OPTIMIZATION OF MACHINING CONDITIONS DURING DRILLING OPERATION OF HYBRID FIBER REINFORCED PLASTICS (HFRP) COMPOSITE – AERO-STRUCTURAL COMPONENT

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2026

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

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A thesis submitted
in fulfillment of the requirements for the degree of
Bachelor of Manufacturing Engineering Technology (Product Design) with Honours

Faculty of Industrial and Manufacturing Technology and Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2026

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

BORANG PENGESAHAN STATUS LAPORAN PROJEK SARJANA MUDA

TAJUK: **OPTIMIZATION OF MACHINING CONDITIONS DURING DRILLING OPERATION OF HYBRID FIBER REINFORCED PLASTICS (HFRP) COMPOSITE – AERO-STRUCTURAL COMPONENT**

SESI PENGAJIAN: **2023-2024 Semester 1**

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DEDICATION

To my beloved parents, Mohd Khari Bin Mat Noh and Zaidah Binti Kapor. Your unwavering belief in me has given me the strength to persevere through the most challenging times. I am forever grateful for your guidance, wisdom, and the values you have instilled in me. This achievement is as much yours as it is mine.

To my esteemed supervisor, TS. DR. Syahrul Azwan Bin Sundi @ Suandi, whose expertise, guidance, and mentorship have been instrumental in shaping this project. Your insights, patience, and dedication have pushed me to strive for excellence and have greatly contributed to my growth as a researcher.

Finally, I dedicate this project to all the researchers and authors whose works have inspired and informed my study. Your contributions to the field have laid the groundwork for this project, and I am grateful for the knowledge you have shared.

ABSTRACT

The drilling of Hybrid Fiber Reinforced Plastics (HFRP) composites, which are extensively used in aerospace structural components, posed significant challenges due to their heterogeneous and anisotropic nature. These materials, typically consisting of a hybrid combination of carbon and glass fibers embedded in a polymer matrix, offered superior mechanical properties, including a high strength-to-weight ratio, enhanced fatigue resistance, and good thermal stability, making them suitable for demanding aerospace applications. Nevertheless, the machining of HFRP composites resulted in critical issues such as delamination, fiber pull-out, and matrix cracking, which could compromise the structural integrity and functional performance of aerospace components. In this study, the drilling conditions for HFRP composites were optimized using the Taguchi L9 orthogonal array method to systematically investigate the effects of key machining parameters, namely feed rate, spindle speed, and drill geometry, on drilling performance. A twist drill with a helix angle of 30° and a point angle of 118° was employed, and its influence on thrust force, surface roughness, and delamination factor was evaluated. These responses were selected as critical quality indicators due to their direct relevance to surface integrity and dimensional accuracy in aerospace manufacturing

Important keys: HFRP, Composite, Twist drill geometry.

ABSTRAK

Proses penggerudian komposit Plastik Bertetulang Serat Hibrid (HFRP), yang digunakan secara meluas dalam komponen struktur aeroangkasa, menimbulkan cabaran ketara disebabkan sifatnya yang heterogen dan anisotropik. Bahan ini, yang lazimnya terdiri daripada gabungan serat karbon dan kaca di dalam matriks polimer, menawarkan ciri mekanikal unggul seperti nisbah kekuatan-berat yang tinggi, ketahanan keletihan dan kestabilan terma, menjadikannya ideal untuk aplikasi aeroangkasa. Namun begitu, pemesinan HFRP sering mengakibatkan masalah seperti delaminasi, tercabutnya serat dan keretakan matriks, yang boleh menjejaskan integriti struktur komponen kritikal. Kajian ini bertujuan mengoptimumkan keadaan penggerudian bagi komposit HFRP menggunakan kaedah tatasusunan ortogon Taguchi L9 untuk menganalisis secara sistematik pengaruh parameter proses seperti kadar suapan, kelajuan gelendong dan geometri gerudi terhadap prestasi penggerudian. Gerudi lilit dengan sudut heliks 30° dan sudut puncak 118° digunakan untuk menilai kesannya terhadap daya tujahan, kekasaran permukaan dan faktor delaminasi—penunjuk kualiti utama dalam pembuatan aeroangkasa.

ACKNOWLEDGEMENTS

In the Name of Allah, the Most Gracious, the Most Merciful

First and foremost, I would like to express my deepest gratitude and praise to Allah the Almighty, my Creator and Sustainer, for His endless blessings, guidance, and mercy throughout every stage of my life. Without His will and grace, none of this would have been possible. He has granted me the strength, patience, and perseverance to overcome challenges and the wisdom to continue learning and growing. Alhamdulillah, for everything I have received from the very beginning until this point in my journey.

I would like to express my deepest appreciation and sincere gratitude to my respected supervisor, TS. DR. Syahrul Azwan Bin Sundi @ Suandi, for his invaluable guidance, continuous support, and unwavering encouragement throughout the duration of this project. His vast knowledge, insightful feedback, and dedicated mentorship have been instrumental in shaping the direction and success of my research. I am truly thankful for the time and effort he has invested in guiding me through this academic journey.

My heartfelt thanks also go to Universiti Teknikal Malaysia Melaka (UTeM) for providing an excellent academic environment and access to essential resources that have enabled me to pursue my research effectively. The university's strong emphasis on academic excellence and innovation has significantly contributed to my intellectual and personal development.

I would also like to acknowledge the unconditional support of my family and friends, who have been my source of strength and motivation throughout this endeavor. Their encouragement, patience, and belief in my abilities have played a vital role in helping me overcome challenges and stay committed to my goals.

Finally, I am sincerely grateful to all individuals who have contributed directly or indirectly to the successful completion of this Final Year Project 1. Whether through technical assistance, valuable advice, or moral support, your contributions have been truly meaningful.

Thank you all for being a part of this remarkable journey and for helping me reach this important milestone in my academic and professional life.

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LIST OF SYMBOLS AND ABBREVIATIONS

HFRP	-	Hybrid Fiber Reinforced Polymer
AFRP	-	Aramid Fiber Reinforced Polymer
CFRP	-	Carbon Fiber Reinforced Polymer
FRP	-	Fiber Reinforced Polymer
HFRP	-	Hybrid Carbon Reinforced Polymer
GFRP	-	Glass Fiber Reinforced Polymer
HSS	-	High-Speed Steel
imp	-	Inches per Minute
ipr	-	Inches per Revolution
L	-	Depth of Hole
N	-	Spindle Speed
N	-	Revolutions of the Job per Minute
Ra	-	Arithmetic Average Roughness
Rmax	-	Maximum Roughness Depth
RPM	-	Revolutions Per Minute
S	-	Cutting Speed
S/N	-	Signal-to-Noise
SFM	-	Surface Feet per Minute
T	-	Time Required for Drilling
Vc	-	Cutting Speed
Vf	-	Feed Rate
Z	-	Number of Flutes
α	-	Alpha (Significance Level)

CHAPTER 1

INTRODUCTION

1.1. Background

The aerospace industry experienced a substantial rise in the adoption of composite materials in recent years, driven by the demand for lighter, more fuel-efficient aircraft with lower maintenance requirements. Aircraft manufacturers increasingly integrated composites such as Fiber Reinforced Polymers (FRP), Carbon Fiber Reinforced Polymers (CFRP), Glass Fiber Reinforced Polymers (GFRP), and Aramid Fiber Reinforced Polymers (AFRP) due to their superior fatigue resistance, corrosion resistance, high stiffness, and reduced weight compared to conventional metallic materials.

Hybrid Fiber Reinforced Plastics (HFRP) composites, which combined two or more types of reinforcing fibers, gained particular attention for aero-structural components, thanks to their exceptional strength-to-weight ratios and mechanical performance. However, the drilling of HFRP composites presented significant challenges due to their heterogeneous, anisotropic nature. Issues such as delamination, fiber pull-out, matrix cracking, and poor surface finish arose when conventional drilling methods were applied, potentially compromising the integrity and performance of aerospace components. Despite extensive studies on composite machining, limited research focused specifically on optimizing drilling parameters and tool geometries for HFRP composites.

In this study, an experimental approach using the Taguchi L9 orthogonal array was employed to optimize machining parameters such as spindle speed, feed rate, and drill bit geometry to enhance drilling quality. A twist drill with a helix angle of 30° and a point angle of 118° was used to investigate its effect on thrust force, surface roughness, and delamination factor. The results highlighted that careful selection of drilling conditions significantly reduced machining-induced damage and improved hole quality, contributing to more reliable and efficient manufacturing of composite components for aerospace applications.

The machining parameters such as cutting speed, feed rate, and tool geometry played a crucial role in the drilling process and significantly influenced the quality of drilled holes and the extent of damage induced in Hybrid Fiber Reinforced Plastics (HFRP) composites. Studies showed that an increase in feed rate led to higher thrust force and surface roughness, while a decrease in cutting speed could reduce delamination and improve hole quality. For instance, research by Ismail et al. (2015) demonstrated that higher cutting speeds reduced delamination and surface roughness, whereas increased feed rates resulted in greater delamination and rougher surfaces.

Similarly, a study by Wei et al. (2016) highlighted the impact of drilling parameters and tool geometry on drilling performance in composite materials, emphasizing the importance of optimizing these parameters to minimize damage. Additionally, a comprehensive review by Davim (2012) underscored that the selection of appropriate machining parameters was essential for achieving high-quality holes and minimizing damage in composite materials. Therefore, a systematic approach to optimizing machining parameters was essential for enhancing the drilling performance of HFRP composites in aerospace.

This project aimed to investigate the optimization of machining parameters to minimize damage to HFRP composites during the drilling process. The primary objectives of this study were to identify the critical drilling parameters such as feed rate, spindle speed, and drill tool geometry that significantly influenced drilling-induced damage in HFRP composites; to develop an optimization methodology using the Taguchi L9 orthogonal array to determine the optimal combination of machining parameters; and to experimentally validate the optimized parameters to assess their effectiveness in reducing damage, including delamination, fiber pull-out, and poor surface finish. The outcomes of this research were expected to advance machining strategies for HFRP composites, facilitate the production of high-quality holes with minimal structural compromise, and enhance the overall performance and reliability of HFRP composite components in aerospace and other high-performance engineering applications.

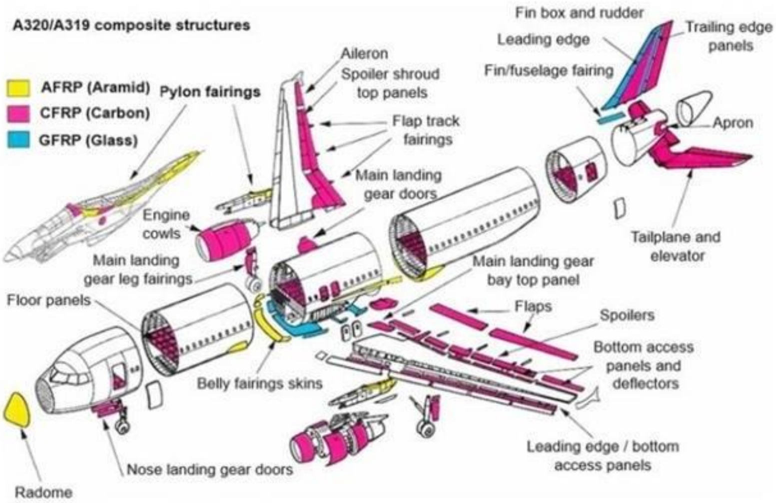


Figure 1.1: Example usage of composite material in aerospace (Mouritz, 2012)

1.2. Problem Statement

The aerospace industry increasingly adopted Hybrid Fiber Reinforced Plastics (HFRP) composites for manufacturing aero-structural components due to their superior strength-to-weight ratios, corrosion resistance, and fatigue durability. These materials, which combined carbon and glass fibers within a polymer matrix, offered enhanced mechanical properties that were crucial for aerospace applications. However, the machining of HFRP composites presented significant challenges. The heterogeneous and anisotropic nature of these materials led to issues such as delamination, fiber pull-out, matrix cracking, and poor surface finish during drilling operations. These machining-induced damages compromised the structural integrity and performance of the components, thereby affecting the overall reliability and safety of aerospace structures.

Traditional drilling methods, originally developed for metals, were often inadequate for HFRP composites. The application of conventional drilling techniques to these advanced materials frequently resulted in various forms of damage. For instance, studies showed that improper machining parameters led to increased thrust forces and surface roughness, while also contributing to delamination and other defects. Research by Ismael and Faidh-Allah (2023) showed that higher spindle speeds significantly reduced delamination in hybrid fiber reinforced polymer composites, while higher feed rates led to increased delamination damage. Similarly, a study by Wei et al. (2016) highlighted the impact of drilling parameters and tool geometry on drilling performance in composite materials, emphasizing the importance of optimizing these parameters to minimize damage. These findings underscored the need for a systematic approach to optimize drilling parameters to mitigate damage and improve hole quality in HFRP composites.

Despite the critical importance of optimizing drilling parameters, limited research specifically focused on the systematic optimization of machining parameters for HFRP composites using statistical methods. Most existing studies emphasized either the tool geometry or the material response in isolation, without a comprehensive approach that considered multiple influencing factors. Therefore, there was a pressing need for a structured investigation to optimize drilling conditions, particularly through robust experimental designs like the Taguchi method, to minimize damage and improve hole quality. Addressing this problem was critical for advancing the machinability of HFRP composites and ensuring the reliability and performance of aerospace components made from these advanced materials.

1.3. Research Objectives

The primary aim of this research was to optimize the machining parameters in the drilling of Hybrid Fiber Reinforced Plastics (HFRP) composites in order to minimize drilling-induced damage and improve hole quality, particularly for aerospace applications. To achieve this, the study was guided by the following specific objectives:To identify the critical machining parameters including spindle speed and feed rate that significantly influence drilling-induced defects such as delamination, drilling temperature, thrust force, holes quality, and surface quality in HFRP composites.

1. To identify the critical machining parameters including spindle speed and feed rate that significantly influenced drilling-induced defects such as delamination, thrust force, hole quality, and surface quality in HFRP composites.
2. To experimentally assess and validate the effect of optimized machining parameters using a twist drill with a helix angle of 30° and a point angle of 118° on drilling performances, including thrust force, surface quality, delamination, and thrust force.
3. To establish guidelines and recommendations for effective drilling practices that ensured minimal damage and high-quality hole production in HFRP composites for aerospace structural applications.

1.4. Scope of Research

This research focused on optimizing drilling parameters for Hybrid Fiber Reinforced Polymer (HFRP) composites that were used in aerospace structures. The study evaluated machining parameters such as spindle speed, feed rate, and to reduce drilling-related defects like delamination, thrust force, hole quality, and surface quality.

The research was limited to twist drill bits with set geometries, specifically a point angle of 118 degrees and a helix angle of 30 degrees, to focus on the effects of the machining parameters. Experiments took place under controlled conditions using a CNC machine. Performance was measured based on cutting temperature, thrust force, delamination, hole circularity, and tool wear. The Shodensha GR3400 and Coordinate Measuring Machine (CMM) were used to evaluate the delamination and circularity of the drilled HFRP panels. The Haas CNC machine, which had a Kistler Dynamometer attached, was used for the actual drilling and Nikon MM-800 Microscopy for tool wear.

A systematic experimental design using the Taguchi L9 orthogonal array was implemented to minimize the number of trials while still achieving meaningful optimization. The findings aimed to improve drilling practices in HFRP machining and provide practical recommendations for the aerospace manufacturing industry.

CHAPTER 2

LITERATURE REVIEW

2.1. Introduction

The purpose of this project was to review recent research relevant to the evaluation and development of optimized machining parameters for drilling Hybrid Fiber Reinforced Plastics (HFRP) composites. The insights gained from this literature review served as a foundational reference to guide and enhance the experimental work, ensuring a more effective and informed approach. A number of relevant studies were examined to provide a comprehensive overview of the state of research in this area, offering context and support for the direction of the investigation.

2.2. Composite material

Composite materials had gained widespread popularity across various engineering applications, serving as a viable alternative to traditional metallic materials due to their exceptional mechanical and physical properties. Among these, fiber-reinforced polymer (FRP) composites attracted particular attention for their high specific strength, excellent fatigue resistance, lightweight nature, and outstanding corrosion resistance. A notable example of their successful application was the Boeing 787 Dreamliner, which extensively utilized composite materials in its structure. Compared to conventional metals, FRP composites also provided greater flexibility in product design, enabling the development of more efficient and innovative engineering solutions.

In aerospace and related industries, composite materials played a vital role in both current and future structural components. Their appeal lay in their superior strength-to-weight and stiffness-to-density ratios, making them especially suitable for aviation applications where performance and weight reduction were critical. A typical composite consisted of high-strength, high-stiffness fibers embedded within a ductile resin matrix. This configuration allowed the material to harness the complementary properties of its constituents, where the fibers offered strength and rigidity, and the matrix contributed toughness and durability.

Common examples of man-made composites used in aerospace included carbon fiber-reinforced plastics (CFRP) and glass fiber-reinforced plastics (GFRP). These materials consisted of strong yet brittle fibers (carbon or glass) embedded in a tough, flexible polymer matrix. This combination allowed for the engineering of materials that exhibited high strength, stiffness, and toughness, while maintaining a low overall density. By leveraging the strengths of each component and mitigating their individual weaknesses, composite materials could be tailored to meet the demanding requirements of advanced aerospace applications (Quilter, n.d.).

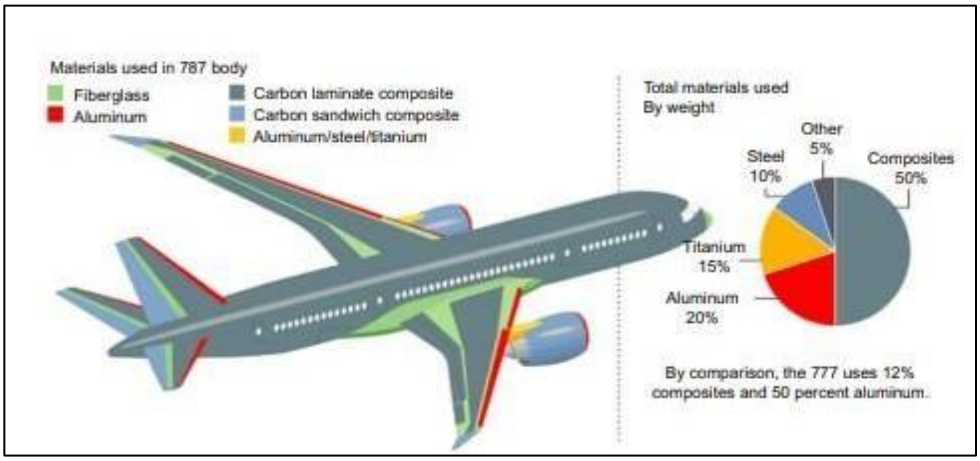


Figure 2.1: B787 Dreamliner and its use of the structural Composites Aly (2017; Hassim, 2018)

2.2.1. Carbon Fiber Reinforced Polymer (CFRP)

The use of Carbon Fiber Reinforced Polymer (CFRP) had grown significantly in recent years, particularly in the aerospace and automotive industries. This surge in adoption was largely attributed to the material's ease of manufacturing via automated lamination processes, combined with its exceptional mechanical properties, chemical stability, and dimensional consistency. CFRP also exhibited high resistance to corrosion and elevated temperatures, primarily due to its low density—an advantage over traditional materials such as steel and aluminum, not only in terms of performance but also from a cost-efficiency standpoint.

Despite these benefits, the complex, multiphase, and heterogeneous structure of CFRP presented considerable challenges during machining. The material was susceptible to various forms of damage, including fiber breakage, fiber pull-out, fuzzing, delamination, and resin degradation. The abrasive nature of carbon fibers, coupled with the low thermal conductivity of the polymer matrix, accelerated tool wear during machining operations. Furthermore, due to its laminated architecture, CFRP was particularly prone to delamination, as the layered plies could easily separate under the influence of cutting forces.

These challenges were further compounded when machining complex components such as CFRP panels, which were widely used in aerospace structural applications. While such panels provided an optimal balance of high strength and low weight, their anisotropic nature and varied fiber orientations across sections made the cutting process more intricate. Therefore, strict control over machining parameters was essential to prevent surface damage and preserve structural integrity. In this context, selecting the appropriate cutting strategies and tooling configurations became critical for ensuring surface quality, maintaining mechanical performance, and enabling the long-term durability of CFRP components under operational loading conditions.

Figure 2.2: CFRP Plate (https://www.carbonfiber-composites.com/sale-44053892-super-light-high-strength-different-thickness-cfrp-plate-carbon-fiber-sheets.html)

2.2.2. Glass Reinforced Polymer (GFRP)

Glass Fiber Reinforced Polymer (GFRP) composites had been widely utilized across various industries due to their advantageous combination of enhanced mechanical properties, cost-effectiveness, and superior resistance to corrosion. Initially developed in the 1930s, glass fibers became a fundamental reinforcement material in polymer matrix composites, primarily owing to their favorable strength-to-weight ratio, despite having lower tensile strength and density compared to carbon fibers. Typically, glass fibers ranged in diameter from 10 to 20 µm. As illustrated in Figure 2.2, GFRP plates had demonstrated broad applicability in engineering fields, highlighting their versatility and adaptability (Sreenivasulu, 2013).

GFRP composites had found extensive use in sectors such as construction, automotive, and aerospace. For example, S-glass fibers known for their higher strength were often employed in aerospace applications, while C-glass fibers were preferred in highly corrosive environments due to their enhanced chemical resistance. Despite these advantages, GFRP materials posed significant challenges during machining processes. The abrasive nature of glass fibers led to rapid tool wear and necessitated the use of specialized machining techniques to maintain precision and tool life (Davim, 2010). Nonetheless, GFRP remained a promising alternative to conventional materials in structural applications, offering a combination of performance and affordability that supported its continued adoption in high-performance engineering systems (Li et al., 2018).

Figure 2.3: GFRP plates find wide applications in engineering fields (Sreenivasulu, 2013)

2.2.3. Aramid Fiber Reinforced Polymer (AFRP)

Aramid Fiber Reinforced Polymer (AFRP) composites have garnered significant attention due to their exceptional performance under fire and high-temperature conditions, enhanced vapor permeability, increased corrosion resistance, and their ability to delay structural buckling. These properties make AFRP a particularly attractive material for strengthening and retrofitting structural elements. As a result, the scientific and engineering communities have shown growing interest in developing comprehensive design standards and evaluating the performance of AFRP in structural applications.

Studies investigating the use of AFRP for strengthening steel beams—employing a variety of external bonding and reinforcement configurations—have demonstrated notable improvements in load-bearing capacity and stiffness, particularly when normal modulus AFRP is used. Experimental results revealed that AFRP wrapping significantly enhances structural behavior by delaying local buckling under compressive loads and mitigating punching failures under flexural conditions. These improvements were further validated through numerical simulations using ANSYS 16.0, where the simulated results closely aligned with the experimental data in terms of deflection and maximum load-bearing capacity.

Overall, the findings underscore the effectiveness of AFRP composites in improving structural performance. The observed failure modes and their correlation with numerical predictions confirm AFRP's potential as a reliable material for structural strengthening applications. These insights are of particular value for the advancement of future projects aiming to enhance the durability, safety, and load-carrying performance of civil and aerospace structures (Nayak, 2021).

2.2.4. Hybrid Fiber Reinforced Plastic (HFRP)

Hybrid Fiber Reinforced Polymer (HFRP) composites emerged as an advanced solution to address the limitations associated with conventional fiber-reinforced polymer (FRP) composites, which typically relied on a single type of reinforcement. Although traditional FRP composites had demonstrated substantial potential in replacing metallic materials across various engineering applications, their performance in structural applications was often constrained by limited ductility and a lack of tailored mechanical behavior. To overcome these challenges, hybrid composites comprising two or more distinct fiber types embedded within a common matrix were developed to enhance overall material performance.

