “the separation of the layers of material in a laminate.” Delamination can occur at any time in the life of a laminate for various reasons and has various effects. It can affect the tensile strength performance depending on the region of delamination.

Among the various defects that are caused by drilling, delamination is recognized as the most critical. Other defects are spalling and fiber pullout, but delamination can result in a reduction in the durability of the composite material and can cause a reduction in the bearing strength of the material and the structural integrity, resulting in performance issues.

Delamination has been one of the major forms of failure in drilled materials due to the composite’s lack of strength in the direction of drilling. This failure can cause a reduction in the compressive load carrying capability of the structure.

Some of the major reasons for the occurrence of delamination are the high thrust force and feed rate, other reasons include rapid tool wear and power. Some previous methods to avoid delamination have been to reduce the feed rate and thereby reduce the
thrust force, using a backing plate. Recent methods have involved vibratory drilling [7].

Schematics and photos of a delaminated specimen are shown in Figures 5 and 6.

Figure 5. Schematics (a) delamination at entry (b) delamination at exit [8].

Figure 6. Photos of delamination at (a) entry and (b) exit.
Delamination is an important problem in the use of composite materials for structural purposes since it is a method of failure that is complex to understand and duplicate on computers. It tends to occur when the laminate is under tensile forces.

Delamination caused by tensile forces has been attributed mainly to the stacking sequence of laminates. It is usually caused between plies due to out-of-plane tensile stresses and is also caused by cyclic loads. This type of delamination is slow because the crack growth rate is very slow. Cyclic loads could be either tensile or compressive.

Earlier research mainly studied delamination at the free edges of laminates. It was found that studying of delamination of free edges was too specific a region to generalize delamination of composites. As the use of composites increased and the methods of machining increased, it was found that more research was needed on delamination. Therefore the use of energy method to model the onset of crack growth was initiated.

The energy method is dependent on concepts from classical fracture mechanics. According to Anderson [9], “the energy approach states that crack extension (i.e., fracture) occurs when the energy available for crack growth is sufficient to overcome the resistance of the material. The material resistance may include the surface energy, plastic work, or other type of energy dissipation associated with a propagating crack.”

Wang et al. [10] further studied delamination by taking into account the energy release rate, which determines the interlaminar fracture toughness of laminates. Anderson [9] also defined the energy release rate, $G$, as “the rate of change in potential energy with crack area for a linear elastic material.” Bower [11] of Brown University provided the following arguments for use of the energy release rate as a fracture criterion:
Regardless of the actual mechanisms involved, crack propagation involves dissipation (or conversion) of energy. A small amount of energy is required to create two new free surfaces (twice the surface energy per unit area of crack advance, to be precise). In addition, there may be a complex process zone at the crack tip, where the material is plastically deformed; voids may be nucleated; there may be chemical reactions; and generally all hell breaks loose. All these processes involve dissipation of energy. We postulate, however, that the process zone remains self-similar during crack growth. If this is the case, energy will be dissipated at a constant rate during crack growth. The crack can only grow if the rate of change of potential energy is sufficient to provide this energy.

1.5 Multi-Facet Drill Bit

The geometry of a drill bit point determines how twist drills perform. Many drill geometries have been created or developed based on the geometry of the conventional drill bit. One such drill geometry that was developed was the multi-facet drill bit (MFD). Some of the commonly used MFD are shown in Figure 7. The point geometry of the MFD has one very obvious advantage. It reduces the thrust force needed, another advantage that it has over the more conventional twist drill is its temperature distribution. Despite these advantages the MFD is not widely used as the drill geometry is hard to machine and needs CNC to grind the geometry. This and the fact that a given geometry cannot be duplicated by hand grinding has led to MFD’s not being widely used. Wu and Shen [12] first published a mathematical for MFD in late of August 1983. Chen and Wu [13] worked further more on the mathematical models for MFDs and published it in late
of November 1984. They studied more than 20 types of MFDs that had been developed. They published models for 9 of the MFDs created.

They stated the following advantages of MFDs over conventional single point drill geometries.

- Lower cutting forces
- Improved heat transfers
- Improved chip ejection
- Improved hole quality
- Higher productivity/longer tool life

Some of the above-mentioned aspects are not necessary for all cutting operations. Various properties can be utilized separately for different applications or materials. Hence, a variety of MFDs have been developed for various applications. A typical MFD
has a shorter chisel edge compared to a conventional drill. Although there have been different types of MFDs, the one common feature in all the MFDs is that they have a single point tool geometry.

Much research has been carried out on calculating the thrust force for MFDs and other drill bits. Huang et al. [14] made theoretical predictions of thrust force and performed experiments to verify them. A completely different approach was necessary for calculating thrust forces while drilling composites. Such a model depending on the various drill geometries and boundary conditions was developed by Hocheng and Tsao [4], including comprehensive analysis where they developed mathematical formulae for thrust force and conducted experiments depending on the values calculated by these formulae.

1.6 Thrust Force

Thrust force during drilling can be defined as “the force acting along the axis of the drill during the cutting process.” Cutting forces help monitor tool wear, since forces increase with tool wear. Thrust force is also used to monitor tool wear and, in turn, monitor tool life. Tool failure can occur if tool wear is not monitored.

Other than being an important factor in the monitoring of tool wear, thrust force is considered to be the major contributor of delamination during drilling. Considerable research has been done to prove that there is a “critical thrust force” that causes delamination, and thrust force below that will constrain or eliminate delamination during drilling.

Vibratory drilling has been known as one of the methods to reduce thrust force during drilling of steel and during drilling of composites. Machining of delamination free
composites using conventional methods would lower the cutting quantities. If the “critical thrust force” is known, then the machining efficiency can be increased and higher quantities can be machined. This thesis deals with the prediction of thrust force at which delamination will occur during drilling of composites.
CHAPTER 2

LITERATURE REVIEW OF DRILLING OF COMPOSITES

A considerable amount of research has been conducted on the effects of drilling on composite materials. Most has been targeted toward the study of delamination. There has been research on the quality of the holes drilled during research as well.