HFRP composites were engineered by strategically combining different fibers, such as carbon, glass, or aramid, within a single polymer matrix, thereby leveraging the unique advantages of each fiber while compensating for their individual drawbacks (Jagannatha et al., 2019). This hybridization approach allowed for a customized balance of properties, such as strength, stiffness, impact resistance, and cost-effectiveness. For example, carbon/glass hybrid composites combined the high strength and modulus of carbon fibers with the low cost and excellent insulating properties of glass fibers, resulting in a material system that was both efficient and economical (Natarajan et al., 2022; Nargis et al., 2024).

The adoption of HFRP composites in the aerospace sector had grown significantly due to their capacity to offer application-specific performance characteristics. In aircraft interiors, carbon/glass hybrids were employed to reduce structural weight while maintaining adequate mechanical strength and stiffness (Natarajan et al., 2022). Similarly, carbon/aramid hybrids were utilized in high-performance components, such as aircraft engine housings, where the combination of carbon's stiffness and aramid's superior impact resistance provided a highly effective and resilient composite material (Bruno et al., 2023). The ability to fine-tune mechanical properties through fiber hybridization positioned HFRP composites as a promising class of materials for future aerospace and high-performance structural applications

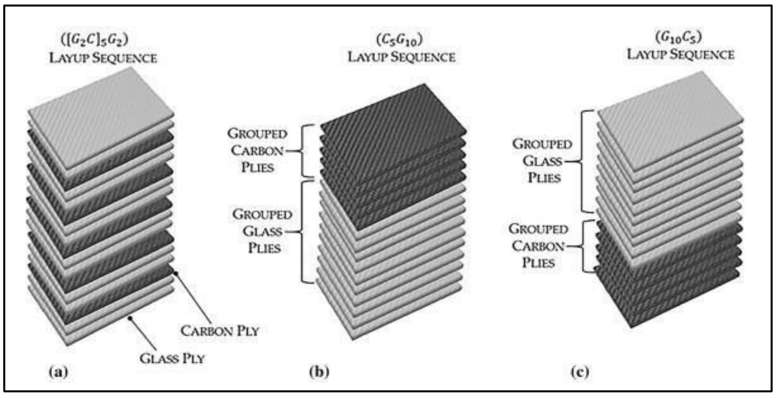


Figure 2.4: Hybrid Layup sequence configuration (Bruno et al., 2023)

2.2.5. Usage of HFRP in The Aerospace Industry

Composites had been part of the aerospace industry since World War II, first appearing in military aircraft. Since then, their use had expanded into everything from private jets to today's commercial airplanes. The three main types—fiberglass, carbon fiber, and aramid fiber composites—had been especially common. Each type had its own subcategories, providing engineers with a wide range of material options. Over the years, aircraft design had seen a major shift in materials, with composites playing a much bigger role than ever before. For example, fiberglass was first used in the Boeing 707 in the 1950s, but it made up only a small part of the structure. Fast forward to today, composites now made up about half of the Boeing 787's structure and roughly a quarter of the Airbus A380's airframe.

Hybrid Carbon Reinforced Polymer (HCRP), a smart mix of carbon fiber and other materials like glass or aramid fiber, had become a go-to choice in the aerospace industry. This blend made the material not only strong and lightweight but also more durable and cost-effective. Carbon fiber provided impressive strength and stiffness, while the other fibers improved impact resistance and reduced cracking

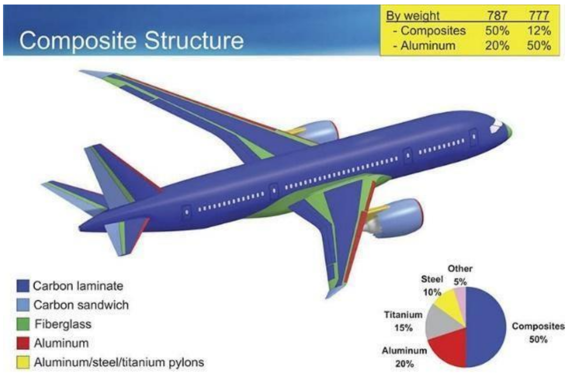


Figure 2.5: Boeing B787 Dreamliner Structure (https://www.hkengineer.org.hk/issue/vol43-jun2015/feature_story/?id=12880)

HCRP had been extensively utilized in the aerospace industry, particularly in the fabrication of both primary and secondary structural components such as fuselage panels, wing skins, spars, and ribs (Mouritz, 2012). The application of HCRP in these critical areas had contributed significantly to the reduction of aircraft weight, while preserving the necessary structural integrity and ensuring optimal performance (George Tecusan, 2019). Several prominent aerospace manufacturers and research organizations had effectively implemented HCRP in structural applications. For instance, Boeing employed HCRP in both the fuselage and wing assemblies of the 787 Dreamliner to optimize structural efficiency (Aversan, 2024). Similarly, Airbus had utilized HCRP in the development of the A350 XWB, capitalizing on its lightweight and high-performance characteristics to enhance aircraft performance (Wikipedia, 2023).

2.3. Drilling of HFRP

Drilling had been one of the most common machining processes used to create cylindrical holes with specific depth and diameter, particularly in metal workpieces. Although several machine tools could be used for this purpose, drilling machines had been specially designed to carry out such tasks efficiently. The process was relatively straightforward, affordable, and time-saving. Typically, the location for the hole was first marked using a center punch. The drill bit mounted in the spindle of the machine was then rotated and slowly pushed into the material, removing material until the hole reached the required depth.

2.3.1. Drilling

Creating circular holes in a material involved using a rotating drill and was one of the most frequently used machining processes. It was estimated that drilling accounted for about a quarter of the total machining time in manufacturing (López De Lacalle et al., 2000a). Because it typically took place toward the end of the production cycle for mechanical parts, drilling was also considered economically significant (López De Lacalle et al., 2000b).

The drilling process involved complex drill geometry and material deformation. During drilling, both the cutting speed and rake angle varied depending on how far they were from the drill's center, with the fastest speed occurring at the outer edge, known as the peripheral cutting speed. As shown in Figure 2.7, the drilling process usually happened in two stages: first, the drill point pierced the material, and then the full hole was drilled (Suresh Kumar et al., 2020).

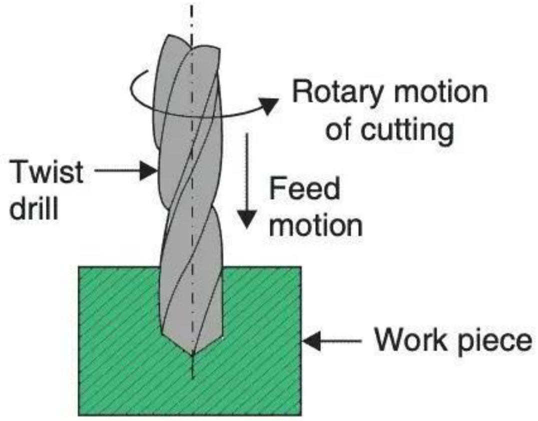


Figure 2.6: Drilling works (https://extrudesign.com/how-drilling-machine-works-different-types/)

Drilling had still been considered one of the toughest machining operations, even with the significant amount of research conducted on it. The feed rate and drill diameter had the biggest impact on thrust force, while feed rate and spindle speed primarily affected surface roughness. One of the main problems during drilling was chip clogging inside the drill's flutes. As the hole got deeper, chips began to jam, increasing friction between the tool, the workpiece, and the chips themselves. This could lead to a sharp and unexpected rise in torque.

In most machining operations, especially drilling, a large amount of heat had been produced. This heat mainly came from two sources: plastic deformation in the shear zone and friction caused by chips sliding along the tool's surface. What made drilling different from simpler machining processes was that the thermal conditions were much more complex and harder to manage (Hocheng & Tsao, 2005).

Conventional drilling, remains one of the most commonly used methods for creating holes in composite materials, especially in secondary machining, due to the necessity of fastening components. To overcome the limitations of conventional methods, various non-conventional machining techniques have been introduced, such as laser beam drilling, abrasive and non-abrasive water-jet drilling, ultrasonic machining, and electrical discharge machining.

Figure 2.7: Conventional Machining (https://glebe.co.uk/services/conventional-machining/)

2.3.2. Drilling Specifications

Drilling techniques had played a pivotal role in determining the success of machining operations on HFRP composites. The selection of a suitable drilling method had directly impacted tool life, surface integrity, dimensional accuracy, and overall component performance. Due to the complex hybrid nature of HFRPs, which often comprised a mix of carbon, glass, and aramid fibers, drilling methods had to be adapted to manage varying material responses and minimize damage. A detailed understanding of these methods had enabled engineers to select optimal processes for aerospace-grade applications.

2.3.2.1. Conventional Drilling (CD)

fundamental machining process in which a rotating drill bit is used to create round holes in a solid material. The tool advances linearly into the workpiece while rotating, cutting away material to form the hole. This method is widely applied in manufacturing industries for its simplicity and effectiveness in producing precise holes (Kalpakjian & Schmid, 2014)

2.3.2.2. Peck Drilling

Peck drilling is a variation of the conventional drilling process where the drill bit is repeatedly retracted and re-entered into the hole in small increments (or "pecks") during the drilling operation. This method helps to break up chips, reduce heat buildup, and prevent clogging—especially useful when drilling deep holes or working with materials that produce long, continuous chips (Kalpakjian & Schmid, 2014)

2.3.2.3. Orbital Drilling

Orbital drilling integrates rotational and orbital motions of the tool to reduce thrust force and enhance hole quality. This method is especially effective for layered materials like HFRP, minimizing delamination, fiber pull-out, and burr formation. It has been widely adopted in the aerospace industry due to its superior performance in composite drilling (Wikipedia, 2024c)

2.3.2.4. CNC Drilling

CNC drilling is a computer-controlled machining process in which drill bits are guided automatically by a programmed code (G-code) to produce holes with high accuracy and repeatability. It is commonly used in manufacturing environments for producing holes in metal, plastic, and composite components, and it allows for automation of complex hole patterns, multi-axis operations, and minimal human intervention (Kalpakjian & Schmid, 2014).

2.3.3. Types of Drilling Tool Bit for Drilling of HFRP Material

A **drilling tool bit** is a cutting tool used to create cylindrical holes in a workpiece by rotating and advancing along its axis. It typically consists of a pointed tip, cutting edges (lips), flutes for chip removal, and a shank for mounting in the drill spindle. The geometry, material, and coating of the drill bit are selected based on the workpiece material and desired hole quality (Kalpakjian & Schmid, 2014).

Figure 2.8: Tool Drill Bits Used in Drilling of Composites (https://www.onsrud.com/Series/Drillsforcomposites.asp)

2.3.3.1. W-Point

Known for its great power of making clean, precise holes with very little tear-out, W-Point drill bits are also called Brad Point bits as shown in Figure 2.9. Their design includes a center spur that helps keep the drill bit exactly where it should be, preventing it from slipping when it touches the surface. This makes them really helpful when you need to drill overlapping holes. If the bit is tipped with carbide, it can also handle tough materials like fiberboard, plastics, laminates, chipboard, and glued wood. These bits are also known as Dowelling Bits or Lip and Spur Bits.

Figure 2.9: W-point drill (https://www.onsrud.com/Series/85-800.asp)

2.3.3.2. Dagger Drill

Making a choice for drilling into un-backed CFRP materials like carbon, graphite, and glass fiber composites, the Dagger Drill is a reliable one as shown in Figure 2.10. Thanks to its smart geometry and point design, it helps reduce delamination and consistently delivers clean, precise holes in these tough materials.

The Dagger Drill stands out for its versatility, as it works well in both manual and CNC setups, making it a reliable option for machining carbon fiber parts in different industries. It's suitable for use in bushing, free-hand, and CNC drilling, which makes it especially useful when working with composite materials (AP Tools Ltd, 2024).

Figure 2.10: Carbide Dagger Drill (https://www.panamericantool.com/carbide-dagger-drills.html, 2024)

2.3.3.3. Step Drill

Materials such as metal, plastic, and wood up to 4 mm thick, and stainless steel up to 1.5 mm use a highly versatile tool as step drills. As shown in Figure 2.11, they're especially effective when used with the CBN grinding process, which helps create precise measuring and shear cutting edges. CBN-treated materials become harder, allowing for smoother and more efficient cutting through the body material.

Designed with a point angle and point thinning, step drills help to center and start the cut in the workpiece. Once the drill pierces the material, two or three cutting edges begin working at once, removing material while smoothly guiding chips along the groove. This leads to clean, burr-free holes with sharp edges. The step angle usually around 90° marks the change between steps and also allows the tool to chamfer or de-burr the hole for a neater finish.

Step drills are available in many types, usually made from strong tool steel like HSS or HSSE-Co 5. Some are also coated with materials such as TiN or TiAlN, which help improve cutting performance and make the drills more durable over time (RUKO, 2017).

Figure 2.11: step drill bit (https://my.rs-online.com/web/p/specialist-drill-bits/1238511)

2.3.3.4. Twist Drill

To deliver different tasks, twist drills have typically been made with fixed point shapes like conical or cylindrical. With the improvements in CAD technology, we can now design drill points more freely. This means drills can have custom-shaped points that meet multiple goals and fit a range of applications (Sambhav et al., 2012). Since the drill point is the first part to touch the workpiece, its shape is incredibly important. As shown in Figure 2.12, it plays a major role in the tool's overall performance (Sambhav et al., 2010).

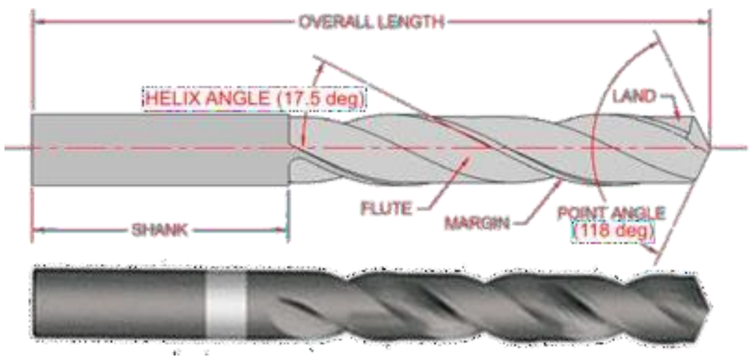


Figure 2.12: Twist Drill (https://wiki.dtonline.org/index.php/Twist_Drills)

2.3.4. Drilling tool Geometry

A drill bit shape and angles of play an important role in how well it performs during cutting. Angles like the point angle and helix angle affect how the tool cuts and handles force. Finding the right balance between cutting strength and efficiency means adjusting these angles based of the type of material you're working with, the tool material, and the shape of the part.

Using the correct drill bit geometry is crucial, as it significantly extends tool life, enhances surface finish, and increases machining efficiency. However, using the wrong geometry can lead to rapid tool wear, poor surface quality, reduced productivity, and misaligned or inaccurate holes that may not meet dimensional or positional requirements.

Using poorly designed drill bits can make production more expensive, create a lot of waste and scrap, and slow things down. That's why it's so important to choose the right tool geometry it directly affects how well the drilling process goes and whether you get the results you want (ToolingU, 2024; Turnad & Bambang, 2014).

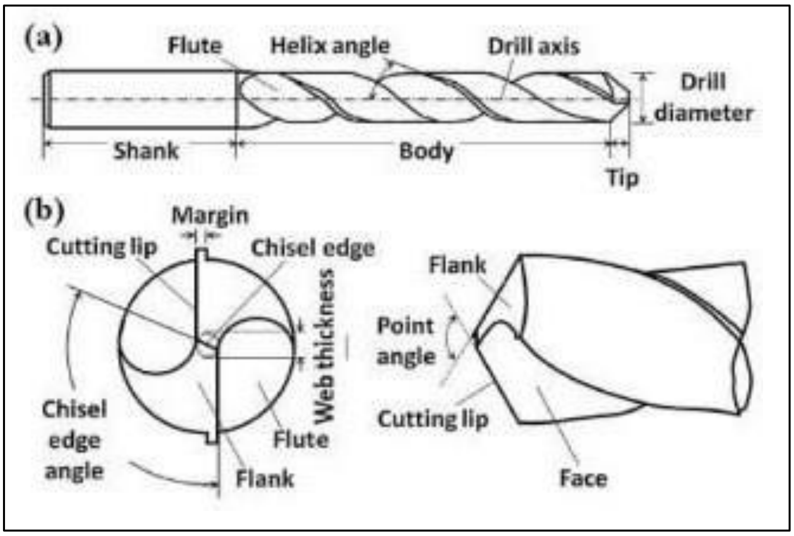


Figure 2.13: Drill bit geometry (a) twist drill bit (b) drill bit tip(Turnad & Bambang, 2014)

When drilling materials with unknown cutting behavior, having the wrong drill geometry or settings can make things worse. It can lead to too much vibration, which increases the cutting force and causes tools to wear out faster. This also makes the surface rougher and the final dimensions less accurate (Chaudhari & Kumar, 2018).

The drill tool’s shape really matters when it comes to how much thrust force is needed during drilling. Figure 2.14 shows that the point angle doesn't change the thrust force much if the drill is still sharp. But once the tool starts to wear out, it affects the force more. Also, when the feed rate goes up, the thrust force increases too—between 50 and 150 N in the tests. Interestingly, the cutting speed doesn’t seem to make a big difference in how much force is needed (Feito et al., 2014).

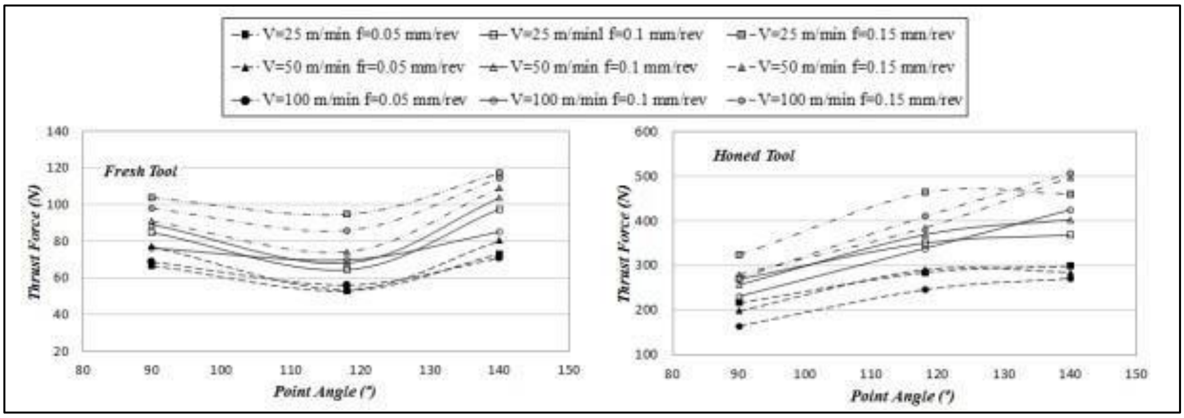


Figure 2.14: Thrust force variation for point angles (Feito et al., 2014)

2.4. Machine Parameters

To drill composite materials effectively, it's important to fully understand how key parameters like spindle speed, feed rate, and drill bit characteristics including shape, material, and coatings affect the process. These factors can impact the smoothness of the hole surface, the amount of thrust force generated, and the extent of mechanical or thermal damage, including delamination and tool wear (Khashaba, 2013). The levels of thrust and torque produced during drilling are also strongly influenced by the overall machining setup such as the cutting speed, tool design, and how rigid the machine and cutting tool are (Rodrigues et al., 2012).

Factor	level 1	level 2	level 3
Speed (rpm)	900	1200	1500
Feed (mm/min)	75	110	150
Drill diameter (mm)	6	8	10
Material thickness (mm)	8	10	12
Drill point angle (º)	90	103	118

Table 2.1: Selection of Machining Parameters (R Rodrigues et al., 2012)

Researchers drilled holes into synthesized composite materials using different settings for speed, drill diameter, and feed rate. They found that the best combination for minimizing both thrust force and torque was 2000 rpm, a 4 mm drill bit, and a feed rate of 50 mm/min. To reduce delamination, the most effective setup was a faster speed of 3000 rpm, a larger 8 mm drill bit, and the same 50 mm/min feed. Based on ANOVA analysis, drill diameter and speed had the most influence on delamination, while drill diameter and feed were more critical for controlling thrust force and torque (Upputuri & Nimmagadda, 2020).

In their study, Professor et al. (2017) explored how different drilling parameters—spindle speed, feed rate, and drill geometry—affect the delamination and surface finish of GFRP composites. Using Grey Relational Analysis, they found that spindle speed had the biggest impact, while the drill's point angle played the smallest role. Thomas (2005) also looked into how drilling settings affect composite materials, and the results are shown in Table 2.2:

Machining parameters	Level 1	level 2	level 3
A Speed (rpm)	1000	2000	3000
B Point angle (º)	100	118	135
C Feed Rate(m/min)	0.05	0.1	0.15

Table 2.2: Machine Parameters for Drilling (Thomas,2005)

Levels	Spindle Speed (rpm)	Feed Rate (mm/rev)
1	318	0.05
2	637	0.1
3	955	0.15
4	1273	0.2

Table 2.3: Machine Parameters for Drilling (Sanad Abdulkareem Ismael1 and Majid Habeeb Faidh Allah2,2023)

In their investigation, the authors examined how drilling parameters—specifically spindle speed and feed rate—affect the delamination factor during the machining of 5 mm thick Hybrid Fiber Reinforced Polymer (HFRP) composites. Using a Taguchi design with an L16 orthogonal array, they identified feed rate as the most influential parameter, with a notable impact compared to spindle speed. The optimal drilling condition resulted in a minimum delamination factor of 1.304, achieved at a spindle speed of 1273 rpm and a feed rate of 0.05 mm/rev. Conversely, the highest delamination factor recorded was 1.496, occurring at a spindle speed of 318 rpm and a feed rate of 0.20 mm/rev.

In drilling, Machine Process Settings (MPS) refer to the machine's adjustable controls that help improve how well and efficiently the operation is carried out. The cutting speed is calculated using the formula where π stands for the circular constant, DC is the drill's diameter, and n represents the spindle speed.

Cutting Speed

$$v_c = \frac{\pi \times DC \times n}{1000} m/min$$

2.4.1. Spindle Speed.

Spindle speed is essentially how fast the cutting tool spins, and it's usually measured in RPM or SFM. This setting affects how quickly the tool's edges meet the material and how much force is applied during drilling. Running the spindle faster gives more cutting action in less time but can cause vibrations and noise that hurt accuracy and finish. Slower speeds reduce those issues, which can help produce cleaner, more precise results.

Formula:

$$n = v_c \div \pi \div D \times 1000$$

2.4.2. Feed Rate

Feed rate basically tells you how fast the tool moves into the material while it's cutting. In operations like turning or boring, it's usually measured per revolution like how far the tool moves for every spin. In milling, it might also be measured that way, but it's more often given as a speed over time, like millimeters per minute. When you're using this time-based method, the number of cutting edges on the tool matters because each one takes a bit of the load.

Formula:

$$Vf = n \times fz \times z$$

Vf = Cutting speed (m/min)

fz = Feed per tooth (mm/tooth)

Z = Number of flutes

Some researchers have found that drilling works better with higher spindle speeds and lower feed rates. However, others point out that the best settings really depend on what the composite is made of, especially the type of fiber and matrix. Also, the kind of drill used, like HSS, solid carbide, or tungsten carbide, can make a big difference in the final hole quality.

In short, these studies make it clear that to get clean, high-quality holes and avoid damaging the material, it's essential to carefully adjust the drilling settings to match the unique features of the HFRP composite being used.

The key research papers and theses on composites like CFRP, HFRP, and GFRP were carefully reviewed.

2.5. Drilling Performance

The surface finish of machined parts is significantly influenced by machine parameters such as spindle speed, feed rate, and cutting depth. Geier and Pereszlai (2020) investigated how variations in these parameters affect surface roughness by conducting experiments using two surface roughness evaluation methods: a contact profilometer and a confocal microscope. Their study demonstrated that changes in machining conditions had a measurable impact on the final surface quality. This underlines the importance of selecting appropriate machine parameters to achieve the desired surface finish.

2.5.1. Hole Quality Assessment

Ensuring high hole quality is key when making tight-tolerance holes for aircraft assembly. This quality is judged by factors like delamination, hole diameter, and circularity. Ashrafi and colleagues (2016b) studied how different drilling feed and speed settings affect fiber pull-out shapes and the overall hole quality in CFRP composites.

When drilling, heat builds up in the cutting area, increasing the temperature of the workpiece and causing it to distort due to the different ways fibers in the laminate expand with heat, especially near the bottom surface. To understand this, a model was developed to predict how thermal distortion affects the drill and the holes specifically their size and roundness when dry drilling. Experiments showed that this model does a good job of predicting how heat moves into both the drill and the workpiece.

2.5.2. Thrust Force

During drilling of FRP composites, the feed rate plays a key role in how much thrust force is generated. As feed rates go up, so does the thrust force, which is shown clearly in Figure 4 for three different drill point angles. When the feed rate was pushed to the maximum, the thrust force jumped by over 50%. Using smaller drill point angles helps keep the thrust force lower, which reduces the chances of delamination (Maoinser et al., 2014).

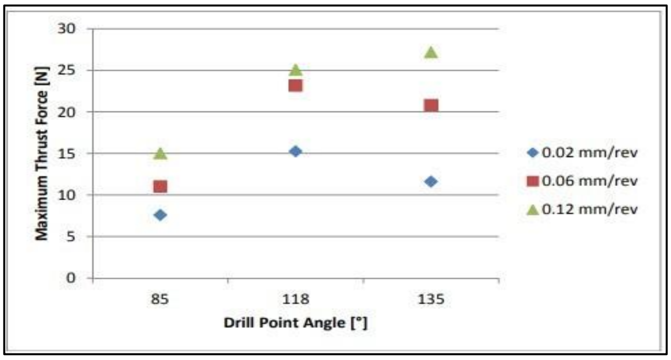


Figure 2.15: Effect of drill point angle on maximum thrust force. (Maoinser et al., 2014)

Durão and colleagues looked at how different drill point angles and feed rates affect drilling in carbon fiber-reinforced laminates. They found that using a 120° drill point resulted in the least amount of delamination when drilling at higher feed rates. The study also showed that as the feed rate goes up, the thrust force increases significantly.

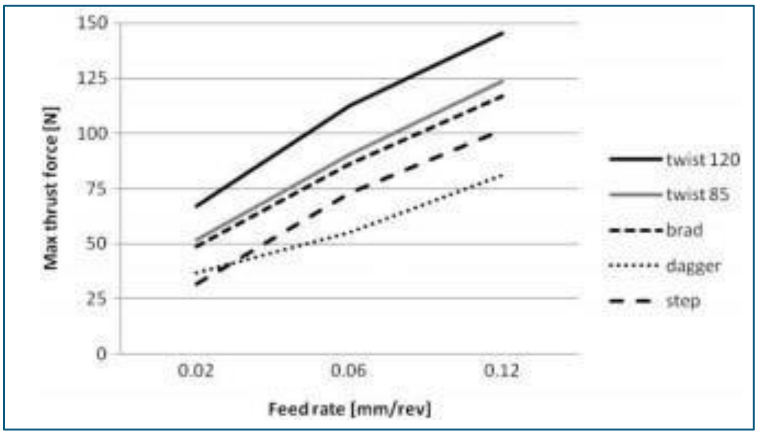


Figure 2.16: Feed rate effect on maximum thrust force (Rakesh et al., 2012)

2.5.3. Tool Wear

Tool wear refers to the gradual alteration of a tool's geometry, which can significantly degrade the surface quality of the machined part. This effect is particularly pronounced in fiber-reinforced polymer (FRP) materials. Unlike conventional metals, FRPs exhibit distinct surface defects due to tool wear, largely because of their anisotropic structure. The interlaminar bonding strength in FRPs is considerably lower than their fracture strength, making them more susceptible to surface defects such as delamination during machining.

As the cutting tool wears and the cuttings edge radius increases, it becomes more difficult to cleanly sever the fibers, often resulting in uncut or frayed fibers on the machined surface (Bi et al., 2022). Furthermore, the wear patterns caused by burr formation or tool workpiece interlocking are complex, typically involving a combination of tip chipping and flank wear, which further exacerbates surface imperfections.

The most commonly observed tool wear when machining FRP are abrasive wear, flank wear, chipping and so on. (Knápek et al, 2023). As shown in figure 2.17, and figure 2.18.

Figure 2.17: Flank wear (Ahmad, 2009)

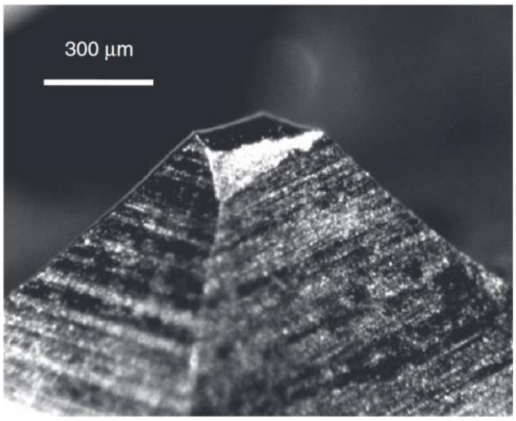


Figure 2.18: Chipping wear (Ahmad, 2009)

2.5.4. Delamination

Along the fiber direction delamination in composites happens and it moves through two stages: the chisel-edge action phase and the cutting-edge action phase. The first stage starts when the thrust force from the chisel edge on the material's exit surface hits a critical point and continues until the chisel edge completely goes through the plate. Knowing these stages well is important for reducing delamination and keeping drilled composite parts strong and reliable.

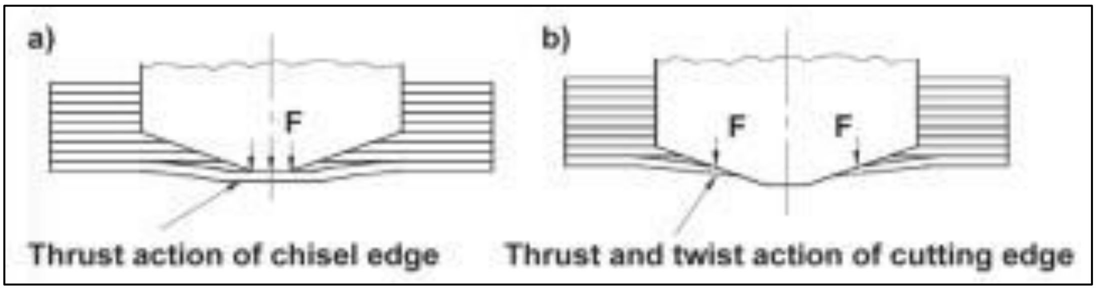


Figure 2.19: Development of Delamination (Sedlacek & Slany, 2019)

Delamination during drilling mainly happens in two ways: peel-up delamination at the hole's entry and push-out delamination at the hole's exit. Peel-up delamination happens because the combination of drilling torque, flute shape, and helix angle causes the drill to vibrate, which means the top layer fibers aren't cut cleanly. As a result, the fibers get pulled up at the hole entry, causing delamination.

Push-out delamination happens at the hole's exit and is caused by the drill bit pushing against the remaining material as it nears the exit surface. If the thrust force becomes stronger than the material's bonding strength between layers, the layers separate, leading to delamination at the hole exit.

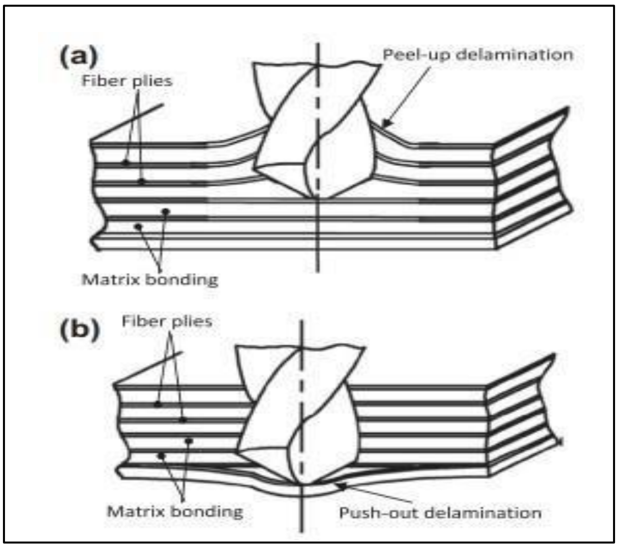


Figure 2.20: Delamination mechanics (peel-up delamination) and (push-out delamination) (Liu et al., 2012)

The effect of drill point angle on delamination in HFRP composites was explored in a study by Ho-Cheng and Dharan (1990). They found that when drilling at low feed rates (0.02 and 0.06 mm per revolution), the drill point angle didn't greatly affect delamination at the hole's entrance or exit. But when the feed rate increased to 0.12 mm per revolution, the drill point angle became important in reducing delamination at both the entrance and exit of the hole.

The authors found that lower delamination in HFRP composites are product of the use of a smaller drill point angle since it results in less thrust force during drilling. This lower thrust force makes delamination less likely, particularly when drilling at higher feed rates. These results highlight why it's important to pay attention to both the drill point angle and feed rate to prevent delamination and ensure strong, accurate holes in HFRP composites.

Maoinser and colleagues explored on a study in 2014 how feed rate and drill point angle impact thrust force and delamination in HFRP composites. They found that using a low feed rate and a smaller drill point angle helps reduce the maximum thrust force during drilling, which effectively minimizes delamination in these materials.

The researchers discovered the drill point angle didn't really impact delamination such that at low feed rates, such as 0.02 mm/rev and 0.06 mm/rev, because the thrust force stayed under the critical level. But when the feed rate went up to the highest value tested, delamination increased as thrust force grew, no matter what drill point angle was used.

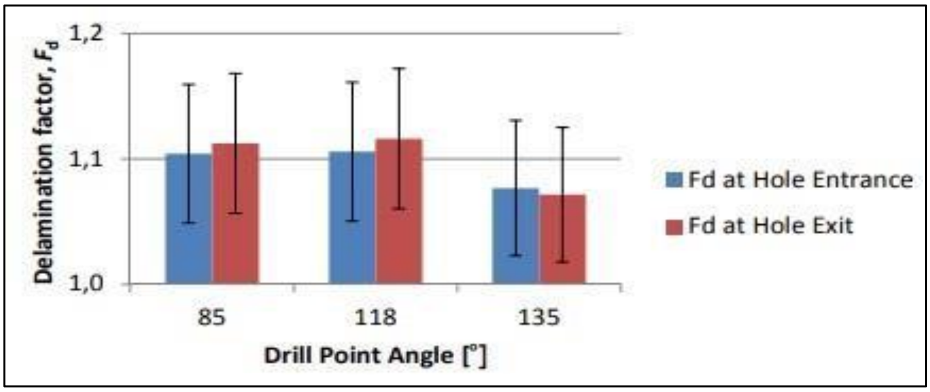


Figure 2.21: Drilling of 0.02 mm/rev of feed rate (Maoinser et al., 2014)

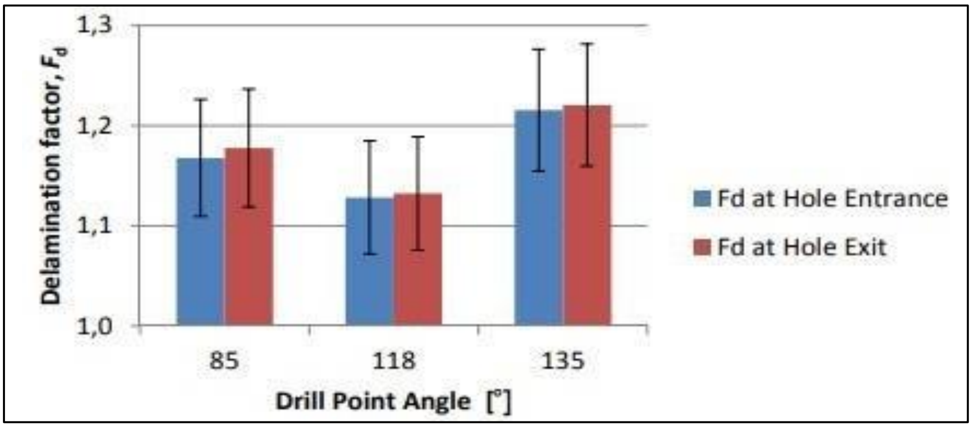


Figure 2.22: Drilling of 0.06 mm/rev of feed rate (Maoinser et al., 2014)

The investigation demonstrated that employing a smaller drill point angle significantly lowers the thrust force, thereby decreasing delamination at elevated feed rates relative to larger drill point angles. These findings underscore the critical role of optimizing drilling parameters, including feed rate and drill point angle, to mitigate thrust force and delamination in the machining of HFRP composite laminates.

2.5 Design of Experiment Method (DOE)

structured statistical method used to investigate the relationship between multiple input variables and their effects on one or more output responses. It enables researchers and engineers to systematically plan and conduct experiments by varying several factors simultaneously, rather than one at a time, which improves efficiency and accuracy. The primary goal of DOE is to identify the most influential factors, understand interactions between them, and determine optimal conditions that lead to improved performance, quality, or productivity. This approach is especially valuable in complex processes like composite material machining, where multiple parameters interact in unpredictable ways. By using DOE, one can minimize trial-and-error, reduce costs, and make data-driven decisions that lead to more consistent and reliable outcomes.

2.5.1. Taguchi Method

The Taguchi Method is a structured approach to experimental design that focuses on improving quality and performance by making products and processes robust against variations, especially those caused by uncontrollable factors. It utilizes orthogonal arrays to study the effect of multiple process parameters efficiently, minimizing the number of required experiments. A defining feature of the method is the use of Signal-to-Noise (S/N) ratios, which help quantify and optimize the consistency of a system's performance under varying conditions. In manufacturing applications such as the drilling of Hybrid Fiber Reinforced Plastics (HFRPs), the Taguchi method aids in identifying optimal settings such as feed rate, spindle speed, and drill geometry to reduce defects like delamination and tool wear. While it is not ideal for detecting complex interactions among variables, it is widely appreciated for its simplicity, cost-effectiveness, and practical implementation in industrial settings (Taguchi & Konishi, 1987, Montgomery, 2017).

$$\frac{S}{N} = -10\ log\frac{1}{n}(\Sigma y^2)$$

Where y is the observed response value and n is several replications.

2.6. Summary

The optimization of twist drill tool geometry is critical for mitigating damage during the drilling of hybrid fiber-reinforced polymer (HFRP) panels. Essential factors include drill point angle, helix angle, spindle speed, and feed rate. Drill point angles ranging from 80° to 120° and helix angles between 25° and 30° have been shown to reduce thrust force and delamination. Operating at moderate spindle speeds of approximately 1500 rpm and low feed rates of 0.02 to 0.08 mm/rev further enhances surface finish and minimizes delamination. Solid carbide twist drills, particularly those coated with TiN or TiAlN, exhibit superior wear resistance. Employing design of experiments (DOE) methodologies, such as the Taguchi method integrated with statistical analysis, facilitates the determination of optimal parameter settings to achieve desired hole quality while minimizing deleterious effects like delamination, surface roughness deterioration, and tool wear during the drilling of HFRP panels.

Table 2.4: Summary of tool geometry by previous research in Drilling of CFRP, GFRP, FRP and HFRP.

Citation	Point Angle	Helix Angle	Type Drill	Drill Size (mm)
(Jagadeesh et al., 2023)	85,115,130	25,30	Din 8038 rn	5
(Natarajan et al., 2022)	80,100,120 (89,120)	30	Tungsten Twist Drill	8
(J. H. Lee et al., 2021)	90	25	Uncoated Tungsten Solid carbide Brad Spur	6
(Jagannatha et al., 2019)	128,132	25,28,30	Coated Solid Carbide	6 8 10
(Xu et al., 2019)	118,118,140	25,35,38	Solid Carbide	0.3 0.4 0.5
(Qiu et al., 2019)	118,120,130	25,27,30	Brad Spur	8 5
(Sugita et al., 2018)	118,125,130	20,25,30	Solid carbide	6

(Satyanarayana & Krishna Prasad, 2016)	100,118,135	20,25,30	Tungsten carbide	6
(Feito et al., 2015)	80,120,130	20,25,30	HSS	6
(Maoinser et al., 2010)	85,118,135	25	Tungsten carbide drill	6
(Campos Rubio et al., 2008)	85,118	30	Carbide Brad	6

Table 2.5: Overall Drilling Parameters used by Researchers

Papers	Spindle speed (RPM)	Feed Rate (mm/rev)	Drill Size (mm)	Type Drill	Fiber
(Abdulkareem Ismael & Habeeb Faidh Allah, 2023)	1000	0.02 0.06 0.08 0.12 0.05	6	Coated Tungsten Twist Drill	CFRP
(Rampal et al., 2022)	800	0.03 0.06 0.09 0.12	6	Twist	CRFP
(Rampal et al., 2022)	500	0.04 0.08 0.12	6 8 10	HSS	GFRP
(Natarajan et al., 2022)	1200	0.2 0.3	6	Tungsten carbide conventional twist	CFRP

				drill	
(Maoinser et al., 2017.)	1100	0.02 0.06 0.12	6	Solid carbide Twist	CFRP
(Kavad et al., 2014)	1400	0.06 0.12	8 5	HSS	GFRP
(Durão et al., 2013)	1400	0.05 0.20 0.025	6	Tungsten carbide drill	GFRP

CHAPTER 3

METHODOLOGY

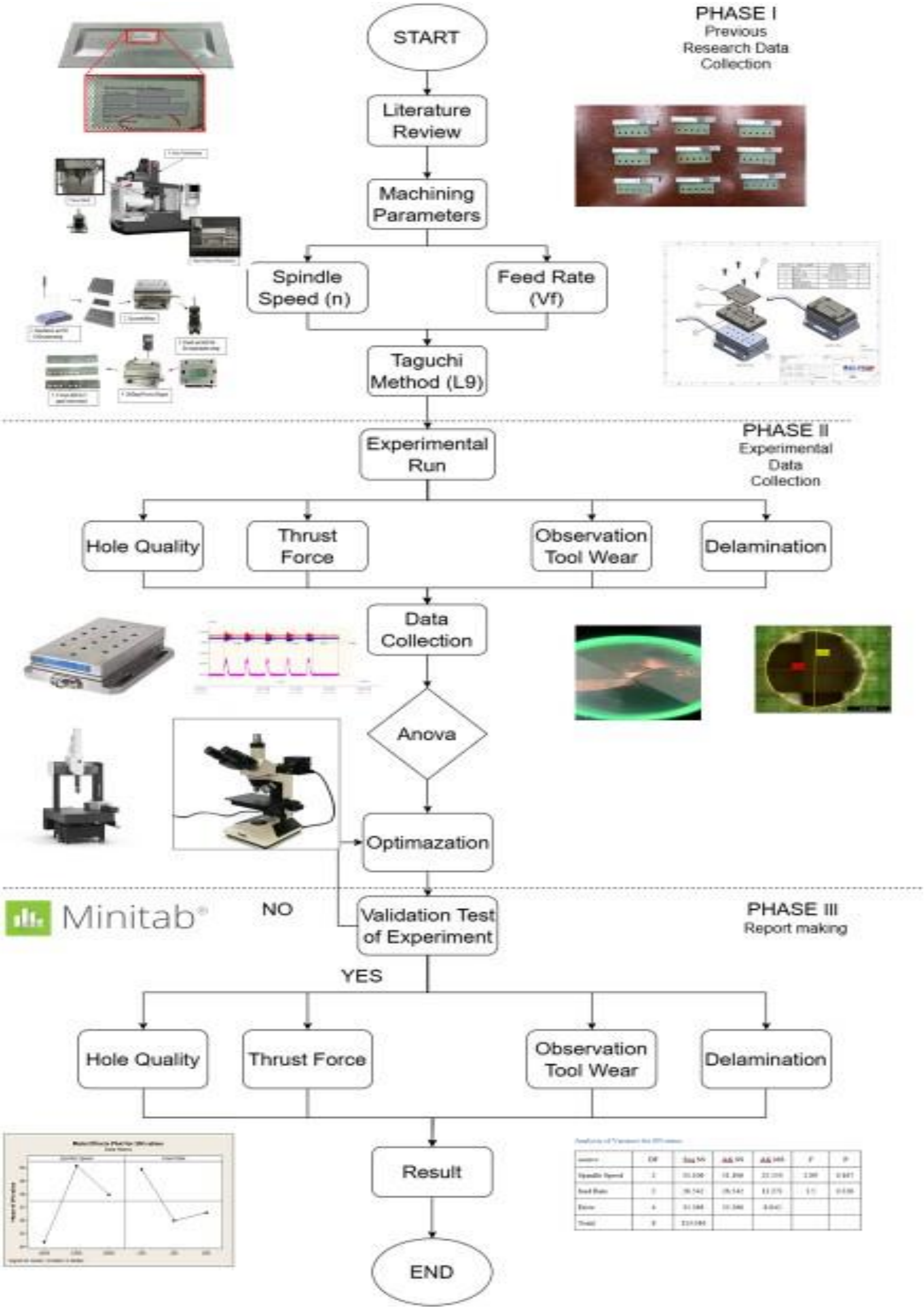
3.1. Introduction

This chapter presented the research methodologies employed in the study, underscoring the fundamental importance of research methodology within the context of scholarly investigation. Research methodology referred to the systematic and structured planning and implementation of research activities to produce valid and reliable findings that effectively addressed the research aims, objectives, and questions.

At the start of this project, a detailed understanding of the basic concepts, theories, experiments, and essential information about drilling Hybrid Fiber Reinforced Polymer (HFRP) materials was explained. The project focused on discovering new factors related to the tool bit's geometry, studying how the tool bit performed with HFRP, looking into the tool bit's material properties, and investigating drilling machining parameters. It also considered how the workpiece was held in place using jigs and fixtures.

The focus shifted to the experimental procedure in the second phase. Data needed for the experiments were gathered from previous studies to make the experimentation easier. The main measurements to be collected were delamination, drilling temperature, thrust force, holes quality and tool wear. Delamination and circularity were assessed with the Shodensha GR3400 and Coordinate Measuring Machine (CMM) on the drilled HFRP panels. The drilling itself was performed on the Haas CNC Machine with Kistler Dynamometer attached and Nikon MM-800 Microscopy for tool wear.

3.2. Flow Chart of The Process



3.3. HFRP Material Detail

This study centered on evaluating the performance of Hybrid Fiber Reinforced Polymer (HFRP) materials, with a particular emphasis on their application in the aerospace industry. The material was provided by Aerospace Composite Malaysia (ACM) Sdn. Bhd. and shown in Figure 3.1, was intended to support innovation in composite manufacturing. The panel used in this study had a cross-plied quasi-isotropic stacking sequence, made up of 19 layers, including one aluminum ply. Table 3.1 gave a breakdown of the stacking arrangement, including how the honeycomb core was integrated into the material.