In their paper, Arul et al. [7] tried to study the effect of vibratory drilling on the quality of the holes drilled. The primary difference between conventional drilling and vibratory drilling is that conventional drilling is a continuous process, whereas vibratory drilling is a pulsed process. Conventional and vibratory drilling were performed on glass fabric reinforced plastic (GFRP) composite 4 mm thick. The reinforcing material used for the experiments was woven glass fabric, and the matrix material was commercially available epoxy resin LY-556. Experiments were performed with cutting speeds of 9.43 to 30.16 m/min, feed rates of 0.02 to 0.06 mm/rev, vibration frequency of 50 to 300 Hz, and vibration amplitude of 5 to 20 µm. The authors utilized an improved technique of low-frequency, high-amplitude vibratory drilling, and inducing vibration in the direction of the feed. They found that, by following this new technique, the thrust force can be reduced which in turn leads to an improvement in the quality of the hole drilled.

Hocheng and Tsao [15] predicted the effects on delamination using a back-up plate in drilling composite materials with a saw drill and a core drill. Delamination can be effectively reduced or eliminated by decreasing the feed rate during exit and by using back-up plates to support and counteract the deflection. The approach used was to perform the experimental work and hold the machinability data to account for delamination of different materials for various tools and machining parameters. A
mathematical analysis was carried out for drilling with a saw drill with and without back-up and with a core drill with and without back-up. Composite laminates from WFC200 fabric carbon fiber of coupon specimens 60 mm by 60 mm and 4 mm thickness were used as specimens. Drilling was carried out on a LEADWELL MCV-610AP vertical machine with a Kistler 9273 piezoelectric dynamometer. Theoretical results were obtained based on classical elasticity, linear elastic fracture mechanics, and energy conservation law. The experiment showed that both drills with back-up offer a lower critical thrust force than those without backup. No delamination was observed at higher feed rate for higher thrust force.

Fernandes and Cook [16] studied the drilling of carbon composites using a “one shot” drill bit. They analyzed the thrust force and the torque produced during drilling. It was shown that drilling could be divided into five stages and that with the data from each stage, the thrust force and torque developed could be related to common defects. The effect of tool wear on the forces induced was analyzed, thus laying a base for further work toward improving quality and productivity of the process. Experiments were conducted on a test bed dedicated for this process. The thrust force and torque were measured using a six-axis force sensor. A data acquisition board was used to control the spindle speed and feed rate, and collect data from the force sensor. A 4.9 mm drill bit, designed for drilling carbon composites, was used for the experiments. This tool is similar to the “dragger” drill bit and drills and reams the hole in one operation, thus earning the name “one shot”. The material used for the experiments was a carbon-epoxy composite. Two thicknesses were maintained for the coupons, 5.2 mm and 2 mm. Each coupon, irrespective of the thickness, was cut into 7 cm x 5 cm specimens to be utilized.
in the test rig. Three thicknesses were used during testing the two previously mentioned and the other was created by using two 2 mm thick coupons during drilling. This was done to simulate the common practice of drilling two plates together so they can be fastened later. Spindle speeds of 750, 1,000 and 1,500 rpm and feed rates of .75, 1, and 1.5 mm/s were used giving eight different feeds varying from 0.03 to 0.12 mm/rev. Results showed that, as the thickness increased, a higher thrust force and a higher torque developed. The authors further divided the drilling process into five stages: Stage I–entrance, Stage II–drilling, Stage III–drilling and reaming, Stage IV–reaming and Stage V–backing out. A force and torque graph for the experiments is shown in Figure 8.

![Figure 8. Thrust force and torque plots for the five stages [16].](image)

During Stage I, the drill bit comes in contact with the specimen and a rapid increase in the thrust force can be observed, whereas a slow increase is observed for the torque created. A common problem during Stage I could be skidding of the drill bit. Other problems that can occur are wandering or deflecting of the drill bit. These problems could affect the hole positioning.
During Stage II, material removal takes place. The graph shows a steady increase in the thrust force, while a rapid increase in the torque can be observed. Delamination and tool wear are common problems associated with this stage. While drilling the 4 mm thick specimen, a sudden decrease in the thrust force was observed. This was attributed to the presence of air gaps between the two specimens. The common problems associated with this stage are delamination and tool wear. Delamination is said to occur due to the presence of high thrust force in this stage.

During Stage III, the drill bit exits the workpiece after removing the material. The graph shows that the thrust force decreases until the tool exits the workpiece. A slight increase in torque is observed. This is attributed to the fact that the tool is in contact with the maximum surface area during this time. Although the occurrence of maximum torque varied throughout this stage a fair assumption was made by the authors to represent the maximum torque as a straight line, since the deviation was small. Common problems associated with this stage are surface finish at the exit and occurrence of delamination at the exit. The risk of delamination occurring is much smaller compared to the previous stage since the thrust force is much smaller compared to the drilling stage.

During Stage IV, the drill bit reams the hole to its final size. The problem associated with this stage is the final size and the finish of this hole. A steady decline in the thrust force and torque values was observed.

During Stage V, the drill bit backs out of the workpiece. Reaming continues as long as there is contact between the workpiece and the tool. This affects the size and the finish of the hole. The torque and thrust force values remain the same as those in the previous stage. The only difference between this stage and the previous one is the
direction of the movement of the drill bit. The problems associated with this stage are the same as the ones associated with the previous stage.

It was also observed that during the course of drilling the thrust force increased as the number of holes increased. This lends more material to the age-old adage in drilling that tool wear is directly related to drilling time.