Table 3.1: Ply Sequence table of HFRP panel

	MATERIAL	ORIENTATION	#
1	SURFACING FILM (BMS8-341 TYPE 3)	-	
2	EROSION STRIP	-	
3	ADHESIVE FILM (BMS8-145)	-	
4	FIBERGLASS (BMS8-139-120-1)	0/90	P1
5	FIBERGLASS (BMS8-139-120-1)	0/90	P2
6	FIBERGLASS (BMS8-139-120-1)	0/90	P3
7	FIBERGLASS (BMS8-139-7781-1)	0/90	P4
8	FIBERGLASS (BMS8-139-7781-1)	0/90	P5
9	HONEYCOMB CORE BMS8-124		
10	ADHESIVE (BMS8-145)		
11	FIBERGLASS (BMS8-139-7781-1)	+/-45	P6
12	FIBERGLASS (BMS8-139-7781-1)	+/-45	P7
13	FIBERGLASS (BMS8-139-7781-1)	+/-45	P8
14	FIBERGLASS (BMS8-139-7781-1)	+/-45	P9
15	FIBERGLASS (BMS8-139-7781-1)	0/90	P10
16	FIBERGLASS (BMS8-139-7781-1)	0/90	P11
17	FIBERGLASS (BMS8-139-120-1)	0/90	P12
18	FIBERGLASS (BMS8-139-120-1)	0/90	P13
19	FIBERGLASS (BMS8-139-120-1)	0/90	P14
20	ALUMINUM FOIL	-	P15

Figure 3.1: HFRP panel from Boeing Composites Malaysia

3.4. Drill Geometry Details

After reviewing relevant studies and academic sources, the geometry and material properties of the drill bits for this project were carefully chosen. The focus was mainly on the chisel and helix angles, as these were key factors affecting drilling quality. From the literature, a suitable range of tool geometries was identified. To explore this further, nine different tool bits with varied geometries were tested during the experiment to find the best-performing drill bit for HFRP panel applications.

The data were gathered from previous studies on drill tool geometry. The review showed that point angles commonly ranged from 80° to 140° and helix angle from 20° to 38° (Table 3.2), but for this research, a point angle of 118° and a helix angle of 30° were selected for testing.

To align with tools readily available in the market, several tool geometry parameters were standardized. These included an overall length of 66 mm, flute length of 40 mm, neck length of 12 mm, and a neck diameter of 6 mm, with a twist flute design. The tool chosen for this study was an uncoated tungsten carbide twist drill with a diameter of 6 mm.

Table 3.2: Summary of tool geometry by previous research in Drilling of CFRP, GFRP, FRP and HFRP.

Citation	Point Angle	Helix Angle	Type Drill	Drill Size (mm)
(Jagadeesh et al., 2023)	85,115,130	25,30	Din 8038 rn	5
(Natarajan et al., 2022)	80,100,120 (89,120)	30	Tungsten Twist Drill	8
(J. H. Lee et al., 2021)	90	25	Uncoated Tungsten Solid carbide Brad Spur	6
(Jagannatha et al., 2019)	128,132	25,28,30	Coated Solid Carbide	6 8 10
(Xu et al., 2019)	118,118,140	25,35,38	Solid Carbide	0.3 0.4 0.5
(Qiu et al., 2019)	118,120,130	25,27,30	Brad Spur	8 5
(Sugita et al., 2018)	118,125,130	20,25,30	Solid carbide	6
(Satyanarayana & Krishna Prasad, 2016)	100,118,135	20,25,30	Tungsten carbide	6
(Feito et al., 2015)	80,120,130	20,25,30	HSS	6
(Maoinser et al., 2010)	85,118,135	25	Tungsten carbide drill	6

(Campos Rubio et al., 2008)	85,118	30	Carbide Brad	6

3.5. Jig and Fixture Preparation

A properly designed fixture was crucial for holding the HFRP material in place during drilling, helping to eliminate any errors outside the scope of the experiment itself. Its main job was to stabilize the material so that drilling could be done accurately and consistently. In this study, the fixture was tailored to ensure the material was aligned and fixed in the correct position using a top and bottom plate, as illustrated in Figure 3.2. This setup ensured reliable results by preventing movement or misalignment throughout the drilling process.

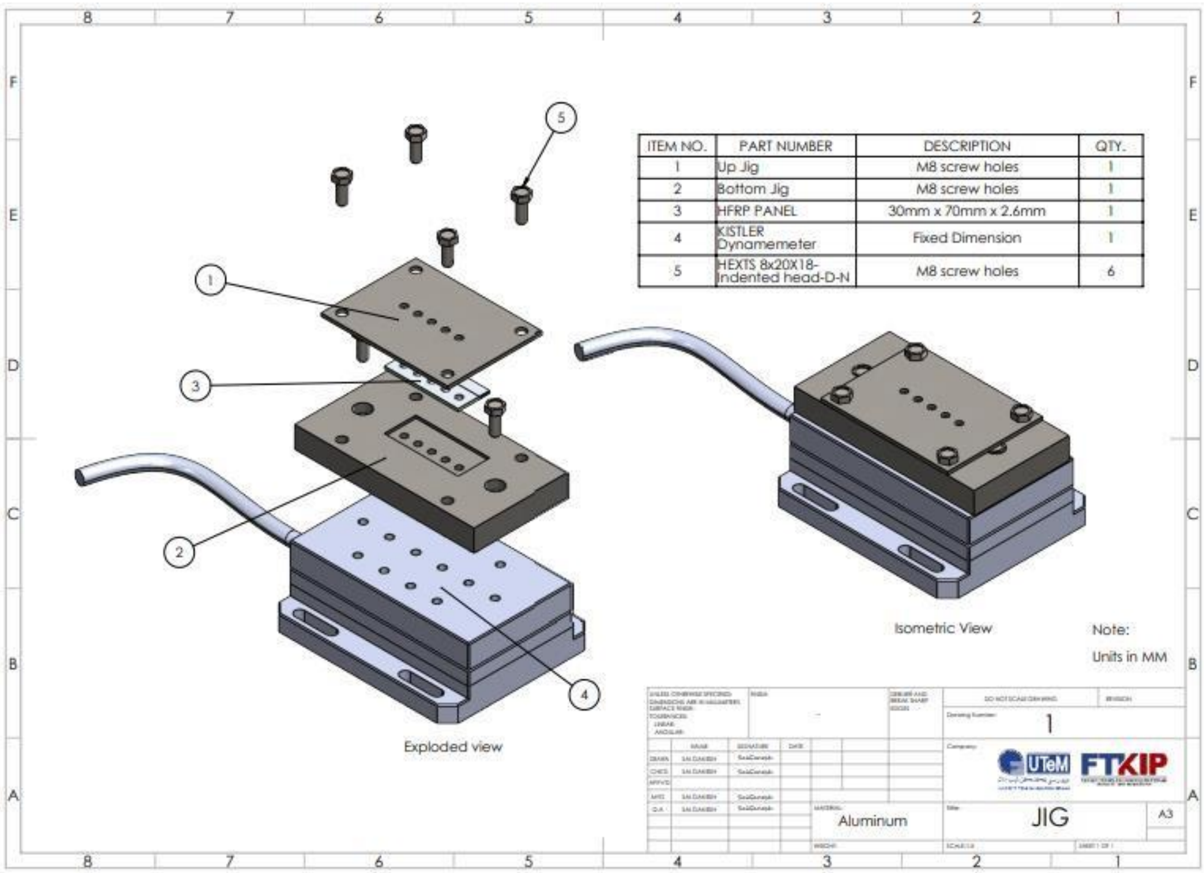


Figure 3.2: Fixture of HFRP material

3.6. Machine Setup

For this research, the Haas CNC vertical milling machine (Figure 3.4) was employed due to its high precision, robust construction, and advanced automation capabilities. Known for its reliability in industrial and research environments, the Haas CNC machine offered excellent repeatability and control over drilling parameters such as spindle speed, feed rate, and tool path. To enhance experimental accuracy, the machine was integrated with a Kistler 9257B multi-component dynamometer (Figure 3.3), enabling real-time measurement of cutting forces during drilling operations. This high-sensitivity piezoelectric system allowed researchers to capture thrust force, torque, and lateral loads with precision. The data acquired through the Kistler software interface was essential for evaluating drilling-induced damage in HFRP composites, including delamination and tool wear, making this setup highly effective for optimizing machining conditions.

Figure 3.3: Kistler 9257B multi-component dynamometer (https://ampl.mech.northwestern.edu/facilities/facilities-dynamometers.html)

Figure 3.4: Haas VF-1 CNC Machine

Running a machining operation on the Haas VF-1 CNC Machine involved a few key setup steps. The drilling program was first created in Catia software, as shown in Figure 3.5, and then processed in Siemens software to generate the NC Code. Once everything was set up properly, the machine could carry out the drilling procedure by following the correct operating protocol.

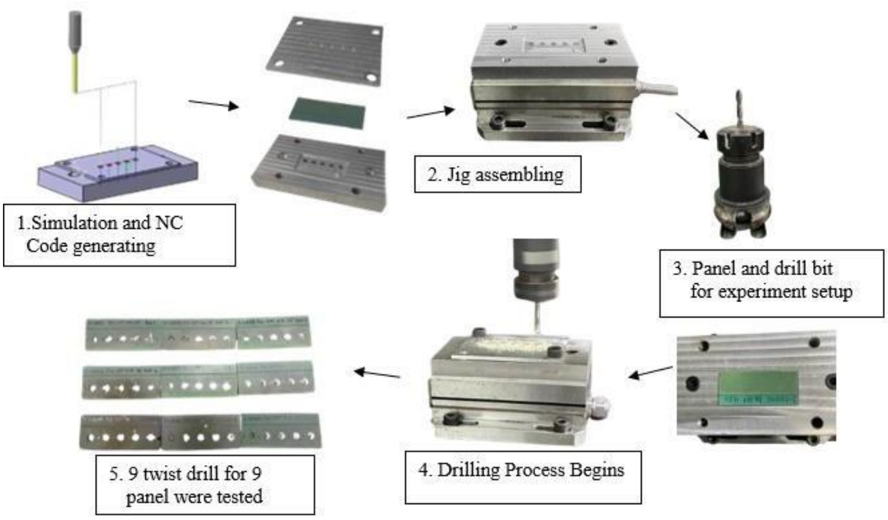


Figure 3.5: Example of Drilling operation illustration

3.7. Machining Parameter for Drilling

Machining parameters like spindle speed and feed rate could greatly affect the drilling quality of HFRP materials, especially when it came to delamination, surface finish, and circularity. That's why it was important to find the right combination of these parameters. Based on previous studies (Table 3.3), this research identified the most used and effective machining values. The final setup (Table 3.4) for this experiment used spindle speeds between 1000,1500 and 2000 RPM and feed rate from 100,150, and 200 mm/min

Table 3.3: Overall Drilling Parameters used by Researchers

Papers	Spindle speed (RPM)	Feed Rate (mm/rev)	Drill Size (mm)	Type Drill	Fiber
(Abdulkareem Ismael & Habeeb Faidh Allah, 2023)	1000	0.02 0.06 0.08 0.12 0.05	6	Coated Tungsten Twist Drill	CFRP
(Rampal et al., 2022)	800	0.03 0.06 0.09 0.12	6	Twist	CRFP
(Rampal et al., 2022)	500	0.04 0.08 0.12	6 8 10	HSS	GFRP
(Natarajan et al., 2022)	1200	0.2 0.3	6	Tungsten carbide conventional twist drill	CFRP
(Maoinser et al., 2017.)	1100	0.02	6	Solid carbide	CFRP

		0.06 0.12		Twist	
(Kavad et al., 2014)	1400	0.06 0.12	8 5	HSS	GFRP
(Durão et al., 2013)	1400	0.05 0.20 0.025	6	Tungsten carbide drill	GFRP

Table 3.4: Drilling Parameters for this research

Spindle Speed (RPM)	Feed Rate(mm/min)
1000	100
1000	150
1000	200
1500	100
1500	150
1500	200
2000	100
2000	150
2000	200

This study used a calculation method to figure out the most suitable drilling parameters to fine-tune the cutting conditions for routing HFRP panels. The focus was on two important aspects: speed (N) and feed rate (Vf). With the help of specific formulas, the theoretical target values for both parameters were identified and used to set the foundation for the experimental setup.

With the help of specific formulas, the theoretical target values for both parameters were identified and used to set the foundation for the experimental setup.

Spindle Speed Formula:

$$N = (Vc \div \pi \div D) \times 1000$$

Feed Rate Formula:

$$Vc = \frac{\pi \times D \times N}{1000}$$

The equation provided served as a manual approach for calculating the machining parameters applicable to the drilling of HFRP materials. Prior to conducting these calculations, essential attributes of the tool bit and machine had to be specified. It was important to recognize that the outcomes derived from this method represented estimated values and might not directly correspond to the optimal conditions required for experimental validation. As such, empirical testing was required to refine and confirm the suitability of these theoretical values for actual drilling operations.

3.8. Signal-To-Noise Ratio

This formula was used to calculate the Smaller is Better S/N ratio:

$$\frac{S}{N} = -10 \times log \frac{\sum y^2}{n}$$

Where:

- y represents measured surface roughness values
- n is number of observations or experimental runs

This analysis focused on finding the best combination of drilling parameters that would minimize surface roughness and ensure consistent results. By using the “Smaller is Better” S/N ratio criterion in Minitab’s Taguchi analysis, the study targeted identifying the ideal point angle and helix angle settings. Minitab not only provided the S/N ratios for each test run but also visual tools like main effects and interaction plots. These visuals helped in clearly seeing how each factor affected surface roughness. Most importantly, Minitab suggested the best factor combinations to achieve the smoothest surface finish, making it easier to choose the right drilling settings.

3.9. Delamination Analysis

Delamination was a critical defect commonly observed during the drilling of composite materials, arising from the interaction between drill tool geometry and machining parameters. This phenomenon compromised the structural integrity and mechanical performance of composite components. In this study, delamination was assessed using the Shodensha GR3400 microscope, which allowed precise visualization and measurement of damage around the drilled holes. Two delamination types were evaluated: peel-up delamination at the hole entry and push-down delamination at the hole exit. The delamination factor was calculated using measurements of the original diameter (Do), corresponding to the drill bit size, and the maximum diameter of the delaminated zone (Dmax), facilitating a quantitative assessment of delamination severity.

Delamination Formula:

$$F_d = \frac{D_o}{D_{max}}$$

Consequently, this study generated a comprehensive dataset comprising peel-up and push-out delamination values for each tool bit configuration utilized in the drilling of HFRP material.

The collected data on peel-up and push-out delamination were subjected to Analysis of Variance (ANOVA). In this study, spindle speed and feed rate served as the primary experimental factors, with assigned values spindle speeds between 200 and 1200 RPM and feed rates from 0.08 to 0.1 mm/rev. These parameters were incorporated into a Taguchi experimental design. The corresponding delamination response values were calculated using the designated formula and subsequently entered the analysis.

The setup for graph generation, particularly the main effects plots, was initiated, followed by configuring the analysis parameters within Minitab. The Signal-to-Noise (S/N) Ratio criterion for this Taguchi design was set to “Smaller is Better,” aligning with the theoretical goal of minimizing delamination during the drilling process. As a final step, interaction plots were generated within the ANOVA settings. The processed delamination data was archived for comparative analysis.

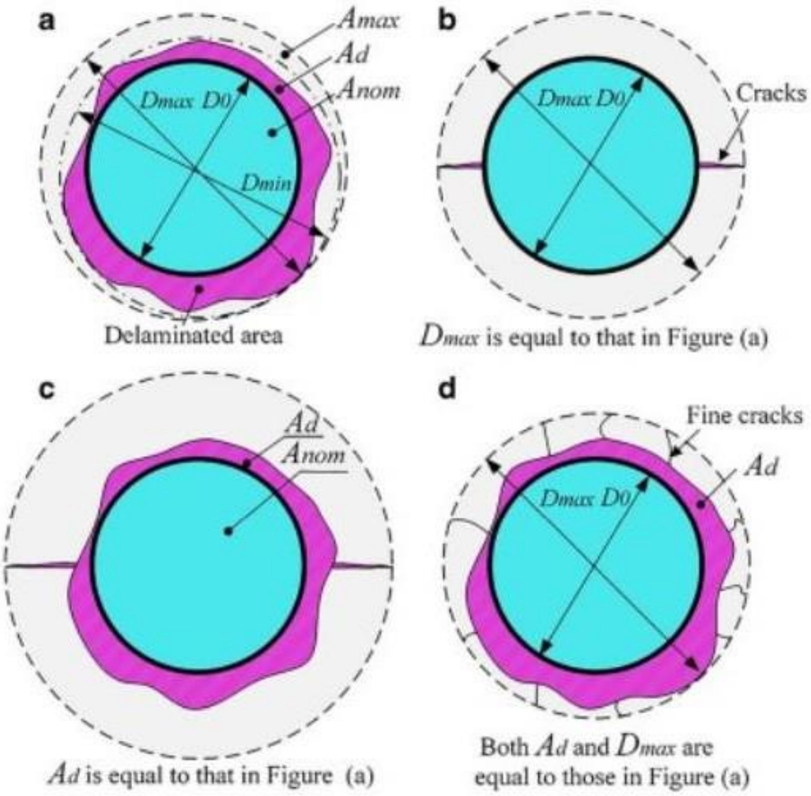


Figure 3.6: Detailed delamination measurements (Aamir et al., 2019b)

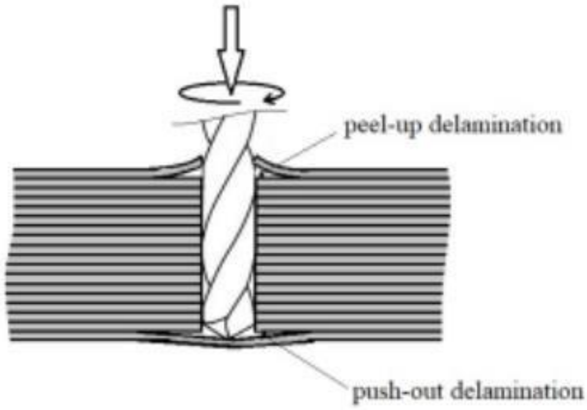


Figure 3.7: Delamination Types (Galińska, 2023)

3.10. Hole Circularity

A WENZEL coordinate measuring machine (CMM), more especially the WENZEL LH Series with WM Quartis metrology software, was utilized to assess hole circularity. Widely utilized in composite and aerospace applications, WENZEL CMMs were renowned for their exceptional precision. Advanced geometric analysis was made possible by the WM Quartis program, which also guaranteed accurate dimensional measurements, including form deviations like roundness and cylindricity.

The drilled HFRP specimen was firmly placed on the CMM's granite table using a fixture to stop it from moving during the analysis. Each drilled hole's inside circumference was measured using a probe, which was usually a tactile scanning stylus with a 2 mm ruby tip. Along the Z-axis, data points were collected at various depths.

The circularity error was then determined by calculating the highest radial deviation from the fitted circle after a least-squares fit circle was done through the measured points at each level using the WM Quartis program. This technique made it possible to identify abnormalities during drilling that were brought on by vibration, tool deflection, or material heterogeneity. The findings offered a quantitative understanding of the relationship between hole geometry precision and machining factors.

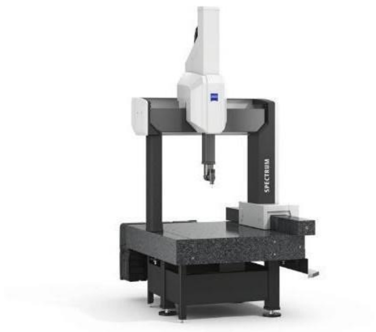


Figure 3.8: Coordinate Measuring Machine

3.11. Hole Quality Measurement

Hole quality could be characterized by several metrics, including delamination, perpendicularity, and circularity. In this study, circularity was the primary metric used to assess hole quality. The measurement process involved using the Shodensha GR400 3D Profilometer (as illustrated in Figures 3.9 and Figure 3.10) to determine the diameter of the drilled holes. The collected measurements were input into Minitab software to facilitate the construction of an Analysis of Variance (ANOVA) test. The circularity error was determined by subtracting the nominal diameter from the measured values. Each hole was measured five times, and the average diameter was recorded for subsequent analysis.

Figure 3.9: Shodensha GR3400 3D Profilometer

(https://emin.com.mm/shodenshagr3400jultra-high-definition-microscope-texture-of-metal-can-be-observed-up-to-600-times-zoom-inshodensha-gr3400-38718/pr.html, 2017)

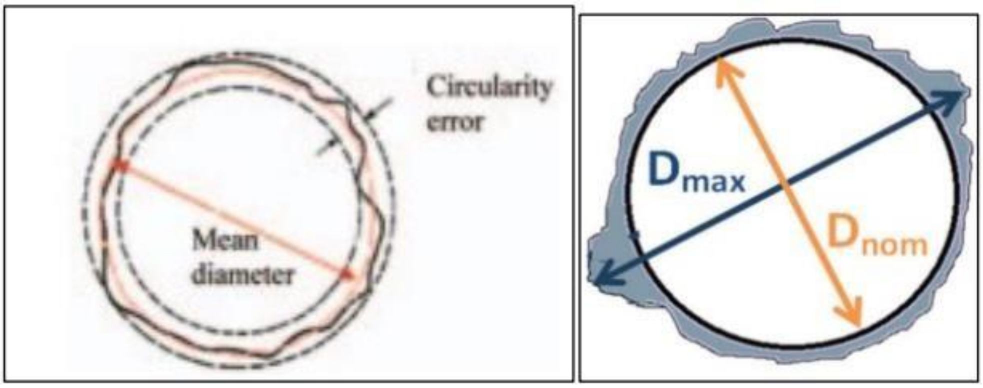


Figure 3.10: Measurement of the circle and the circularity error

3.12. Microscopy Observation of Twist Drill Tool Bit

Examining the twist drill bit under a microscope was an important step to check its wear condition and better understand how the tool functioned. As noted by Zhang et al. (2016), the part of the drill most likely to wear was the flank, which was located just behind the cutting lip. This study looked closely at both the cutting lip and the flank to evaluate their conditions. The analysis also involved reviewing the drill's geometry, and some theoretical calculations were carried out using established formulas to better understand the tool's performance.

$$Average\ flank\ wear = \frac{A + B + C + D}{4}$$

After the tool bit was examined under a microscope, the Nikon MM-800 Microscopy was used to accurately measure the wear on the flank. The drill bit was held vertically in place with a jig so the drilling face could be clearly viewed. The microscope captured flank measurements at four key points A, B, C, and D, which were then used to calculate the average wear. This experiment used drill bits with point angles of 108, and helix angles of 30°.

After obtaining the average flank wear values from the nine tool bits, the data was entered into Minitab using a Taguchi L9 design. The two factors selected were Point Angle and Helix Angle, and the corresponding values were defined in the Taguchi table.

The Signal-to-Noise Ratio setting was adjusted to “Smaller is Better,” since lower tool wear was preferred. Once all the settings were finalized, the interaction plots were generated using the ANOVA analysis option. The results and output from Minitab were saved for later reference and comparison.