Velayudham et al. [17] evaluated the drilling characteristics of glass reinforced polymeric composite. The glass reinforced composite used in their experiments had high volume fraction fiber glass reinforcement, which means that the volumetric fraction of the reinforcement to that of the matrix material was high. The authors tried to study the drilling characteristics of a composite material that is used mainly for structural purposes and have tried to study the drilling characteristics. A higher volume fraction composite is used generally in places that need higher load bearing capacity. A higher fraction would mean that the energy absorption of the composite will be higher. The experiments were performed on a universal milling machine. A two-component piezoelectric dynamometer was used to measure thrust force and torque. Vibrational analysis was performed using an accelerometer. Data from the dynamometer and the accelerometer were fed to the computer for further analysis. The author also measured flank wear using a Universal measuring microscope. Flank wear was measured after a specific number of holes were drilled.

The glass fiber workpiece that was used for experimental purposes was made of glass/phenolic woven fabric with a fiber volume fraction of 66%, i.e., 66% of the composite material was glass fabric. The thickness of the workpiece was maintained at 7 mm. A 6.5 mm diameter tipped carbide tool was used with cutting speeds of 51.5, 64.3,
and 80.4 m/min, and feed rates of 250, 315, and 400 mm/min were maintained during the experiment.

These cutting conditions helped determine the following observations: Initially the thrust force increased rapidly, and then there was a gradual increase during the process. Torque, however, displayed a gradual increase at the start but climbed rapidly until the cutting lips engaged in the machining process. A gradual decrease in the thrust force was observed when full engagement took place. Thrust force decreased further as the tool exited the workpiece and approached a zero value. Experimentally, it was also determined that the thrust force and torque increased with an increase in feed rate. Other drilling characteristics evaluated were the effect on thrust force and torque relative to the number of holes drilled, effect on drill wear relative to the number of holes drilled and the effect of cutting variables on hole quality.

Other than the drilling conditions, such as feed rate and spindle speed, the number of holes drilled also influenced the thrust and torque values. For every combination of feed rate and cutting speed, the peak thrust force and the peak torque for the tool increased with an increase in the number of holes drilled. The different combinations of feed rate and cutting speed with the increasing number of holes showed that the increase in the number of holes led to higher tool wear overall, the number of holes did not have a negative effect on the experiment. During the initial periods of drilling, it was observed that the hole drilled was oversized by 5 to 15 µm. As the number of holes increased, the oversize was shown to decrease for all combinations of feed rates and cutting speeds.

Zitoune et al. [18] tried to understand the mechanisms of chip removal for unidirectional laminated plates. Their experiments were performed on laminated plates.
For laminated plates with different values of $\theta$, the mechanisms of material removal were different. Studying the material removal during drilling of laminated plates is more difficult since the number of conditions to be controlled and observed is very high. To simplify the experimental setup, a similar material removal process that is much simpler to observe and control is used. Orthogonal cutting is a simplified framework to build and is representative of the drilling conditions. The use of orthogonal cutting provides some advantages over drilling. The material removed or the chip formed is in the plane of the laminate. Hence, observing chip formation becomes easier. The surface quality after machining is observed easily without having to destroy the specimen to observe machined areas.

For their experiments, the authors used a tungsten carbide tool insert (NFE 66 366) of grade K20. Test specimens were unidirectional laminate with stacking sequences of $[0^\circ]\text{16}$, $[90^\circ]\text{16}$, $[+45^\circ]\text{16}$, and $[-45^\circ]\text{16}$. The plate’s dimensions were 100 mm x 50 mm x 4 mm. The machined surface was observed using a scanning electron microscope (SEM). A force sensor was used to measure the forces and moments to the tool. The conditions for the experiments were a cutting speed of 0.5 m/min and depth of cut between 0.05 and 0.25 mm. The experiments were conducted without any use of lubrication.

During the machining of the $[0^\circ]\text{16}$ specimen, chips of thickness equivalent to the depth of cut were formed without any deformation. During the machining of $[+45^\circ]\text{16}$, compact chips were formed, which were very brittle. During the machining of $[90^\circ]\text{16}$ the chip obtained was more like powder or very fine particles. In the case of $[-45^\circ]\text{16}$, the machining was not observable at all, since the machining destroyed the workpiece. The surface quality of the material machined was also observed during these experiments.
The best surface finish for orthogonal cutting was observed in the $+45^\circ$ since the matrix and the fiber were sheared in a clear way. The machined surface for $0^\circ$ was not as fine as the surface for $+45^\circ$. For the machining of the $90^\circ$ the surface finish was poor compared to the other two angles.

Lachuad et al. [5] further studied the effects of drilling of composites and discussed methods to reduce them. They blamed the defects caused during drilling on the mechanical characteristics and nature of the fibers used in the laminates, the stacking sequences, and differently oriented matrix interfaces. They developed a set of equations to determine the thrust force above which delamination would occur. They did this by applying classical plate theory and relating it to the strain energy release rate in mode I for a particular thickness of the specimen.

The general defects observed during drilling were defects at the entry of the drill bit, defects at the exit, and defects of the hole, such as hole size, hole quality, and hole shape. The analytical model that they developed gave them the maximum thrust force that a material could withstand before defects are produced. The values obtained from the analytical model were compared to the experimental results and were found to be in agreement with the theoretical values.

These authors developed two different models with different assumptions. The first model developed assumed that contact between the drill bit and the plate is under a uniformly distributed load and under a thrust force. This thrust force was then calculated using plate theory for a uniformly distributed load. A coefficient $D_{ij}$, from the theory of laminates, was then calculated based on the stress/strain law. The displacement for the
clamped circular plate under uniform loading was found using classical plate theory. Energy methods were then applied to find the final equation for thrust force.

The second model was developed based on the assumption that no drill geometry is defined. The geometry was assumed to be a single point of contact. The displacements were developed from classical plate theory, and the critical thrust force equation was developed using energy methods. The thrust force was found to be dependent on the material properties and the thickness of the specimen used for the experiments.

Experiments were conducted on three different fiber orientations (0°, 45°, and 90°) of carbon/epoxy plates with a different number of plies. Although both models were found to be close to the experimental results, the first model developed was more in agreement than for the second model.