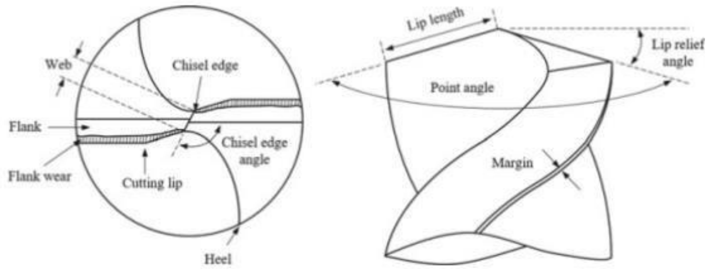


Figure 3.11: Geometrical Theories of the Flank Wear, Flank, and Cutting Lip

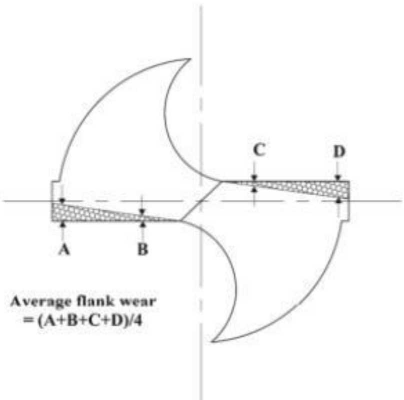


Figure 3.12: Measurements of average flank Wear of a twist drill bit (Garg et al., 2014)

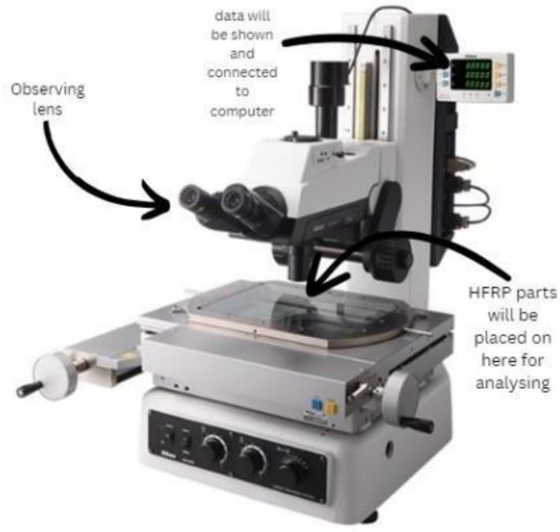


Figure 3.13: Nikon MM-800 Microscopy (https://industry.nikon.com/enaom/products/optical-manual-measuring/measuring-microscopes/mm-400-mm-800/, 2024)

3.13. Summary

To begin, the experimental setup was carefully arranged, ensuring that the right cutting tools and drilling parameters were selected for the study. The HFRP material used was fully characterized, including its stacking sequence and key material properties. Measurements were taken to assess delamination, surface roughness, hole quality, and tool wear using microscopy. The data collected was then analyzed statistically to pinpoint which factors had the greatest impact on drilling damage. To improve the effectiveness of the tool design, the study applied Design of Experiments (DOE) methods, specifically the Taguchi approach, to find the best combination of point angle and helix angle. This was done to help reduce damage during drilling and make the process more efficient overall.

CHAPTER 4

RESULT AND DISCUSSION

4.1. Introduction

This chapter presented important infographic results of the study on optimization of machining conditions during drilling operation of hybrid fiber reinforced plastics (HFRP) composite – aero-structural component. The data gathered was based on the research and insights provided related to aerospace engineering and manufacturing. The main objective of the experiment was to identify the critical machining parameters, including spindle speed and feed rate, that significantly influenced drilling-induced defects. To achieve this objective, several unique techniques were implemented. A twist drill with a helix angle of 30° and a point angle of 118° was used as the tool geometry. The experiment varied two main factors: spindle speed (1000, 1500, 2000 RPM) and feed rate (100, 150, 200 mm/min). Using the Taguchi design in Minitab Software, the optimal number of test runs was determined. The evaluation focused on delamination, hole quality (circularity), thrust force, and tool wear, with measurements conducted using microscopic observation and equipment.

4.2 Drilling Performance

The machining performance was evaluated by applying Taguchi Design and ANOVA testing methods to analyze delamination effects, hole quality, thrust force, and tool wear during the drilling operation of the HFRP panel. To optimize the machining conditions, two critical parameters, spindle speed and feed rate, were varied. These factors were assessed to determine the ideal conditions that would minimize damage, optimize thrust force, and ensure the integrity of the drilled holes in the HFRP panels.

4.2. Thrust Force

Thrust force observation involved monitoring and recording the force exerted on the tool during the drilling process. Thrust force was a critical parameter, as excessive force could lead to increased tool wear, poor hole quality, and potential delamination of the HFRP material. The results were tabulated as shown in (Table 4.1) the negative values for thrust force (Fz) as shown in figure (Figure 4.1) represent the compressive forces acting along the axis of the drilling tool. These negative values reflect the resistance the drill bit encounters as it penetrates the material. The thrust force is considered negative because it opposes the motion of the tool, indicating the axial force required to drive the tool into the material. This is a typical observation in drilling processes, where thrust force is influenced by material resistance during tool engagement (Pillai, 2007). Therefore, negative thrust force values represent the material's opposition to the tool's movement, which is a critical factor in evaluating drilling efficiency.

Table 4.1: Thrust Force Fz value

Panel	Spindle Speed	Feed Rate	Fz
1	1000	100	-77.4
2	1000	150	-115.3
3	1000	200	-77.95
4	1500	100	-75.63
5	1500	150	-74.06
6	1500	200	-76.5
7	2000	100	-75.79
8	2000	150	-77.49
9	2000	200	-85.5

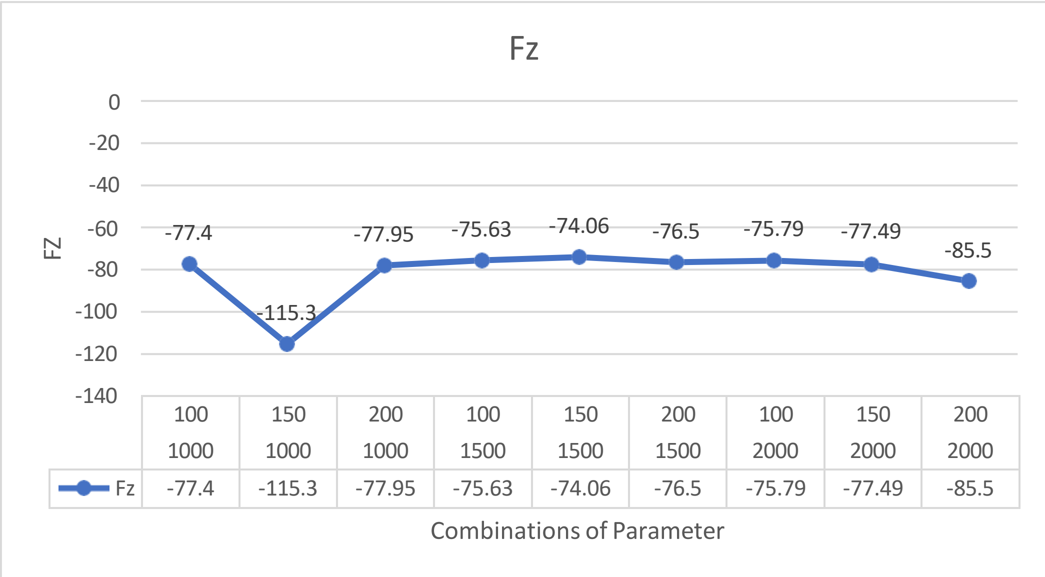


Figure 4.1: Fz Thrust Force Trend graph

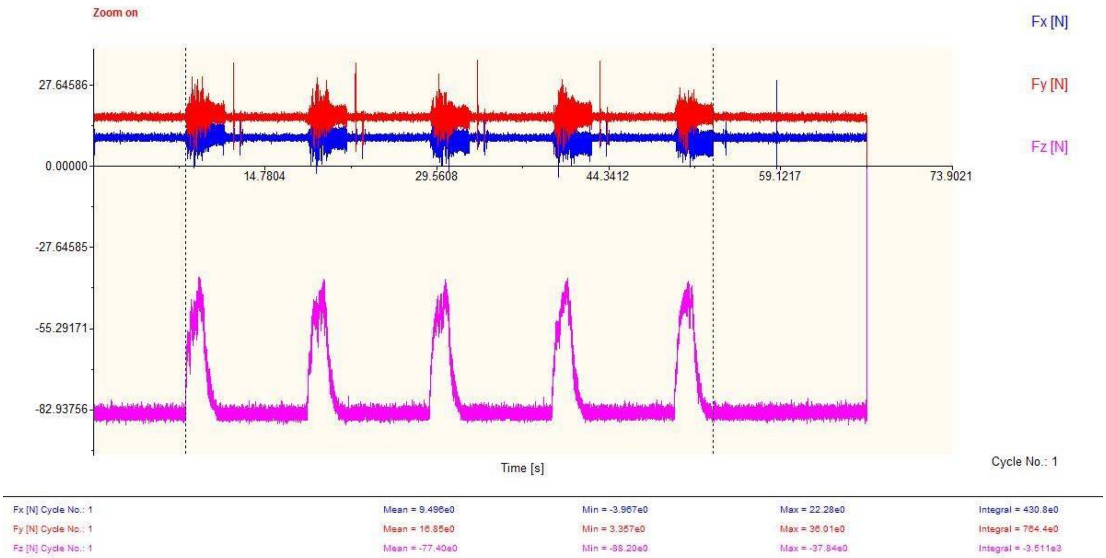


Figure 4.2: Thrust Force graph reading of drilling HFRP panel 1

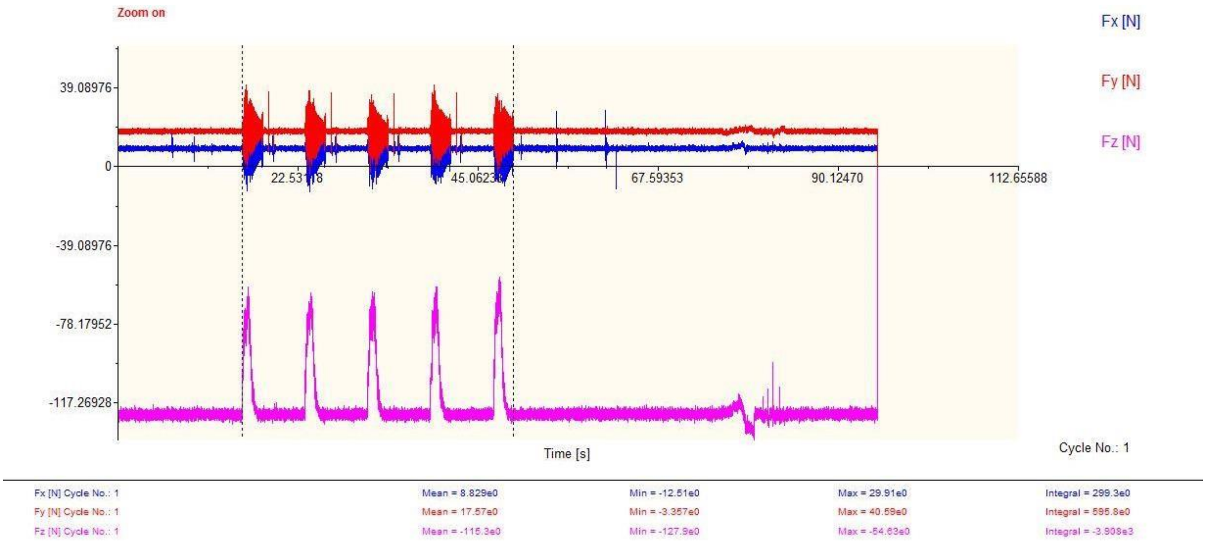


Figure 4.3: Thrust Force graph reading of drilling HFRP panel 2

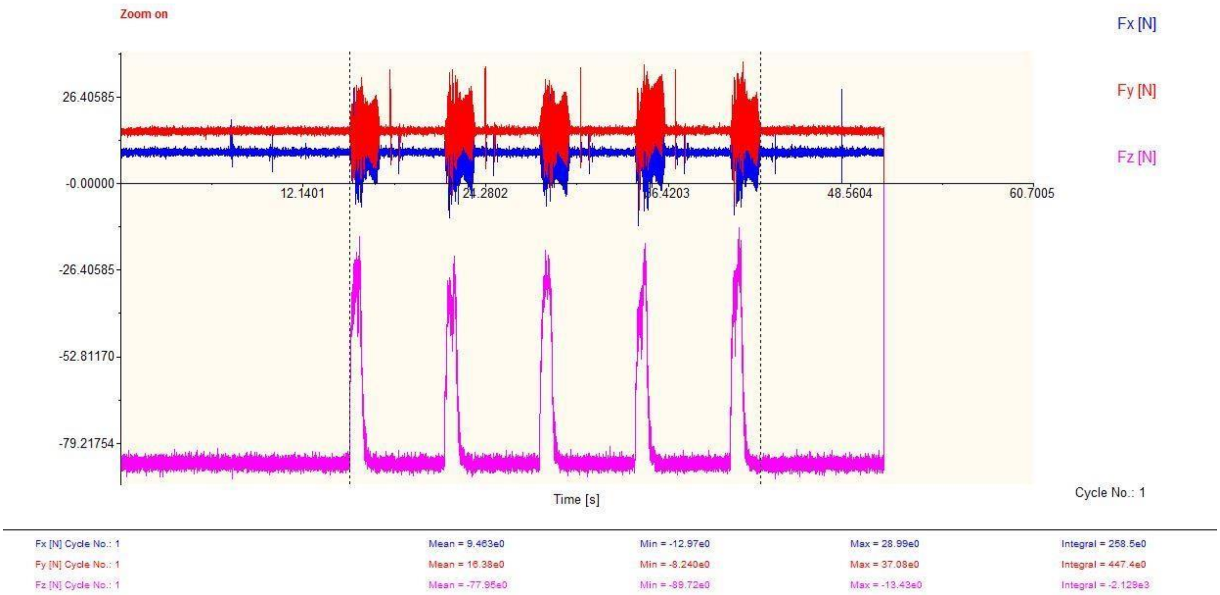


Figure 4.4: Thrust Force graph reading of drilling HFRP panel 3

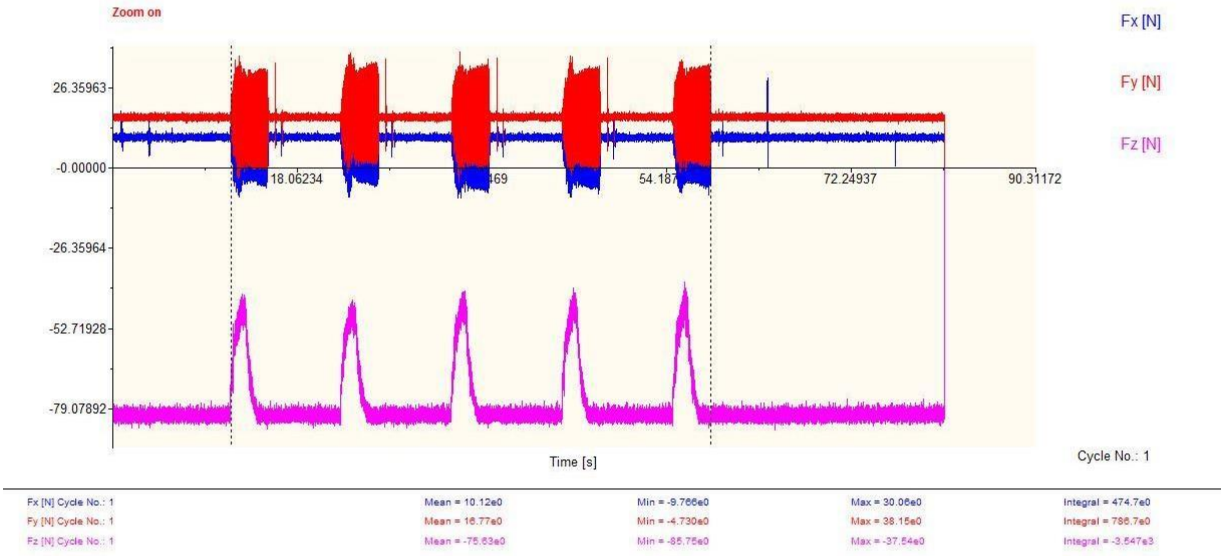


Figure 4.5: Thrust Force graph reading of drilling HFRP panel 4

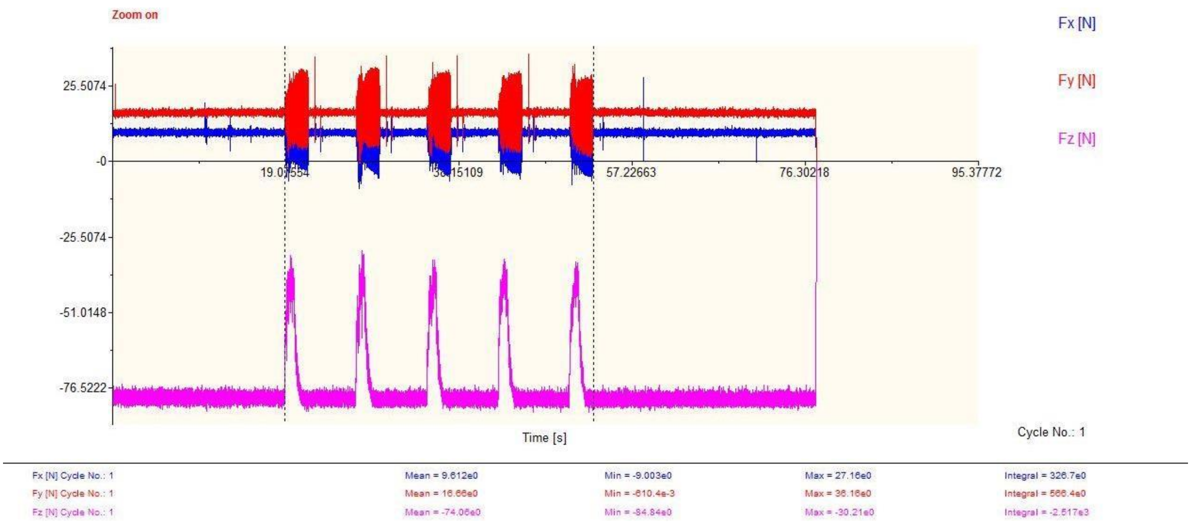


Figure 4.6: Thrust Force graph reading of drilling HFRP panel 5

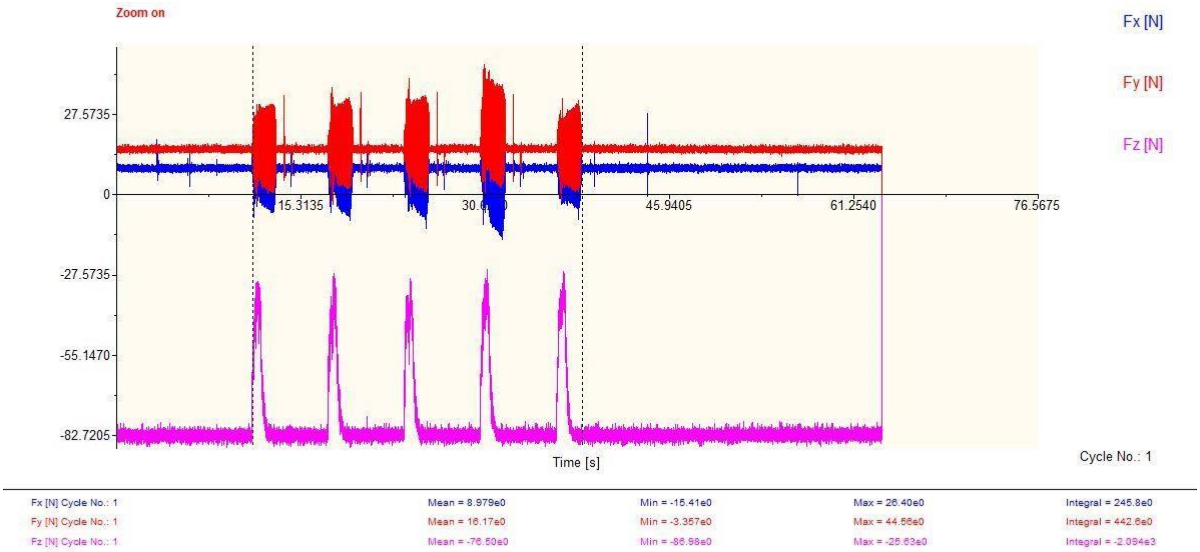


Figure 4.7: Thrust Force graph reading of drilling HFRP panel 6

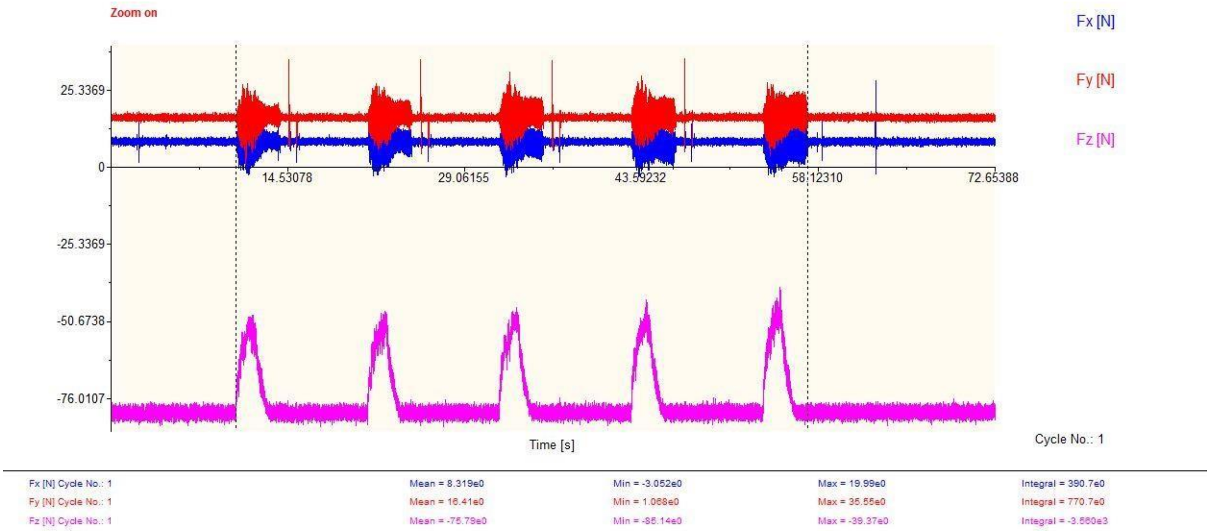


Figure 4.8: Thrust Force graph reading of drilling HFRP panel 7

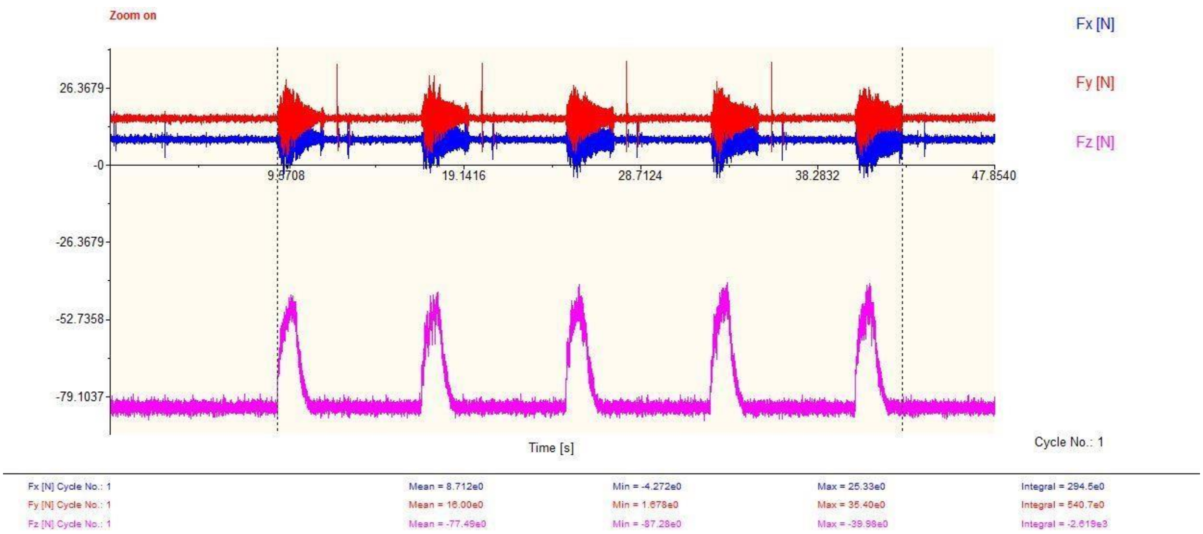


Figure 4.9: Thrust Force graph reading of drilling HFRP panel 8

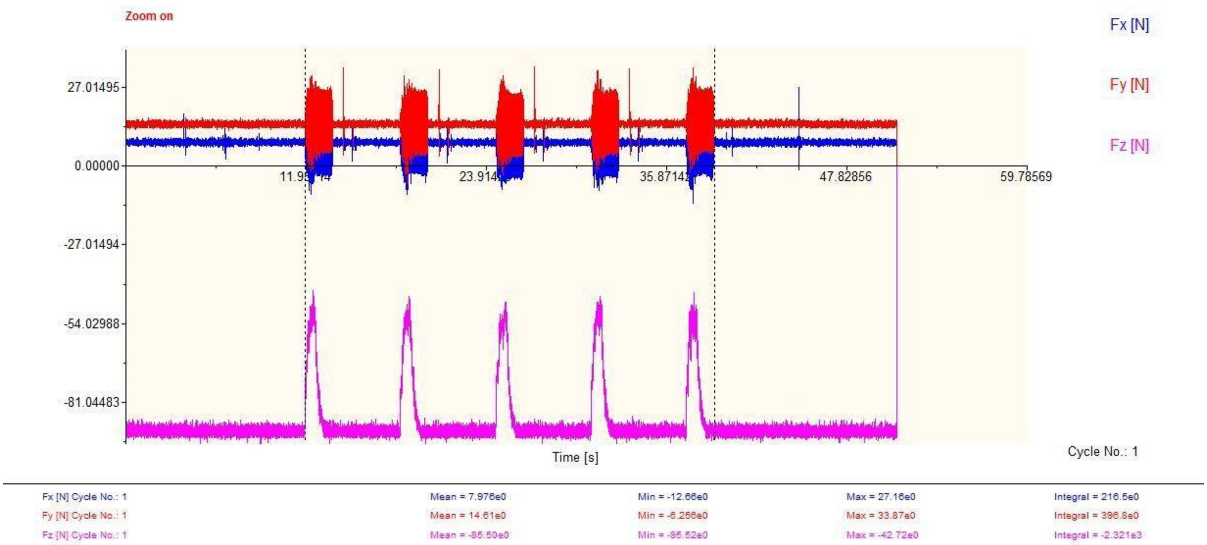


Figure 4.10: Thrust Force graph reading of drilling HFRP panel 9

At spindle speed 1000 rpm, the thrust force is relatively high compared to higher spindle speeds. For feed rate 100 (Panel 1), the thrust force is -77.4 N. However, when the feed rate increases to 150 (Panel 2), the thrust force increases significantly to -115.3 N, marking the highest thrust force at this spindle speed. This increase is due to the tool spending more time engaging with the material, creating higher resistance and thrust forces. However, at feed rate 200 (Panel 3), the thrust force decreases slightly to -77.95 N, suggesting more efficient material removal, reduced resistance, and possibly a more stabilized cutting process (Ramesh et al., 2018).