Hocheng and Tsao [4] took it further from where Lachaud et al. [5] left off. They developed physical models to predict the thrust force required for delamination of clamped circular plates. Based on classical plate theory and energy methods, they developed models to calculate critical thrust forces for a twist drill, candle stick drill, saw drill, core drill, and step drill.

The model developed for the twist drill was similar to the model developed by Lachaud et al. [5], assuming a single-point concentrated load at the center of the circular plate. The circular plate was assumed to be clamped for all drill bits. The models varied because the kinds of drills used were different, the contact point geometry differs for each one of them. Depending on the classical plate theory, the displacement was obtained and then energy methods were applied to find the critical thrust force. Thrust forces for the saw drill were developed assuming that the contact geometry was circular and hence the
kind of loading acting on it was circular. The thrust force developed was then divided by the thrust force calculated for the twist drill, in order to compare the two. For the candle stick drill, it was assumed that loading was concentrated at the center of the load associated with the circular load. The thrust force equations were developed by superposition theory. This thrust force was also compared with the thrust force for the twist drill. For the core drill, a distributed circular load was assumed and the thrust force equation was developed from superposition and energy balance equations. The thrust force values were also compared with the values for the twist drill. The stepwise drill bit is assumed to be a stepwise distributed circular load. The thrust force equation developed was also compared with that of the twist drill.

The authors further compared the thrust force equations with the thrust force equation for a twist drill. They showed that the critical thrust force equation for each of the drill bits could be reduced to that of the twist drill by assuming different cases for each of the drill bits. The drill geometry and their specific physical models are shown in Figures 9 to 11.

![Circular plate models for delamination analysis twist drill and saw drill](image)

**Figure 9.** Circular plate models for delamination analysis twist drill and saw drill [4].
Figure 10. Circular plate models for delamination analysis candle stick drill and core drill [4].

Figure 11. Circular plate models for uniform load and delamination analysis for step drill [4].
CHAPTER 3

OBJECTIVES

3.1 Delamination Prediction

The main objective of this thesis was to predict delamination during drilling of composites. Prediction of delamination is not simple, since it involves a number of experiments to predict the spindle speed and feed rate at which delamination occurs and the speed at which delamination does not occur. The task to perform experiments for many different materials at different spindle speed and different feed rates is tedious.

One of the more recent methods to determine delamination has been to use fracture mechanics. In fracture mechanics, crack initiation and crack growth are important factors to determine the failure of the material. A similar method can thus be applied for composite materials to determine when delamination will occur.

Lachuad et al. [5] used such a method to determine at what thrust force delamination would occur in a clamped circular plate. Hocheng and Tsao [4] found similar methods and physical models to determine thrust forces at which delamination occurred for various drill bits. They determined models for twist, saw and candle stick drill bits.

Using similar steps, a physical model can be developed that determines the thrust force at which delamination occurs. The physical model developed by Hocheng and Tsao [4] has been taken further and applied for different boundary conditions. While earlier papers were concerned with clamped plate, this thesis deals with simply supported plates. A physical model to calculate the necessary thrust force to be applied for delamination
has been developed based on the Hocheng and Tsao [4] model. The calculated thrust force causes delamination in composite materials during drilling.

3.2 Development of Physical Model to Predict Delamination

For a circular plate that is simply supported and under concentrated load, as shown in Figure 12, the stored strain energy $U$ [19] is given by

$$U = \pi D \int_0^a \left[ \left( \frac{d^2 w}{dr^2} + \frac{1}{r} \frac{dw}{dr} \right)^2 - 2(1-\nu) \frac{d^2 w}{dr^2} \frac{1}{r} \frac{dw}{dr} \right] rdr$$  \hspace{1cm} (3.1)

where $w$ [20] is

$$w = \frac{P}{16\pi D} \left[ \frac{3+v}{1+v} \left( a^2 - r^2 \right) + 2r^2 \log \left( \frac{r}{a} \right) \right]$$  \hspace{1cm} (3.2)

Differentiating equation (3.2) with respect to $r$ gives

$$\frac{dw}{dr} = \frac{P}{16\pi D} \left[ \frac{-2(3+v)}{(1+v)}r + 4r \log \left( \frac{r}{a} \right) + 2r \right]$$  \hspace{1cm} (3.2.1)

Differentiating equation (3.2.1) with respect to $r$ gives

$$\frac{d^2 w}{dr^2} = \frac{P}{16\pi D} \left[ \frac{-2(3+v)}{(1+v)} + 4 \log \left( \frac{r}{a} \right) + 6 \right]$$  \hspace{1cm} (3.2.2)
Substituting equations (3.2.1) and (3.2.2) in \( \frac{d^2 w}{dr^2} + \frac{1}{r} \frac{dw}{dr} \) gives

\[
\frac{d^2 w}{dr^2} + \frac{1}{r} \frac{dw}{dr} = \frac{P}{16\pi D} \left[ \frac{-2(3 + v)}{(1 + v)} + 4 \log \left( \frac{r}{a} \right) + 6 \right] + \frac{1}{r} \frac{P}{16\pi D} \left[ \frac{-2(3 + v)}{(1 + v)} r + 4 r \log \left( \frac{r}{a} \right) + 2r \right]
\]

\[
= \frac{P}{16\pi D} \left[ \frac{-2(3 + v)}{(1 + v)} + 4 \log \left( \frac{r}{a} \right) + 6 + \frac{-2(3 + v)}{(1 + v)} + 4 \log \left( \frac{r}{a} \right) + 2 \right]
\]

\[
= \frac{P}{16\pi D} \left[ \frac{-4(3 + v)}{(1 + v)} + 8 \log \left( \frac{r}{a} \right) + 8 \right] \quad (3.2.3)
\]