The reduction in thrust force observed from Panel 2 (feed rate 150, -115.3 N) to Panel 3 (feed rate 200, -77.95 N) can also be explained by heat softening of the material. As the feed rate increases, more material is removed per unit of time, generating more friction and heat at the cutting interface. This heat affects the HFRP material, particularly the resin matrix, which holds the fibers together. The resin softens at higher temperatures, reducing the material's resistance to cutting. As the resin softens, the material becomes easier to cut, which leads to a decrease in the thrust force required to penetrate the material, as observed between Panel 2 and Panel 3, despite the increase in feed rate.

For spindle speed 1500 RPM, the thrust force decreases compared to 1000 RPM, which is consistent with the reduction in cutting time per revolution. For feed rate 100 (Panel 4), the thrust force is -75.63 N, and at feed rate 150 (Panel 5), it decreases slightly to -74.06 N, the lowest value observed at this spindle speed. However, at feed rate 200 (Panel 6), the thrust force increases to **-76.5 N**. The reduction in thrust force with increasing spindle speed is well-documented, where faster spindle speeds lead to less material engagement per rotation, thereby reducing resistance and thrust force. Despite the increase in feed rate, the thrust force increase is less pronounced than at lower spindle speeds, highlighting the effect of spindle speed in reducing cutting resistance.

At spindle speed 2000 RPM, for feed rate 100 (Panel 7), the thrust force is -75.79 N, and for feed rate 150 (Panel 8), the thrust force increases slightly to -77.49 N, indicating that faster rotation reduces cutting time, resulting in lower resistance and thrust force. However, at feed rate 200 (Panel 9), the thrust force increases to -85.5 N, which is the highest thrust force observed at this spindle speed. This increase can be attributed to the higher feed rate, which leads to greater material removal per unit of time, thereby increasing cutting force and resistance, despite the faster spindle speed. The data shows that while higher spindle speeds generally reduce thrust force, higher feed rates at those speeds can still lead to higher thrust forces due to increased material engagement.

In conclusion, the data clearly shows that both spindle speed and feed rate significantly influence thrust force (Fz) during the drilling of HFRP. Lower spindle speeds result in higher thrust forces because the tool spends more time in contact with the material, increasing resistance. Higher spindle speeds reduce thrust force by shortening the cutting time per revolution, which decreases material engagement and friction. However, higher feed rates increase thrust force as more material is cut, generating greater resistance. The reduction in thrust force between Panel 2 and Panel 3 can also be explained by heat softening of the material, which makes drilling easier as the resin softens at higher temperatures, reducing the material's resistance. This analysis underscores the importance of optimizing both spindle speed and feed rate to minimize thrust force while ensuring efficient material removal.

4. 3 Roundness

Roundness observation involved monitoring and recording the circularity of the holes drilled during the machining process. Roundness was a critical parameter, as any deviation from a perfect circle could affect the performance and fit of the component, leading to issues like poor sealing, increased wear, and reduced efficiency. The results were tabulated as shown in (Table 4.2) and (Figure 4.11)

Table 4.2: Average Deviation Value

Panel	Spindle Speed	Feed Rate	Average Deviation
1	1000	100	0.021
2	1000	150	0.016
3	1000	200	0.021
4	1500	100	0.006
5	1500	150	0.013
6	1500	200	0.013
7	2000	100	0.009
8	2000	150	0.019
9	2000	200	0.012

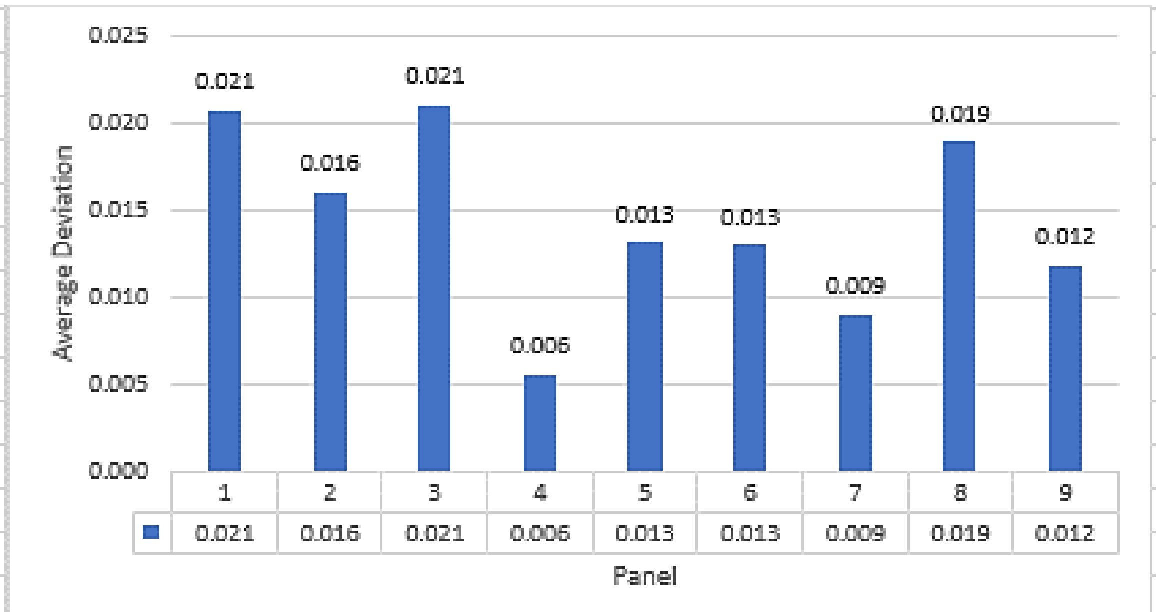


Figure 4.11: Average Deviation Graph

Spindle Speed 1000 RPM (Panels 1 to 3)

At 1000 RPM, the deviation values range from 0.016 to 0.021, indicating significant variability in the drilled holes across the panels. The influence of feed rate on deviation is clear. Panel 1 (feed rate 100) has the highest deviation (0.021) and a %Dev of 41%, showing the greatest inconsistency in the drilled holes at this spindle speed. Increasing the feed rate to 150 in Panel 2 results in a slight improvement, with a deviation of 0.016 and a %Dev of 32%, indicating that a moderate feed rate can help reduce deviation and improve precision. However, Panel 3 (feed rate 200) shows a deviation of 0.021 and a %Dev of 42%, which is similar to Panel 1. This suggests that further increasing the feed rate does not improve precision and may even worsen the drilling accuracy.

Increasing the feed rate generally results in a higher material removal rate, which can lead to more heat generation and, consequently, increased deviation. This aligns with the data, where Panel 2 with a moderate feed rate shows a better result compared to Panel 3 with a higher feed rate.

Spindle Speed 1500 RPM (Panels 4 to 6)

At 1500 RPM, the deviation values are much lower, ranging from 0.006 to 0.013, indicating better precision in drilling compared to the 1000 RPM group. Panel 4 (feed rate 100) achieves the best result, with the lowest deviation of 0.006 and a %Dev of just 11%, highlighting the superior accuracy when using a slower feed rate at this spindle speed. Increasing the feed rate to 150 in Panel 5 and Panel 6 results in a slightly higher deviation of 0.013 and a %Dev of 26% in both panels, indicating a small increase in deviation. However, these deviations are still lower than those in the 1000 RPM group, suggesting that the 1500 RPM spindle speed provides a better overall balance between feed rate and hole precision.

The reduced deviation at 1500 RPM can be attributed to the optimal balance between feed rate and spindle speed. Studies have shown that 1500 RPM offers more stability and reduces vibration, which can improve hole quality (Tanaka et al., 2019). However, even with the moderate feed rate of 150, a slight increase in deviation occurs, which emphasizes the importance of precise feed rate control at this spindle speed.

Spindle Speed 2000 RPM (Panels 7 to 9)

At the highest spindle speed of 2000 RPM, the deviations increase again, ranging from 0.009 to 0.019, suggesting that higher spindle speeds may cause more instability in hole precision. Panel 7 (feed rate 100) has the lowest deviation of 0.009 and a %Dev of 18%, indicating that a slower feed rate helps maintain accuracy at this higher spindle speed. However, Panel 8 (feed rate 150) shows a significant increase in deviation (0.019) and a %Dev of 38%, suggesting that increasing the feed rate at 2000 RPM leads to poorer precision, likely due to excessive heat generation and material displacement during drilling. Panel 9 (feed rate 200) shows a deviation of 0.012 and a %Dev of 24%, which is better than Panel 8 but still worse than Panel 7, further reinforcing the point that higher feed rates at high spindle speeds degrade the hole quality.

Research indicates that higher spindle speeds, such as 2000 RPM, lead to increased tool wear and higher temperatures, which can distort material properties and result in higher deviations (Kumar et al., 2018). In the case of Panel 8 and Panel 9, the higher feed rates further exacerbate these issues, leading to a significant drop in precision.

Conclusion

From Panel 1 to Panel 3 (1000 RPM), the drilling accuracy improves with a moderate feed rate of 150, achieving the lowest deviation in Panel 2. At 1500 RPM (Panels 4 to 6), the slowest feed rate of 100 gives the best precision in Panel 4, and increasing the feed rate results in a slight increase in deviation. At 2000 RPM (Panels 7 to 9), a slower feed rate of 100 in Panel 7 provides the best result, while higher feed rates in Panel 8 and 9 lead to larger deviations.

Overall, moderate feed rates provide the best precision at 1000 RPM, while slower feed rates optimize drilling at 1500 RPM. 2000 RPM benefits from a slower feed rate as well, but further increasing the feed rate significantly reduces hole quality. This analysis emphasizes the importance of fine-tuning feed rates at varying spindle speeds to achieve optimal drilling precision and roundness.

4.4 Tool wear

This chapter provided an in-depth analysis of the experimental results obtained from the drilling tests conducted on High-Performance Fiber Reinforced Plastic (HPFRP) using various tool conditions. The primary objective of these experiments was to evaluate the effect of spindle speed and feed rate on the average flank wear of cutting tools. The data collected included measurements for four different parameters (A, B, C, and D), and the average flank wear was calculated for each tool under varying conditions.

The average flank wear observed for each tool, ranging from 0.88375 to 0.97825, reflected the varying impact of spindle speed and feed rate on tool degradation. Tools 1 through 9 displayed fluctuations in wear, indicating that the interaction between spindle speed and feed rate did not follow a straightforward linear trend. Notably, Tool 2 exhibited the highest flank wear (0.97825), while Tool 5 showed the lowest (0.88375). These observations suggested that the combination of specific tool parameters directly influenced tool longevity during the drilling process, but other unaccounted factors may have also.

To provide a clearer view of the overall results, the data measurements of the average flank wear obtained were graphically represented in Figure 4.12 and Table 4.3 for easier visualization and comparison.

Table 4.3: Average Flank Wear

Tool Number	Spindle Speed	Feed Rate	A	B	C	D	Average Flank wear
1	1000	100	0.98	0.819	0.878	0.98	0.91425
2	1000	150	0.992	0.98	0.941	1	0.97825
3	1000	200	0.996	0.82	0.839	1	0.91375
4	1500	100	0.987	0.886	0.857	0.98	0.9275
5	1500	150	0.96	0.798	0.857	0.92	0.88375
6	1500	200	0.98	0.86	0.817	0.957	0.9035
7	2000	100	0.981	0.862	0.838	0.976	0.91425
8	2000	150	0.987	0.898	0.898	0.959	0.9355
9	2000	200	0.983	0.919	0.919	0.98	0.95025