Substituting equations (3.2.1) and (3.2.2) in \( \frac{d^2 w}{dr^2} \frac{1}{r} \frac{dw}{dr} \) gives

\[
\frac{d^2 w}{dr^2} \frac{1}{r} \frac{dw}{dr} = \frac{P}{16\pi D} \left[ \frac{-2(3 + v)}{(1 + v)} + 4 \log \left( \frac{r}{a} \right) + 6 \right] \frac{1}{r} \frac{P}{16\pi D} \left[ \frac{-2(3 + v) r}{(1 + v)} + 4 r \log \left( \frac{r}{a} \right) + 2r \right]
\]

\[
= \frac{P}{16\pi D} \left[ \frac{-2(3 + v)}{(1 + v)} + 4 \log \left( \frac{r}{a} \right) + 6 \right] \frac{P}{16\pi D} \left[ \frac{-2(3 + v)}{(1 + v)} + 4 \log \left( \frac{r}{a} \right) + 2 \right]
\]

\[
= \left( \frac{P}{16\pi D} \right)^2 \left[ \frac{-2(3 + v)}{(1 + v)} + 4 \log \left( \frac{r}{a} \right) + 6 \right] \left[ \frac{-2(3 + v)}{(1 + v)} + 4 \log \left( \frac{r}{a} \right) + 2 \right] \quad (3.2.4)
\]

Substituting equations (3.2.3) and (3.2.4) in equation (3.1) gives

\[
U = \pi D \int_0^a \left[ \frac{P}{16\pi D} \left[ \frac{-4(3 + v)}{(1 + v)} + 8 \log \left( \frac{r}{a} \right) + 8 \right] \right]^2 - 2(1 - v) \left[ \frac{P}{16\pi D} \left[ \frac{-2(3 + v)}{(1 + v)} + 4 \log \left( \frac{r}{a} \right) + 6 \right] \right]^2 \left[ \frac{-2(3 + v)}{(1 + v)} + 4 \log \left( \frac{r}{a} \right) + 2 \right] r dr
\]

\[
U = \pi D \left( \frac{P}{16\pi D} \right)^2 \int_0^a \left[ \frac{-4(3 + v)}{(1 + v)} + 8 \log \left( \frac{r}{a} \right) + 8 \right]^2 - 2(1 - v) \left[ \frac{-2(3 + v)}{(1 + v)} + 4 \log \left( \frac{r}{a} \right) + 6 \right] \left[ \frac{-2(3 + v)}{(1 + v)} + 4 \log \left( \frac{r}{a} \right) + 2 \right] r dr \quad (3.2.5)
\]

Leaving the constants and integrating only what is between the integral sign yields

\[
\int_0^a \left[ \frac{-4(3 + v)}{(1 + v)} + 8 \log \left( \frac{r}{a} \right) + 8 \right]^2 - 2(1 - v) \left[ \frac{-2(3 + v)}{(1 + v)} + 4 \log \left( \frac{r}{a} \right) + 6 \right] \left[ \frac{-2(3 + v)}{(1 + v)} + 4 \log \left( \frac{r}{a} \right) + 2 \right] r dr
\]
\[
\left[ 16 \left( \frac{v+1}{v+1} \right)^2 \log^2 \left( \frac{r}{a} \right) r^2 + \frac{1}{2} (v+3) r^2 - 2 (v+1) \log^2 \left( \frac{r}{a} \right) r^2 \right]_0
\]

Substituting the values of \( 0 \) and \( a \) in the above equation yields

\[
\frac{16 \left( \frac{v+1}{v+1} \right)^2 a^2}{v+1} = \frac{8 (v+3) a^2}{(1+v)}
\]

Substituting equations (3.2.6) in (3.2.5) yields

\[
U = \pi D \left( \frac{P}{16\pi D} \right)^2 \frac{8 (v+3) a^2}{(1+v)}
\]

\[
U = \frac{P^2}{32\pi D} \frac{(v+3) a^2}{(1+v)}
\]

The energy balance equation [4] is

\[
G_{IC} dA = P dw - dU
\]

where \( P \rightarrow \) thrust force applied

\( dU \rightarrow \) infinitesimal strain energy

\( dA \rightarrow \) increase in the area of the delamination crack

\( G_{IC} \rightarrow \) strain energy release rate

\( dw \rightarrow \) work done during drilling when a thrust force \( P \) is applied

\[
dA = \pi (a + da)(a + da) - \pi a^2 = 2\pi ada
\]

\[
U = \frac{P^2}{32\pi D} \frac{(v+3) a^2}{(1+v)}
\]
where $D$ is flexural rigidity, $D = \frac{Eh^3}{12(1-v^2)}$

Differentiating $U$ with respect to $a$ gives

$$\frac{dU}{da} = \frac{P^2 a (3+\nu)}{16\pi D(1+\nu)}$$  \hspace{1cm} (3.6)

Differentiating $w_{\text{max}}$ with respect to $a$ gives

$$w_{\text{max}} = \frac{(3+\nu)Pa^2}{16\pi(1+\nu)D}$$

$$\frac{dw_{\text{max}}}{da} = \frac{Pa (3+\nu)}{8\pi D(1+\nu)}$$  \hspace{1cm} (3.7)

Substituting equations (3.5), (3.6), and (3.7) in equation (3.4) gives

$$G_{ic} 2\pi a = P \left[ \frac{Pa (3+\nu)}{8\pi D(1+\nu)} - \frac{P^2 a (3+\nu)}{16\pi D(1+\nu)} \right]$$

$$G_{ic} 2\pi a = \frac{P^2 a (3+\nu)}{8\pi D(1+\nu)} - \frac{P^2 a (3+\nu)}{16\pi D(1+\nu)}$$

$$G_{ic} 2\pi a = P^2 \left[ \frac{a (3+\nu)}{8\pi D(1+\nu)} - \frac{a (3+\nu)}{16\pi D(1+\nu)} \right]$$

$$G_{ic} 2\pi a = P^2 \left[ \frac{a (3+\nu)}{16\pi D(1+\nu)} \right]$$

$$\frac{G_{ic} 2\pi a 16\pi D}{a} = P^2 \left[ \frac{(3+\nu)}{(1+\nu)} \right]$$

$$\frac{G_{ic} 2\pi 16\pi D(1+\nu)}{(3+\nu)} = P^2$$

$$P^2 = \frac{G_{ic} 32\pi^2 D(1+\nu)}{(3+\nu)}$$
3.3 Determining Values Needed in the Physical Model

In the equation (3.9) some material properties are needed, such as $G_{IC}$, $v$ and $E$. These values, although generally available for metals in data handbooks and material tables, are not easily available and are not standard for composites.