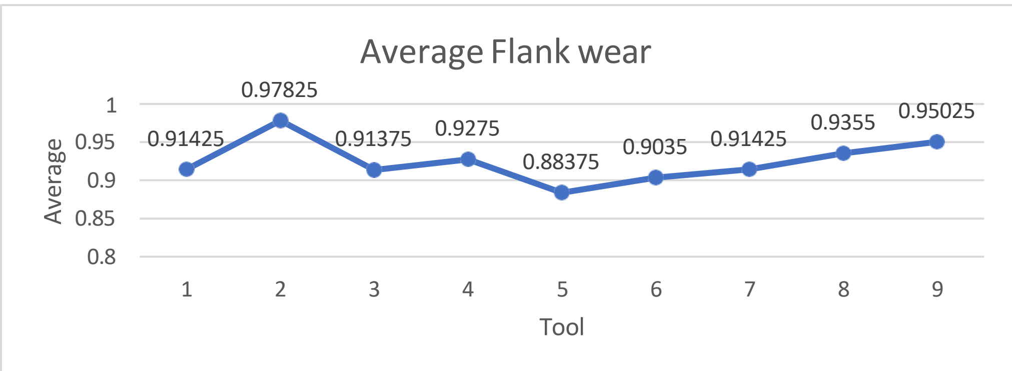


Figure 4.12: Average Flank Wear

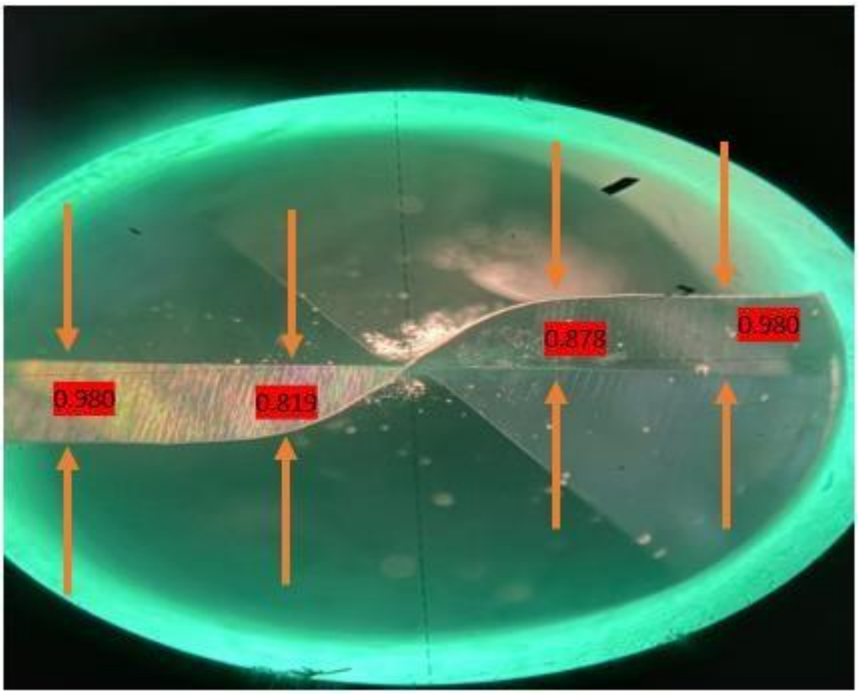


Figure 4.13: Flank Wear Measurements of Tool 1

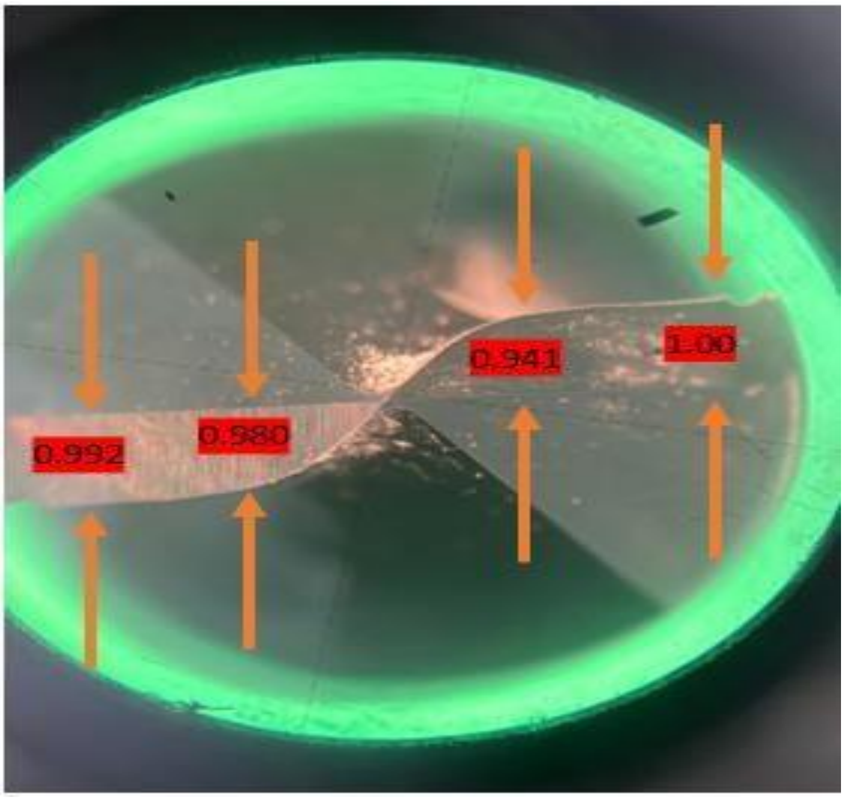


Figure 4.14: Flank Wear Measurements of Tool 2

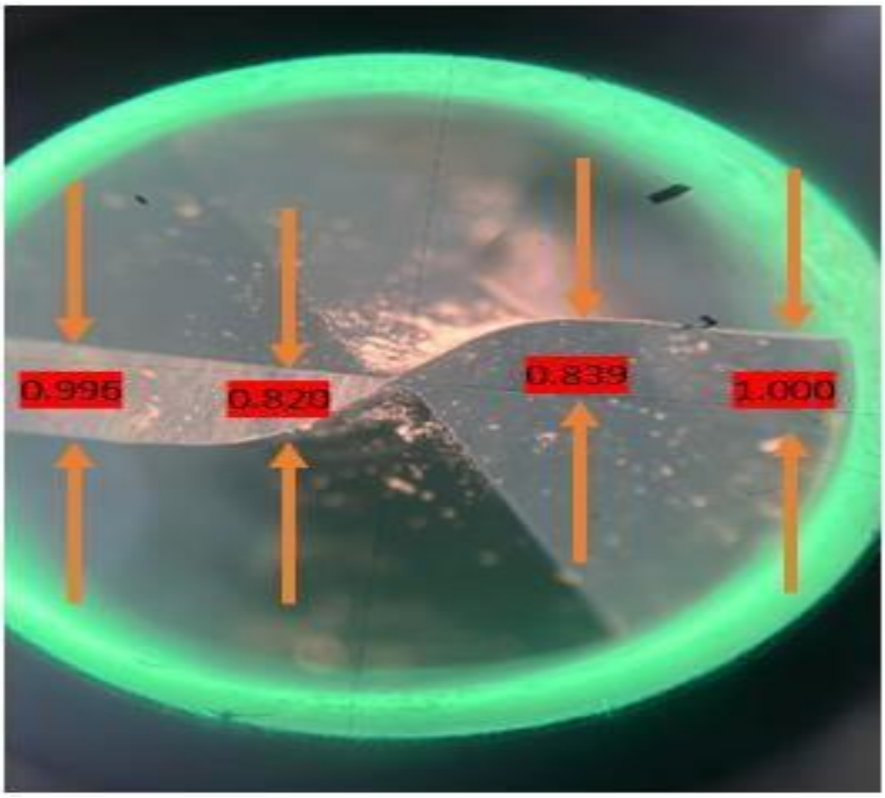


Figure 4.15: Flank Wear Measurements of Tool 3

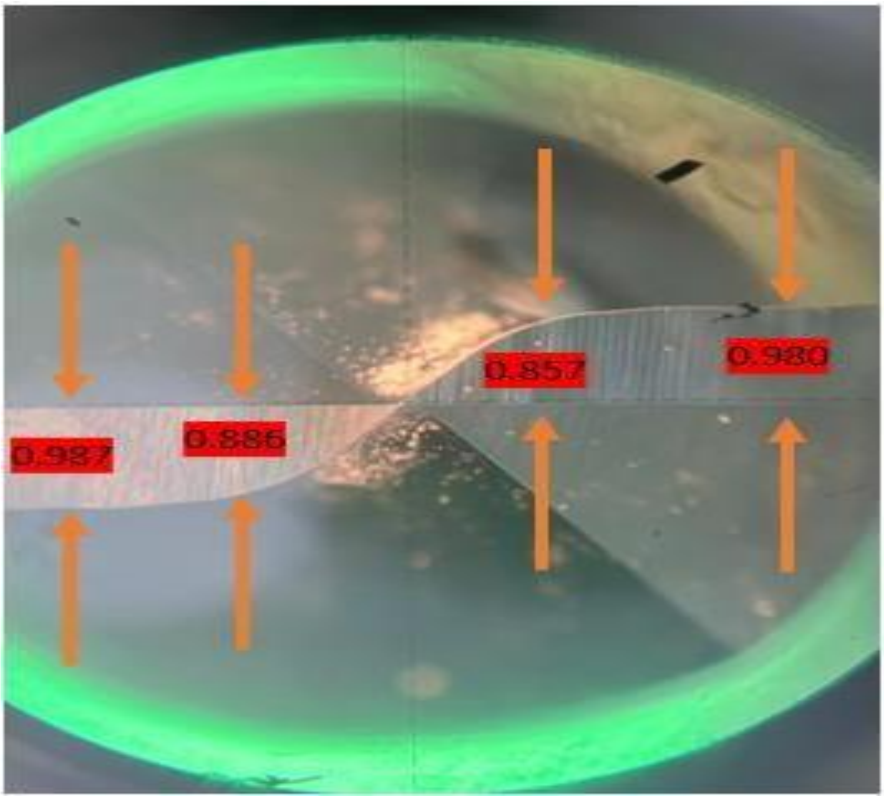


Figure 4.16: Flank Wear Measurements of Tool 4

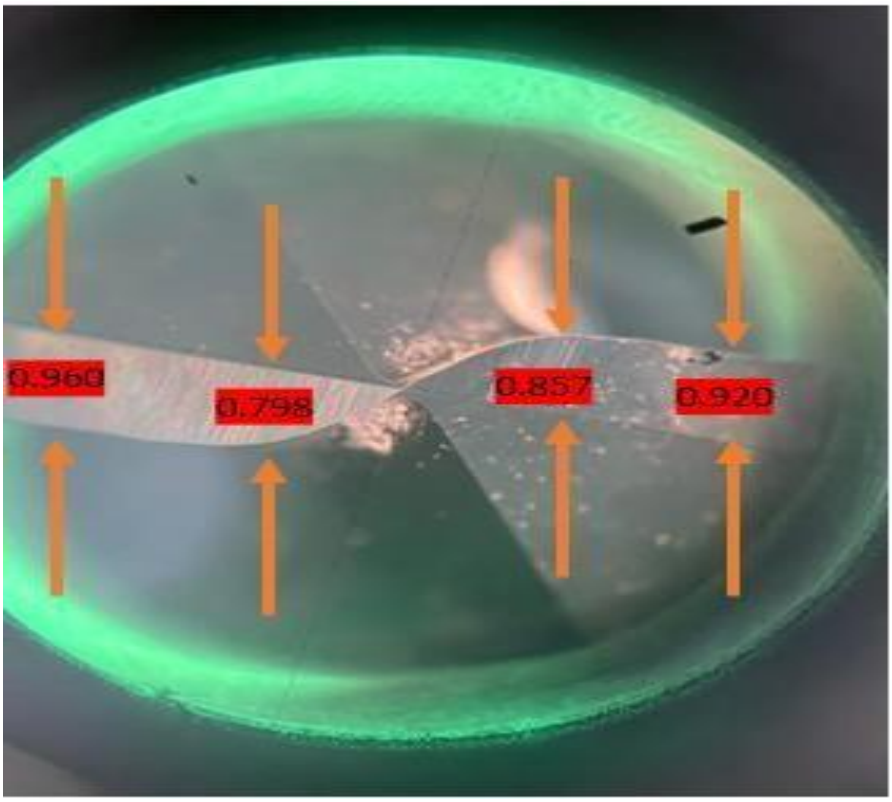


Figure 4.17: Flank Wear Measurements of Tool 5

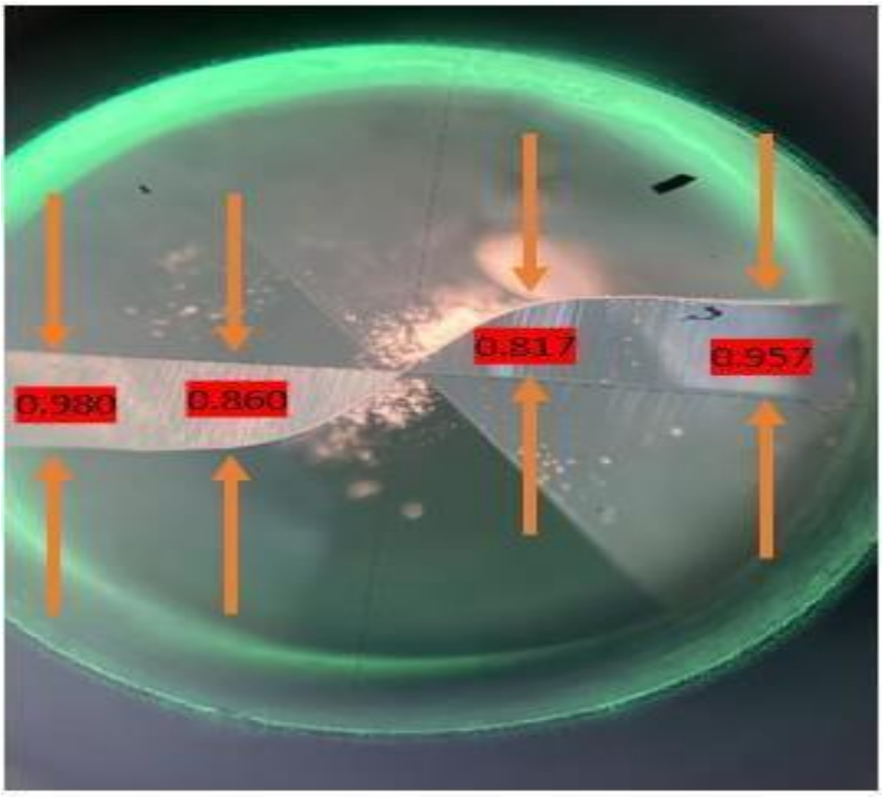


Figure 4.18: Flank Wear Measurements of Tool 6

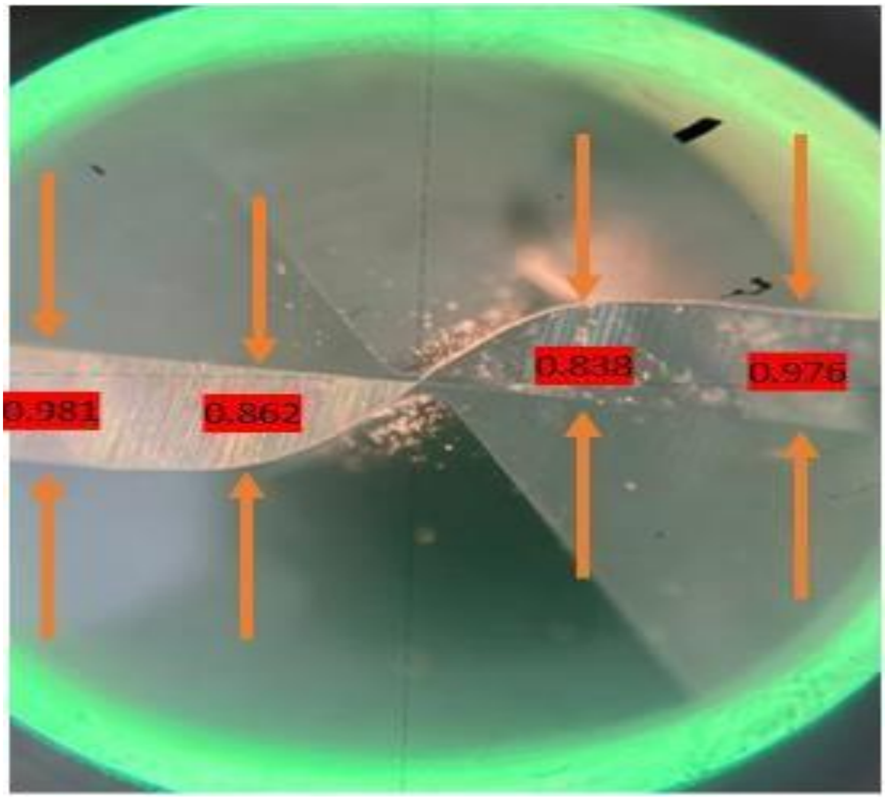


Figure 4.19: Flank Wear Measurements of Tool 7

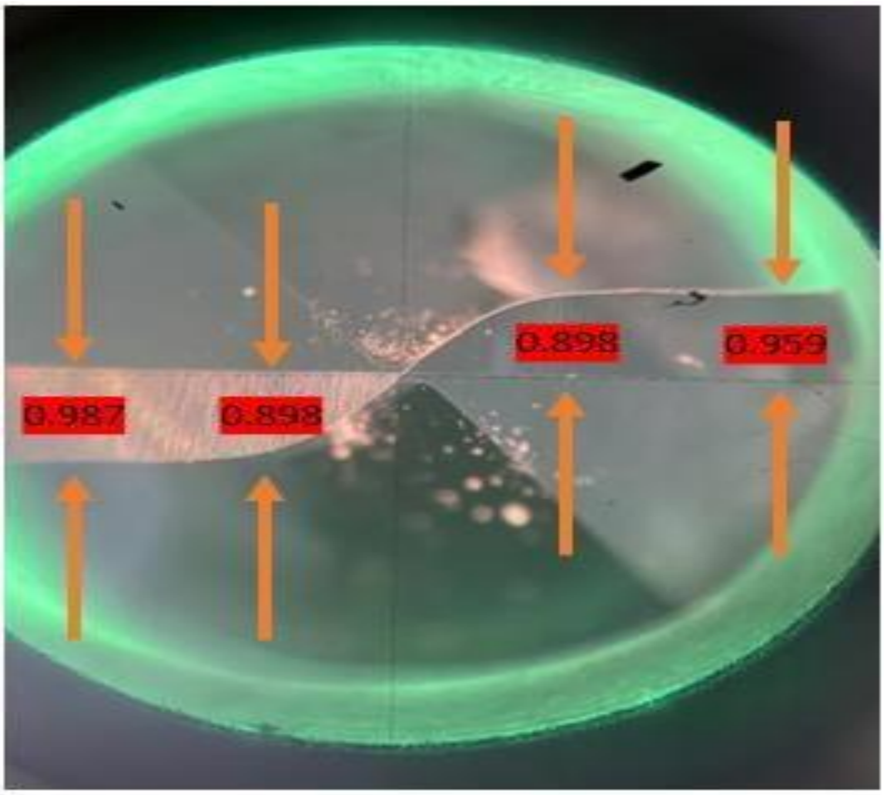


Figure 4.20: Flank Wear Measurements of Tool 8

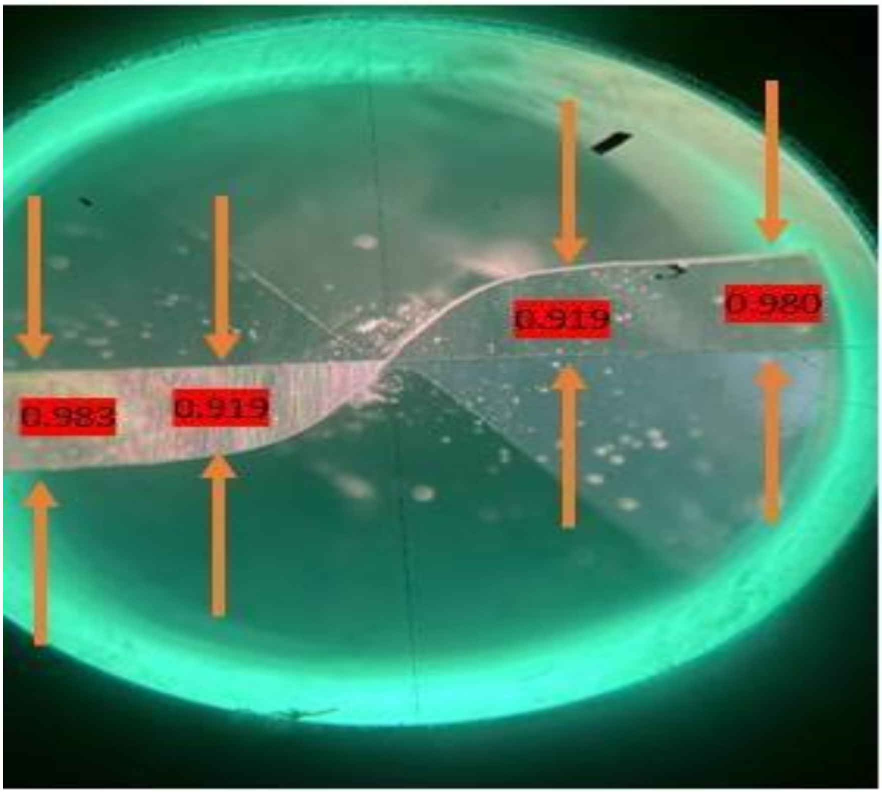


Figure 4.21: Flank Wear Measurements of Tool 9

The influence of feed rate on flank wear was evident, particularly when comparing tools with varying feed rates while keeping the spindle speed constant. Tools 1, 2, and 3, with increasing feed rates of 100, 150, and 200, respectively, showed a clear trend: higher feed rates generally resulted in higher flank wear. This was particularly noticeable in Tools 1 and 2, where a feed rate increase from 100 to 150 corresponded to a wear increase from 0.91425 to 0.97825.

This trend suggested that higher feed rates led to greater material removal per unit of time, which placed more stress on the tool, thereby increasing flank wear. The cutting tool likely experienced higher thermal and mechanical loads, contributing to accelerated wear when the feed rate was increased. Further research could explore the relationship between cutting forces, temperature, and wear in this context.

The relationship between spindle speed and flank wear was less straightforward, as evidenced by the results from Tools 1 through 3 (at 1000 RPM), Tools 4 through 6 (at 1500 RPM), and Tools 7 through 9 (at 2000 RPM). While it was hypothesized that an increase in spindle speed would result in higher wear due to increased cutting speeds, the data did not show a consistent trend in this regard.

For instance, Tools 4 and 5, both at 1500 RPM, showed different levels of flank wear (0.9275 for Tool 4 and 0.88375 for Tool 5). This discrepancy suggested that while spindle speed was an important factor, it likely interacted with feed rate and other variables, such as tool material or HPFRP's composition, which could have influenced the wear pattern.

Tools 8 and 9, with 2000 RPM, showed slightly higher wear compared to Tools 1 and 2 at 1000 RPM. However, this relationship was not statistically significant enough to draw broad conclusions. The absence of a consistent spindle speed wear pattern suggested that additional experiments were required to explore the interplay between speed, cutting forces, and material properties.

The data also indicated that the interaction between spindle speed and feed rate may have been an important factor in determining flank wear. For example, Tools 5 and 6, both at 1500 RPM but with different feed rates (150 and 200, respectively), exhibited differing levels of wear. Tool 5, with the lower feed rate of 150, showed less wear than Tool 6, which had a feed rate of 200. This implied that the increase in feed rate (at constant spindle speed) could have contributed significantly to the observed wear, reinforcing the earlier finding that higher feed rates tended to result in higher wear.

Moreover, the varying results between tools with the same spindle speed but different feed rates highlighted the complex interaction between these two parameters. It was plausible that, beyond just increasing the material removal rate, the feed rate influenced the cutting mechanism in a way that altered the contact conditions between the tool and the material, further contributing to wear.

4.5 Delamination

This chapter provided an in-depth analysis of the experimental results obtained from the drilling tests conducted on High-Performance Fiber Reinforced Plastic (HPFRP) using various tool conditions. The primary objective of these experiments was to evaluate the effect of spindle speed and feed rate on the average delamination of the material. The data collected included measurements for four different parameters (Average Dmax, Average Dmin, Average Delamination), and the average delamination was calculated for each tool under varying conditions.

The average delamination observed for each tool, ranging from 1.016 to 1.126, reflected the varying impact of spindle speed and feed rate on the material. Tools 1 through 9 displayed fluctuations in delamination, indicating that the interaction between spindle speed and feed rate did not follow a straightforward linear trend. Notably, Tool 1 exhibited the highest delamination (1.126), while Tool 4 showed the lowest (1.016). These observations suggested that the combination of specific tool parameters directly influenced the material's delamination during the drilling process, but other unaccounted factors may have also

To provide a clearer view of the overall results, the data measurements of the average delamination obtained were graphically represented in Figure 4.22 and Table 4.4 for easier visualization and comparison.

Table 4.4: Average Delamination

Spindle Speed	Feed Rate	Average Dmax	Average Dmin	Average Delamination
1000	100	6.743	5.991	1.126
1000	150	6.374	6.007	1.061
1000	200	6.118	5.992	1.021
1500	100	6.106	6.012	1.016
1500	150	6.154	6.004	1.025
1500	200	6.640	6.000	1.107
2000	100	6.483	5.998	1.081
2000	150	6.449	5.998	1.075
2000	200	6.439	5.996	1.074

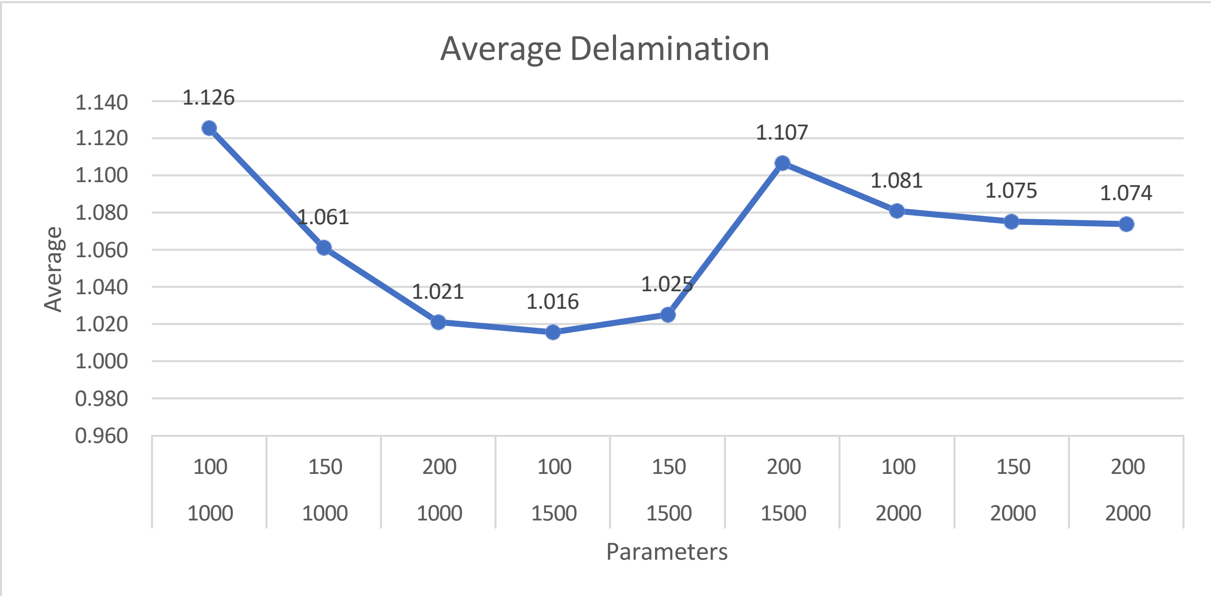


Figure 4.22: Average Delamination Graph

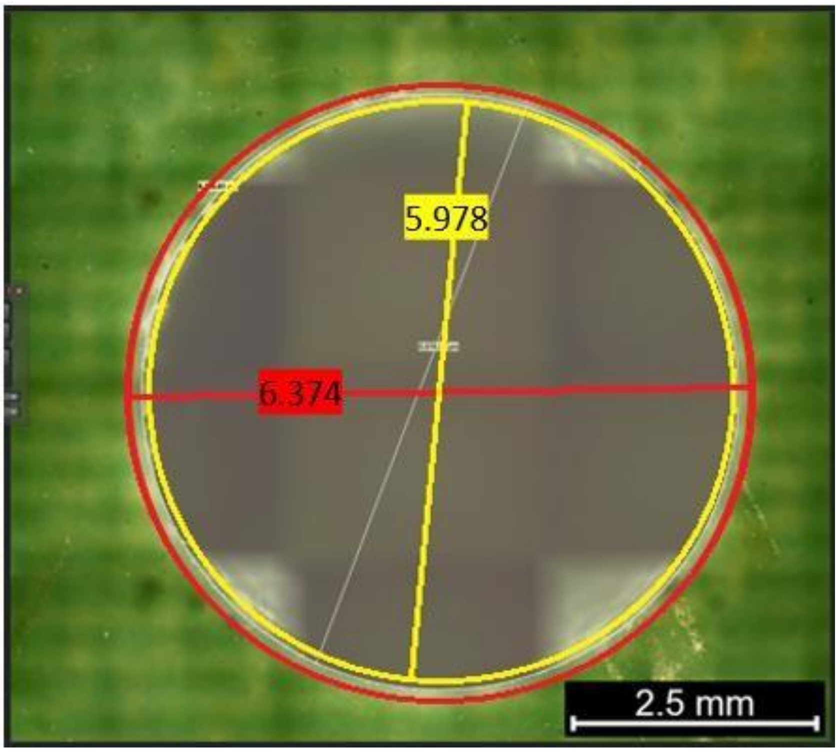


Figure 4.23: Example of the best drilling hole

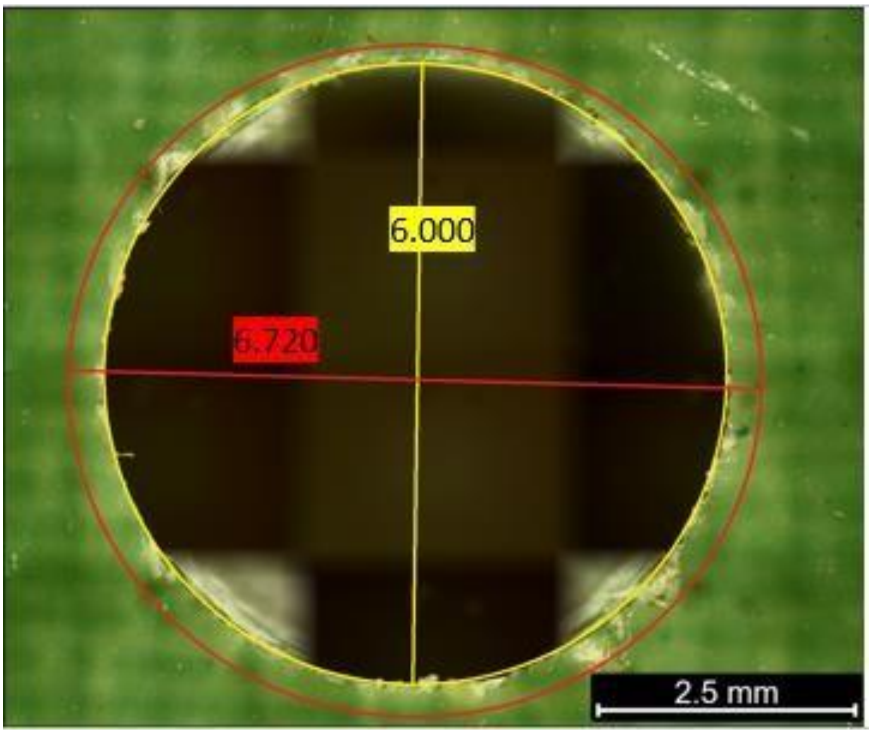


Figure 4.24: Example of the worst drilling hole

The influence of feed rate on delamination was evident, particularly when comparing tools with varying feed rates while keeping the spindle speed constant. Tools 1, 2, and 3, with increasing feed rates of 100, 150, and 200, respectively, showed a clear trend: higher feed rates generally resulted in higher delamination. This was particularly noticeable in Tools 1 and 2, where a feed rate increase from 100 to 150 corresponded to a delamination decrease from 1.126 to 1.061.

This trend suggested that higher feed rates led to greater material removal per unit of time, which placed more stress on the material, thereby increasing delamination. The cutting tool likely experienced higher thermal and mechanical loads, contributing to accelerated delamination when the feed rate was increased. Further research could explore the relationship between cutting forces, temperature, and delamination in this context.

The relationship between spindle speed and delamination was less straightforward, as evidenced by the results from Tools 1 through 3 (at 1000 RPM), Tools 4 through 6 (at 1500 RPM), and Tools 7 through 9 (at 2000 RPM). While it was hypothesized that an increase in spindle speed would result in higher delamination due to increased cutting speeds, the data did not show a consistent trend in this regard.

For instance, Tools 4 and 5, both at 1500 RPM, showed different levels of delamination (1.016 for Tool 4 and 1.025 for Tool 5). This discrepancy suggested that while spindle speed was an important factor, it likely interacted with feed rate and other variables, such as tool material or HPFRP's composition, which could have influenced the delamination

Tools 8 and 9, with 2000 RPM, showed slightly lower delamination compared to Tools 1 and 2 at 1000 RPM. However, this relationship was not statistically significant enough to draw broad conclusions. The absence of a consistent spindle speed delamination pattern suggested that additional experiments were required to explore the interplay between speed, cutting forces, and material properties.