3.3.1 Determining Poisson’s Ratio and Young’s Modulus

One of the most common procedures to determine material properties and to study the stress-strain relationships is the tensile test. In this test, a force is applied that pulls the material, elongating it. Depending on the elongation and the change in length and area it causes, various properties of the material can be determined. Stress is force/area or $\sigma = F/A$, and strain is the change of length per unit length $\epsilon = \Delta L/L$. Stress and strain are related to the Young’s Modulus of the material by Hooke’s Law $\sigma = E*\epsilon$ where $E$ is the Young’s modulus (lb/in$^2$). Young’s modulus measures the stiffness of material and varies depending on the material and its stiffness.

A specimen, when subjected to tensile loading, will exhibit shrinkage in the lateral direction. If the ratio of change in the axial direction to the original length is defined as linear strain and the change in lateral direction to the original lateral dimension is defined as lateral strain, it then can be found that within the elastic limit, there is a constant ratio between lateral strain and linear strain. This constant ratio is called Poisson’s ratio or $\nu = -\epsilon_{yy}/\epsilon_{xx}$.
Tensile testing was conducted on each of the specimens to determine their material properties, Young’s modulus and Poisson’s ratio. These are much needed material properties for the physical model. Testing was conducted using a tensile testing machine as shown in Figure 13. Results for the first specimen are shown in Figures 14 and 15.

![Tensile Testing Machine](image)

**Figure 13.** A general tensile testing machine.

![Stress-Strain Graph](image)

**Figure 14.** Stress-strain graph to determine Young’s modulus for specimen 1.
3.3.2 Determining Strain Energy Release Rate

The physical model developed was based on the theory of fracture mechanics. Fracture mechanics is a science that deals with flaw size, stresses, and toughness in the material. The crack (flaw) develops when the resistance of material weakens with the applied stress. The energy release rate ($G$) is defined by Griffith as the rate of change in potential energy with the crack area for linear elastic material.

The strain energy release rate for a material can be found using another parameter called the stress intensity factor ($K$). Stresses and strains near the crack are an important aspect for fracture analysis. Stresses near the crack tip of a linear elastic plate vary and are infinitely proportional to the reciprocal of the square root of the distance from the crack tip. The stress intensity factor (SIF) determines crack behavior at the tip. The relation between $K$ and $G$ is shown as

\[ y = -0.0547x + 1.6262 \]

\[ R^2 = 0.9990 \]

Figure 15. Graph to determine Poisson’s ratio for specimen 1.
\[ G = \frac{K^2}{E} \rightarrow \text{Plane Stress} \]

\[ G = \left( \frac{(1-v^2)}{E} \right) K_i^2 \rightarrow \text{Plane Strain} \]

where \( G \rightarrow \) strain energy release rate

\( K_i \rightarrow \) stress intensity factor

\( E \rightarrow \) Young’s modulus

\( v \rightarrow \) Poisson’s ratio

It is difficult to calculate the stress intensity factor for complex cracks in finite plates. This difficulty is due to the handling of stress singularities near the crack tip the finite element method is the most popular tool to estimate the stress intensity factor. The advantage of using this method is that three-dimensional structures like plates can be modeled in two-dimensions and analyzed. Doing so reduces computational time and cost involved, and gives accurate results. Phan [21] and Xin [22] have developed a detailed step-by-step manual to find the stress intensity factor using Ansys. The meshed area, boundary conditions and loading, and the calculated values using Ansys are shown in Figures 16 to 18.

![Figure 16. Meshed area.](image-url)
3.4 Calculating Thrust Force for Each Specimen: Once all the material properties needed for calculating the thrust force at which delamination occurs have been found, the physical model can be recalled.

\[ P = 4\pi \sqrt{\frac{G_{lc}2D(1+\nu)}{(3+\nu)}} \]
For Specimen 1, 

\[ v = 0.055, \quad E = 7.79 \text{ Msi} \] 

from which \( D \) can be calculated using 

\[ D = \frac{Eh^3}{12(1-v^2)}. \]

Using finite element analysis the value for \( K \) for specimen 1 has been found. If 

\[ G = \left(\frac{1-v^2}{E}\right)K^2, \] 

then \( G = 50.4 \text{ cals/ in}^2 \). From these values, \( P \) can be determined as 

\[ D = \frac{7790000 \times 0.112^3}{12(1-0.055^2)} = 914.77, \]

\[ P = 4\pi \sqrt{\frac{G_{ic} \cdot 2D(1+v)}{(3+v)}} \]

\[ = 4\pi \sqrt{\frac{50.4 \times 2 \times 914.77 \times (1+0.055)}{(3+0.055)}} = 2241 \text{ lbf} = 70 \text{ lbs} \]

Similarly, for each specimen, the calculated thrust force values are listed in Table 3.

**Table 3**

<table>
<thead>
<tr>
<th>SPECIMEN</th>
<th>THICKNESS</th>
<th>TENSILE MODULUS (Msi)</th>
<th>POISSON'S RATIO</th>
<th>KI</th>
<th>FLEXURAL RIGIDITY</th>
<th>Gic</th>
<th>THRUST FORCE (lbf)</th>
<th>THRUST FORCE (lbs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>sp1</td>
<td>0.112</td>
<td>7790000</td>
<td>0.055</td>
<td>19840</td>
<td>914.77</td>
<td>50.4</td>
<td>2241</td>
<td>70</td>
</tr>
<tr>
<td>sp2</td>
<td>0.139</td>
<td>7140000</td>
<td>0.415</td>
<td>1940.59</td>
<td>264.4</td>
<td>8127</td>
<td>255</td>
<td>70</td>
</tr>
<tr>
<td>sp3</td>
<td>0.069</td>
<td>8440000</td>
<td>0.034</td>
<td>42032</td>
<td>256.83</td>
<td>55.6</td>
<td>2555</td>
<td>70</td>
</tr>
<tr>
<td>sp4</td>
<td>0.091</td>
<td>2210000</td>
<td>0.490</td>
<td>12713</td>
<td>184.80</td>
<td>42.7</td>
<td>1033</td>
<td>32</td>
</tr>
<tr>
<td>sp5</td>
<td>0.12</td>
<td>9100000</td>
<td>0.052</td>
<td>22840</td>
<td>2313.95</td>
<td>52.3</td>
<td>2735</td>
<td>85</td>
</tr>
</tbody>
</table>
CHAPTER 4

EXPERIMENTAL PROCEDURE

4.1 Experimental Setup

4.1.1 Drilling Setup

The drilling setup used for this experiment was a vertical spindle Computer Numerical Control (CNC) machine manufactured by HAAS Automation Inc. This setup is located at the Wichita Area Technical College and is rented for research purposes by Dr. Behnam Bahr, Chair, Department of Mechanical Engineering, Wichita State University. This CNC machine has been specifically designated for drilling experiments. The feed rate and spindle speed are controlled by a program written, specifically for drilling of composites with G codes and M codes. Various combinations of spindle speed and feed rate can be used to obtain different thrust forces. The experimental setup is shown in Figure 19.

![Experimental setup](image)

Figure 19. Experimental setup.
4.1.2 Dynamometer

A dynamometer is used to measure torque and thrust forces. A Kistler dynamometer was used in these experiments. It was mounted on a vice located within the CNC machine. Readings from the dynamometer were fed to a computer, for analytical and saving purposes, through a NI-DAQmx card. The dynamometer measured the torque generated, the thrust force generated, and the X and Y forces. Each of these values was measured by the voltage fluctuations recorded by the dynamometer during drilling. Figure 20 shows the dynamometer placed on the vice. A fixture is placed over the dynamometer to hold the coupon during drilling. The fixture protects the dynamometer from being machined during the drilling process.

![Figure 20. Kistler dynamometer.](image)

4.1.3 Data Acquisition

The data acquisition software used for this setup was National Instruments VI Logger Lite, a flexible ready-to-use data logger. It was configured to acquire data from the dynamometer for viewing and sharing data. The data collected was analyzed using
MS Excel. The VI Logger was compatible with LabVIEW and was used with LabVIEW to enhance the capabilities of the system. VI Logger allows both high-speed and low-speed data logging. It also has real time and historical viewing, i.e., data is be viewed at the same time it is being logged and it can also be reviewed again using historical viewing once the experiment is done.

4.1.4 Drill Bit

The drill bit used in these experiments was a Cessna composite drill bit, specifically manufactured for drilling of composites. It is a multi-facet drill bit and was used because it can produce high thrust forces, which were required for one or two specimen. Figure 21 shows this drill bit.

![Cessna drill bit](image)

Figure 21. Cessna drill bit.

Figure 22 shows the final drilling setup after the fixture and specimen have been placed and are ready for the experiment to be conducted.
4.2 Applying the Calculated Thrust Force

After the physical model was developed, the material properties found, and the thrust forces calculated. The calculated thrust forces were applied to individual specimens. Two features that can be controlled during the drilling process are spindle speed and feed rate. Thrust force is a correlation of feed rate and spindle speed; hence, experiments were conducted to find the thrust force needed for each specimen. Coupons of each specimen were placed on the fixture, and combinations of spindle speed and feed rate were tried to see what kind of thrust forces were generated. Using a trial-and-error method the correct spindle speeds and feed rates were found for individual specimens, which then generated the necessary thrust forces. An example graph for the spindle speed and feed rate for specimen 5 is shown in Figure 23.
Figure 23. Spindle speed 2,000 feed rate 0.02 ipr, thrust force generated 47 lbs.
CHAPTER 5

EXPERIMENTAL RESULTS

Individual specimens were drilled at the center of their plates with the calculated thrust force using the spindle speed and feed rate obtained experimentally. Thrust force graphs for all five specimens and their delamination pictures are shown in Figures 24 to 68. The delamination pictures show the drilled holes of each specimen. 

![Time(s) Vs Thrust Force(lbs) Graph](image)

Figure 24. Specimen 1 spindle speed 2,000 rpm, feed rate 0.016 ipr, thrust force generated 76 lbs.
Figure 25. Specimen 1 – Hole 1 – Front

Figure 26. Specimen 1 – Hole 1 – Back
Figure 27. Specimen 1 spindle speed 2,000 rpm, feed rate 0.014 ipr, thrust force generated 65 lbs.

Figure 28. Specimen 1 – Hole 2 – Front
Figure 29. Specimen 1 – Hole2 – Back

Figure 27. Specimen 1 spindle speed 2,000 rpm, feed rate 0.012 ipr, thrust force generated 65 lbs.
• Clean surface at entrance.
• Minimal fiber pullout and breakouts at exit.
• Smooth and shiny hole wall.
• Amorphous chips.
Figure 33. Specimen 2 spindle speed 3,000 rpm, feed rate 0.008 ipr, thrust force generated 195 lbs.

Figure 34. Specimen 2 – Hole 1 – Front
Figure 35. Specimen 2 – Hole 1 – Back

Figure 36. Specimen 2 spindle speed 3,000 rpm, feed rate 0.01 ipr, thrust force generated 255 lbs.
Figure 37. Specimen 2 – Hole 2 – Front

Figure 38. Specimen 2 – Hole 2 – Back
Figure 39. Specimen 2 spindle speed 3,000 rpm, feed rate 0.012 ipr, thrust force generated 260 lbs.

Figure 40. Specimen 2 – Hole 3 – Front
Figure 41. Specimen 2 – Hole 3 – Back

- Clean surface at entrance, with very little fiber pullout.
- Clear view of fiber pullout and occurrence of delamination.
- Rough hole wall.
- Brittle chips but a little like strands.

Figure 42. Specimen 3 spindle speed 2,000 rpm, feed rate 0.01 ipr, thrust force generated 50 lbs.
Figure 43. Specimen 3 – Hole 1 – Front

Figure 44. Specimen 3 – Hole 1 – Back
Figure 45. Specimen 3 spindle speed 2,000 rpm, feed rate 0.012 ipr, thrust force generated 55 lbs.

Figure 46. Specimen 3 – Hole 1 – Front
Figure 47. Specimen 3 – Hole 1 – Back

Figure 48. Specimen 3 spindle speed 2,000 rpm, feed rate 0.014 ipr, thrust force generated 73 lbs.
Figure 49. Specimen 3 – Hole 3 – Front

- Poor surface at entrance and exit.
- Clear view of fiber pull out and occurrence of delamination.
- Seemingly rough hole wall and different hole geometry.
- Amorphous chips.

Figure 50. Specimen 3 – Hole 3 – Back
Figure 51. Specimen 4 spindle speed 2,000 rpm, feed rate 0.008 ipr, thrust force generated 28 lbs.

Figure 52. Specimen 4 – Hole 1 – Front
Figure 53. Specimen 4 – Hole 1 – Back

Figure 54. Specimen 4 spindle speed 2,000 rpm, feed rate 0.014 ipr, thrust force generated 36 lbs.
Figure 55. Specimen 4 – Hole 2 – Front

Figure 56. Specimen 4 – Hole 2 – Back
Figure 57. Specimen 4 spindle speed 2,000 rpm, feed rate 0.018 ipr, thrust force generated 43 lbs.

Figure 55. Specimen 4 – Hole 3 – Front
- Good surface finish at entrance with very little fiber pullout.
- Clear view of fiber pullout and occurrence of delamination at exit.
- Seemingly smooth hole wall and maintained hole geometry.
- Amorphous chips.

Figure 60. Specimen 5 spindle speed 2,000 rpm, feed rate 0.025 ipr, thrust force generated 55 lbs.
Figure 61. Specimen 5 – Hole 1 – Front

Figure 62. Specimen 5 – Hole 1 – Back
Figure 63. Specimen 5 spindle speed 2,000 rpm, feed rate 0.018 ipr, thrust force generated 53 lbs

Figure 64. Specimen 5 – Hole 2 – Front
Figure 65. Specimen 5 – Hole 2 – Back

Figure 66. Specimen 5 spindle speed 2,000 rpm, feed rate 0.035 ipr, thrust force generated 85 lbs.
Good surface finish at entrance with fiber pullout.

Clear view of fiber pullout and occurrence of delamination at exit.

Slightly uneven hole wall and maintained hole geometry.

Amorphous chips.

A comparison between the theoretical and the experimental forces is shown in Table 4. The experimental values are found to be in good agreement with the theoretical values.
**Table 4**
Comparison of Thrust Force Values -- Theoretical and Experimental

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Theoretical Thrust Force (lbs)</th>
<th>Experimental Thrust Force (lbs)</th>
<th>difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50</td>
<td>66</td>
<td>25</td>
</tr>
<tr>
<td>2</td>
<td>180</td>
<td>200</td>
<td>10</td>
</tr>
<tr>
<td>3</td>
<td>55</td>
<td>53</td>
<td>8</td>
</tr>
<tr>
<td>4</td>
<td>25</td>
<td>28</td>
<td>12</td>
</tr>
<tr>
<td>5</td>
<td>60</td>
<td>85</td>
<td>12</td>
</tr>
</tbody>
</table>
CHAPTER 6

SUMMARY, CONCLUSION AND FUTURE WORK

6.1 Summary

A physical model that calculates the critical thrust force for a simply supported circular plate under a single-point central loading was developed. The equation was developed based on the principles of classical plate theory and energy balance equations.

In Chapter 1, various components of this thesis were discussed and reasons for using these components and their advantages and disadvantages were listed.

In Chapter 2, presented a literature review of the various aspects of drilling of composites. It was established that, during drilling, thrust force plays an important role in the quality of the hole drilled. It was also shown that thrust force to predict delamination can be developed based on energy balance equations.

In Chapter 3, a physical model to predict delamination was developed, based on fracture mechanics and energy balance equations. Material properties of the specimen needed for the equation were found, and thrust forces to predict delamination were calculated for each specimen.

In Chapter 4, the experimental setup and the application of the calculated thrust forces were discussed, as well as the experiments conducted.

In Chapter 5, the results were discussed thrust values for specimen 1 and their respective graphs were displayed. Also, hole quality for each specimen was discussed. For hole quality, undesirable effects like fiber pullout were also discussed.
6.2 Conclusions

Theoretical values for critical thrust force were found to be in agreement with experimental values. This critical thrust force can be used to predict delamination in a simply supported circular plate under a single-point concentrated loading. An equivalent or larger thrust force than the critical thrust force will cause delamination during drilling of the plate. Operating under optimum conditions where the thrust force is less than the critical thrust force should prevent delamination.

6.3 Future Work

The following recommendations are made for future studies

- Development of a model to predict the optimum thrust force necessary for drilling of composites without delamination since a very low thrust force is known to cause fiber pullout and other defects during drilling.

- Development of similar models for different tool geometries and comparing them to the existing one.

- Development of physical models including Mode II and Mode III failures.
REFERENCES
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