The data also indicated that the interaction between spindle speed and feed rate may have been an important factor in determining delamination. For example, Tools 5 and 6, both at 1500 RPM but with different feed rates (150 and 200, respectively), exhibited differing levels of delamination. Tool 5, with the lower feed rate of 150, showed less delamination than Tool 6, which had a feed rate of 200. This implied that the increase in feed rate (at constant spindle speed) could have contributed significantly to the observed delamination, reinforcing the earlier finding that higher feed rates tended to result in higher delamination

Moreover, the varying results between tools with the same spindle speed but different feed rates highlighted the complex interaction between these two parameters. It was plausible that, beyond just increasing the material removal rate, the feed rate influenced the cutting mechanism in a way that altered the contact conditions between the tool and the material, further contributing to delamination.

4.6 Analysis of variance (ANOVA) of Thrust Force

This analysis aimed to assess the effect of spindle speed and feed rate on thrust force during the drilling of High-Performance Fiber Reinforced Plastic (HPFRP). The ANOVA results, summarized in Table 4.5, showed that neither spindle speed nor feed rate significantly impacted thrust force. The F-value for spindle speed was 0.95 with a P-value of 0.459, and for feed rate, the F-value was 0.64 with a P-value of 0.573, both indicating no statistically significant effect.

Table 4.5: Analysis of Variance

Analysis of Variance for SN ratios

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Spindle Speed	2	3.07	3.07	1.535	0.95	0.459
feed Rate	2	2.071	2.071	1.036	0.64	0.573
Error	4	6.44	6.44	1.61		
Total	8	11.582				

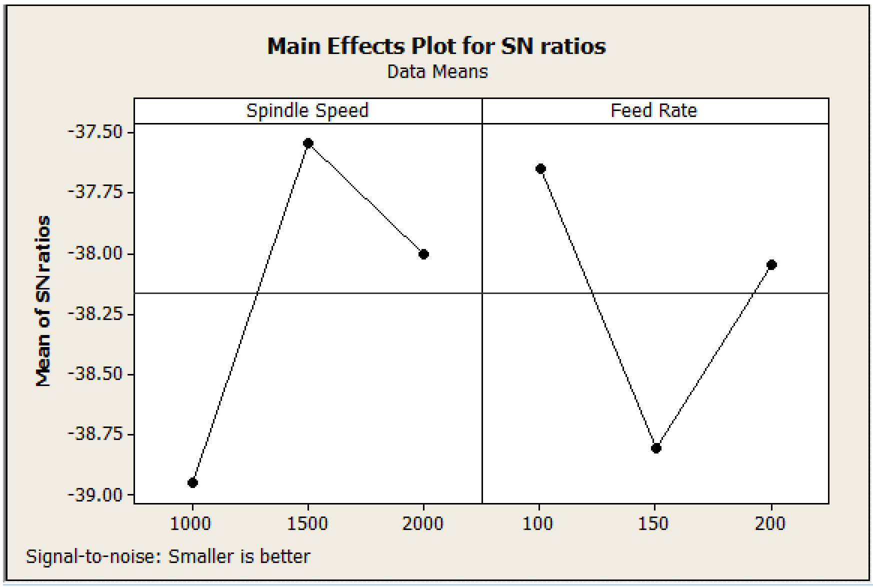


Figure 4.25: Main Effect Plot for SN ratios

The main effects plot in Figure 4.25 revealed that increasing spindle speed from 1000 RPM to 2000 RPM led to a decrease in thrust force. Similarly, feed rate increases from 100 mm/min to 200 mm/min resulted in lower thrust force, suggesting that optimizing these parameters may improve drilling efficiency.

Despite the lack of statistical significance, the trends suggest that higher spindle speeds and feed rates could reduce thrust force, aligning with findings from previous studies (Gokhan & Gokhan, 2014; Liu et al., 2004).

In conclusion, although the effects of spindle speed and feed rate on thrust force were not statistically significant, the trends indicate that adjusting these parameters could enhance drilling performance on HPFRP materials.

4.7 Analysis of variance (ANOVA) of Roundness

This analysis aimed to assess the impact of spindle speed and feed rate on roundness during drilling of High-Performance Fiber Reinforced Plastic (HPFRP). The results from the ANOVA, shown in Table 4.6, indicate that neither spindle speed nor feed rate had a significant effect on roundness. The F-values were 2.89 for spindle speed (P-value = 0.167) and 1.5 for feed rate (P-value = 0.326), both showing no statistically significant impact.

Table 4.6: Analysis of Variance

Analysis of Variance for SN ratios

source	DF	Seq SS	Adj SS	Adj MS	F	P
Spindle Speed	2	51.106	51.106	25.553	2.89	0.167
feed Rate	2	26.542	26.542	13.271	1.5	0.326
Error	4	35.368	35.368	8.842		
Total	8	113.016				

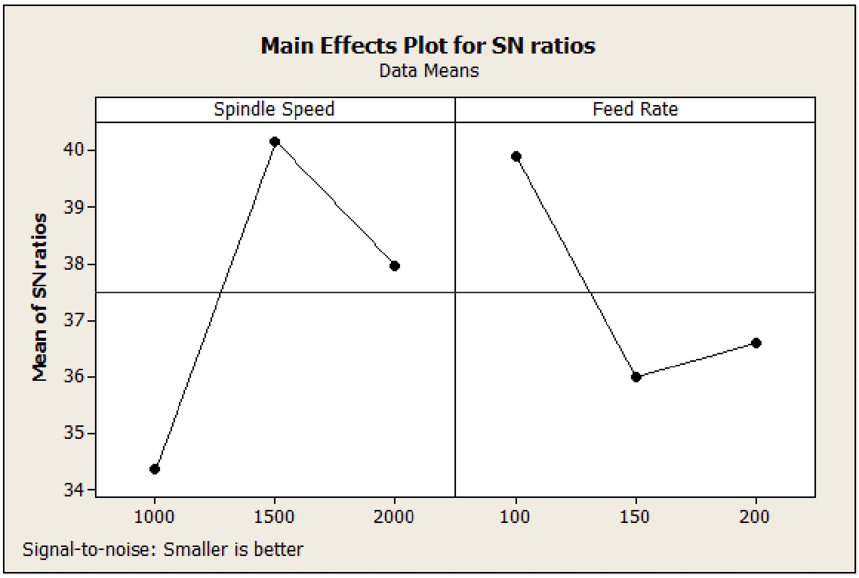


Figure 4.26: Main Effect Plot for SN ratios

The main effects plot (Figure 4.26) shows that 1500 RPM spindle speed resulted in the best roundness, and 100 mm/min feed rate provided the highest roundness. Despite no significant statistical results, these trends suggest that spindle speed and feed rate might still affect roundness and can be optimized for better drilling performance.

In conclusion, while the ANOVA did not show significant effects, adjusting spindle speed and feed rate may still help improve roundness in HPFRP drilling. Further studies should explore other factors like tool geometry or cutting fluid to better understand their impact on roundness.

4.8 Analysis of variance (ANOVA) of Tool Wear

This analysis aimed to evaluate the effect of spindle speed and feed rate on tool wear during the drilling of High-Performance Fiber Reinforced Plastic (HPFRP). The ANOVA results, summarized in the table below (Table 4.7) show that neither spindle speed nor feed rate had a statistically significant effect on tool wear. The F-value for spindle speed was 0.87 with a P-value of 0.485, and the F-value for feed rate was 0.14 with a P-value of 0.877.

Table 4.7: Analysis of Variance

Analysis of Variance for SN ratios

source	DF	Seq SS	Adj SS	Adj MS	F	P
Spindle Speed	2	0.15401	0.15401	0.077	0.87	0.485
feed Rate	2	0.02397	0.02397	0.01199	0.14	0.877
Error	4	0.3533	0.35339	0.08835		
Total	8	0.5313				

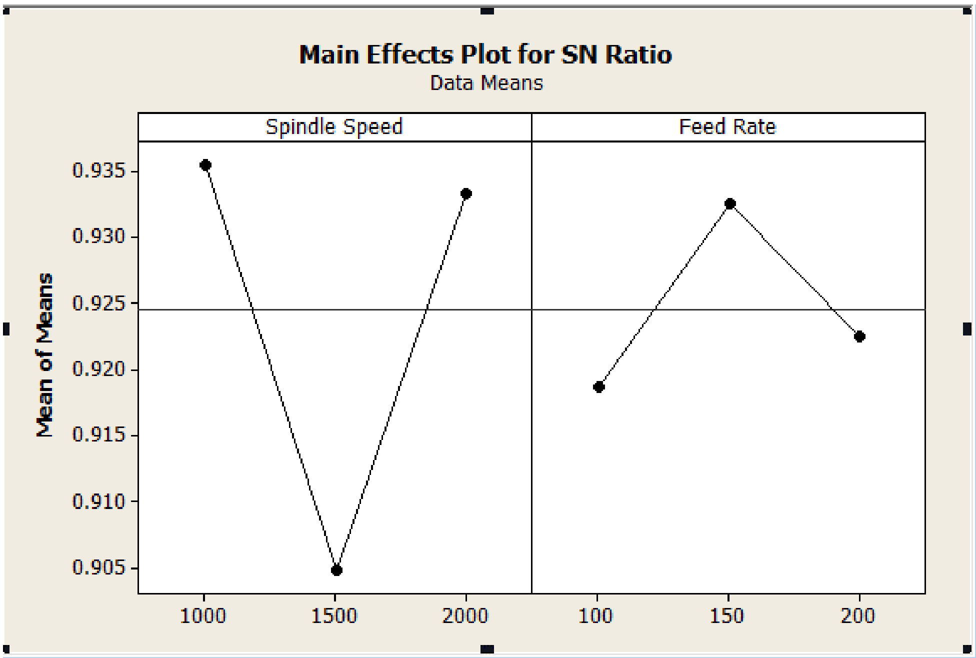


Figure 4.27: Main Effect Plot for SN ratios

The main effects plot for spindle speed (Figure 4.27) shows that tool wear is lowest at 1000 RPM and increases at both 1500 RPM and 2000 RPM, indicating that lower spindle speeds may be more favorable for reducing wear. For feed rate, the main effects plot suggests that 150 mm/min leads to the lowest tool wear, with an increase in wear at 100 mm/min and 200 mm/min.

Although the effects of spindle speed and feed rate were not statistically significant, the trends observed in the main effects plot suggest that optimizing these parameters could still help reduce tool wear. These trends align with previous research that suggests lower spindle speeds and feed rates can result in lower tool wear during drilling (Gokhan & Gokhan, 2014).

In conclusion, while spindle speed and feed rate did not show statistically significant effects on tool wear, the observed trends indicate that adjusting these parameters may reduce wear and improve the drilling performance. Further research could explore additional factors such as cutting speed and depth of cut to fully understand their impact on tool wear.

4.9 Analysis of variance (ANOVA) of Delamination

This analysis evaluated the impact of spindle speed and feed rate on delamination during the drilling of High-Performance Fiber Reinforced Plastic (HPFRP). The ANOVA results in Table 4.8 show that neither spindle speed nor feed rate significantly affected delamination. The F-values were 0.26 for spindle speed ($P = 0.785$) and 0.12 for feed rate ($P = 0.877$), indicating no significant impact.

Table 4.8: Analysis of Variance

Analysis of Variance for SN ratios

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Spindle Speed	2	0.0852	0.0852	0.0426	0.26	0.785
feed Rate	2	0.0396	0.0396	0.0198	0.12	0.89
Error	4	0.6608	0.6608	0.1652		
Total	8	0.7856				

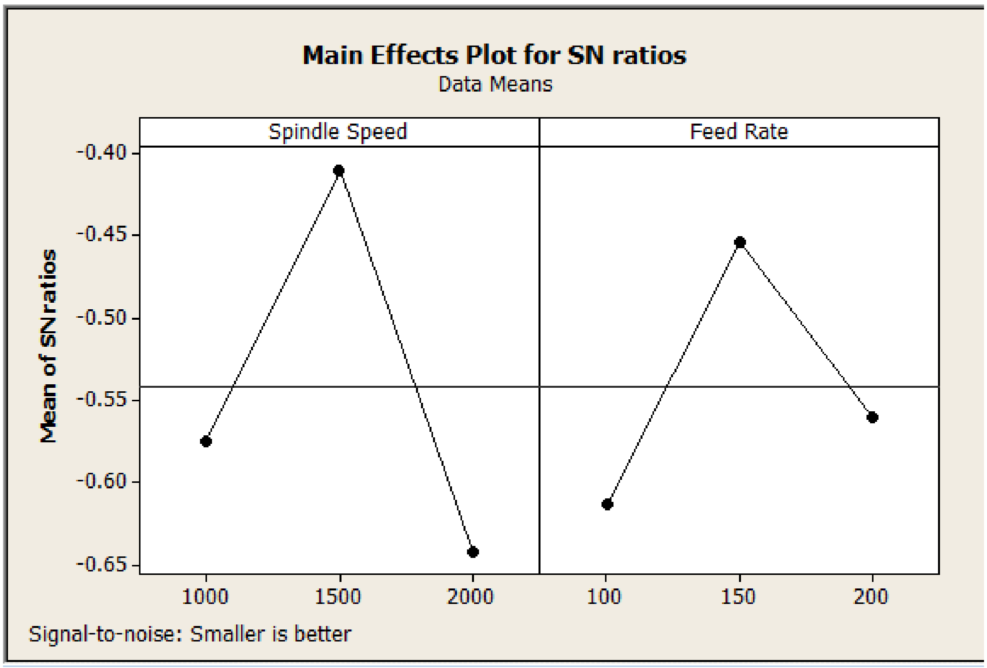


Figure 4.28: Main Effect Plot for SN ratios

The main effects plot for spindle speed (Figure 4.28) shows the highest delamination at 1000 RPM, while 1500 RPM and 2000 RPM had lower values. For feed rate, 100 mm/min led to the most delamination, with 150 mm/min and 200 mm/min showing a reduction in delamination.

Although not statistically significant, these trends suggest that optimizing spindle speed and feed rate could help reduce delamination. Future studies should consider other factors such as cutting speed and depth of cut for further insights.

4.10 Summary

In summary, the experimental analysis of drilling HPFRP materials revealed that spindle speed and feed rate significantly impacted parameters such as delamination, thrust force, and tool wear, though their individual effects were not statistically significant according to the ANOVA results. Despite this, the trends observed in the main effects plots indicated that a spindle speed of 1500 RPM and feed rate of 150 mm/min were optimal, leading to reduced delamination, thrust force, and tool wear. These settings provided a balanced combination that minimized stress on both the material and the tool, thereby improving drilling performance. The results highlighted the importance of optimizing spindle speed to improve overall efficiency and reduce tool damage during HFRP drilling.

CHAPTER 5

CONCLUSION

5.1 Introduction

This chapter presents a comprehensive analysis of the experimental study conducted to optimize spindle speed and feed rate for drilling HPFRP materials. The purpose of this chapter is to discuss key findings, offer recommendations, outline the limitations of the study, and provide a summary of the results. Drilling performance in composite materials is crucial, as factors such as delamination, thrust force, and tool wear directly affect the quality and efficiency of the drilling process. Despite the lack of statistically significant effects for spindle speed and feed rate on these parameters, the study reveals trends suggesting that optimizing these factors can still improve overall drilling performance. By exploring the effects of these parameters, this study contributes valuable insights into refining drilling conditions, ultimately leading to better material handling, reduced tool wear, and enhanced operational efficiency.

5.2 Recommendation

Based on the experimental findings, it is recommended that manufacturers optimize spindle speed at 1500 RPM and feed rate at 150 mm/min for drilling HPFRP materials. This combination showed potential for reducing delamination, thrust force, and tool wear. Additionally, it is recommended to use advanced monitoring tools, such as dynamometers, to track drilling performance in real-time. Regular tool inspections and wear analysis should be implemented to maintain optimal performance and extend tool life. For more accurate data, it is suggested to increase the number of test runs in future studies to improve the reliability of the results.

5.3 Project Potential

This study offers valuable insights into optimizing drilling parameters for HPFRP materials, which are increasingly used in industries such as aerospace, automotive, and construction. The findings suggest that by fine-tuning spindle speed **and** feed rate, manufacturers can improve drilling efficiency, reduce tool wear, and minimize material damage during drilling processes.

The potential of this project lies in its ability to enhance drilling performance in composite materials, ultimately leading to better product quality and reduced operational costs. Additionally, the study's results could be applied to other composite materials, broadening its scope and impact across various manufacturing sectors.

Future work can explore the scalability of these findings in industrial settings, particularly with advanced technologies such as real-time process monitoring, automation, and more robust drilling tools. The insights from this study can contribute to ongoing efforts to refine manufacturing processes, resulting in higher efficiency and better outcomes in composite material processing.

REFERENCES

Aamir, M., Tolouei-Rad, M., Giasin, K., & Nosrati, A. (2019a). Recent advances in drilling of carbon fiber–reinforced polymers for aerospace applications: a review. *International Journal of Advanced Manufacturing Technology*, *105*(5–6), 2289–2308. https://doi.org/10.1007/s00170019-04348-z

Aamir, M., Tolouei-Rad, M., Giasin, K., & Nosrati, A. (2019b). Recent advances in drilling of carbon fiber–reinforced polymers for aerospace applications: a review. *International Journal of Advanced Manufacturing Technology*, *105*(5–6), 2289–2308. https://doi.org/10.1007/s00170019-04348-z

Aly, N. M. (2017). A review on utilization of textile composites in transportation towards sustainability. *IOP Conference Series: Materials Science and Engineering*, *254*(4). https://doi.org/10.1088/1757-899X/254/4/042002

Ashrafi, S. A., Miller, P. W., Wandro, K. M., & Kim, D. (2016a). Characterization and effects of fiber pull-outs in hole quality of carbon fiber reinforced plastics composite. *Materials*, *9*(10). https://doi.org/10.3390/ma9100828

Ashrafi, S. A., Miller, P. W., Wandro, K. M., & Kim, D. (2016b). Characterization and effects of fiber pull-outs in hole quality of carbon fiber reinforced plastics composite. *Materials*, *9*(10). https://doi.org/10.3390/ma9100828

Babu, J., Paul, L., & Davim, J. P. (2018). 4. Drilling of composite materials: methods and tools. In *Drilling Technology* (pp. 109–148). De Gruyter. https://doi.org/10.1515/9783110481204-004

Bruno, M., Esposito, L., Papa, I., & Viscusi, A. (2023). Design, Manufacturing, and Numerical Characterization of Hybrid Fiber Reinforced Polymer under Dynamic Loads. *Journal of Materials Engineering and Performance*, *32*(9), 3905–3913. https://doi.org/10.1007/s11665023-07926-1

Catche, S., Piquet, R., Lachaud, F., Castanié, B., & Benaben, A. (2015). Analysis of hole wall defects of drilled carbon fiber reinforced polymer laminates. *Journal of Composite Materials*, *49*(10), 1223–1240. https://doi.org/10.1177/0021998314532668

Chaudhari, M., & Kumar, M. S. (2018). Reinforcement and Cutting Tools Interaction during MMC Machining - A Review. *Nano Hybrids and Composites*, *22*, 47–54. https://doi.org/10.4028/www.scientific.net/nhc.22.47

Dubey, A. K., & Yadava, V. (2008). Experimental study of Nd:YAG laser beam machining-An overview. In *Journal of Materials Processing Technology* (Vol. 195, Issues 1–3, pp. 15–26). https://doi.org/10.1016/j.jmatprotec.2007.05.041

Durão, L. M. P., Gonçalves, D. J. S., Tavares, J. M. R. S., de Albuquerque, V. H. C., Aguiar Vieira, A., & Torres Marques, A. (2010a). Drilling tool geometry evaluation for reinforced composite laminates. *Composite Structures*, *92*(7), 1545–1550. https://doi.org/10.1016/j.compstruct.2009.10.035

Durão, L. M. P., Gonçalves, D. J. S., Tavares, J. M. R. S., de Albuquerque, V. H. C., Aguiar Vieira, A., & Torres Marques, A. (2010b). Drilling tool geometry evaluation for reinforced composite laminates. *Composite Structures*, *92*(7), 1545–1550. https://doi.org/10.1016/j.compstruct.2009.10.035

Durão, L. M. P., Gonçalves, D. J. S., Tavares, J. M. R. S., de Albuquerque, V. H. C., Aguiar Vieira, A., & Torres Marques, A. (2010c). Drilling tool geometry evaluation for reinforced composite laminates. *Composite Structures*, *92*(7), 1545–1550. https://doi.org/10.1016/j.compstruct.2009.10.035

Feito, N., Díaz-Álvarez, J., Díaz-Álvarez, A., Cantero, J. L., López-Puente, J., & Miguelez, H. (2014). *INFLUENCE OF TOOL GEOMETRY IN DRILLING CFRP*.
Five Key Features of a Step Drill and Its Applications _ RUKO _ RUKO. https://ruko.de/en/knowledge/know-how/five-features-of-a-step-drill-and-its-applications/

Franz, G., Vantomme, P., & Hassan, M. H. (2022). A Review on Drilling of Multilayer FiberReinforced Polymer Composites and Aluminum Stacks: Optimization of Strategies for Improving the Drilling Performance of Aerospace Assemblies. In *Fibers* (Vol. 10, Issue 9). MDPI. https://doi.org/10.3390/fib10090078

Galińska, A. (2023). Influence of drill bit material on the bearing strength of holes in GFRP composite. *Archive of Mechanical Engineering*, *70*(2), 287–310. https://doi.org/10.24425/ame.2023.144818

Gambo Mohammed, A. (2014). *EXPERIMENTAL AND NUMERICAL APPROACH TO STUDY THE MECHANICAL BEHAVIOR OF THE FILAMENT WOUND COMPOSITE LEAF SPRING*. https://doi.org/10.13140/RG.2.2.21637.29925

Garg, S., Patra, K., & Pal, S. K. (2014). Particle swarm optimization of a neural network model in a machining process. *Sadhana - Academy Proceedings in Engineering Sciences*, *39*(3), 533–548. https://doi.org/10.1007/s12046-014-0244-7

Geier, N., Xu, J., Pereszlai, C., Poór, D. I., & Davim, J. P. (2020). Drilling of carbon fibre reinforced polymer (CFRP) composites: Difficulties, challenges and expectations. *Procedia Manufacturing*, *54*, 284–289. https://doi.org/10.1016/j.promfg.2021.07.045

George Tecusan. (2019). *Niu_Composite_Airframe_Structures*.
Hassim, B. (2018). *Advanced composite in aerospace application: A review on future aspect of fiberreinforced polymer (frp) in aerospace industry*. https://www.researchgate.net/publication/348759759

Ho-Cheng Graduate Student Research Assistant K H Dharan Associate Professor, H. C. (1990). *Delamination During Drilling in Composite Laminates*. http://www.asme.org/about-asme/termsof-use

Hocheng, H., & Tsao, C. C. (2003). Comprehensive analysis of delamination in drilling of composite materials with various drill bits. *Journal of Materials Processing Technology*, *140*(1-3 SPEC.), 335–339. https://doi.org/10.1016/S0924-0136(03)00749-0

Hocheng, H., & Tsao, C. C. (2005). The path towards delamination-free drilling of composite materials. *Journal of Materials Processing Technology*, *167*(2–3), 251–264. https://doi.org/10.1016/j.jmatprotec.2005.06.039

https://cuttingtoolschicago.com/step-drills/. (2023). *Step Drills - Cutting Tools Chicago*. https://cuttingtoolschicago.com/step-drills/

(2017). *GR3400J - shodensha*. https://emin.com.mm/shodenshagr3400j-ultra-high-definition-microscope-texture-of-metal-canbe-observed-up-to-600-times-zoom-in-shodensha-gr3400-38718/pr.html.

(2023). *Airbus A350*. https://en.wikipedia.org/wiki/Airbus_A350

Https://En.Wikipedia.Org/Wiki/Drill_bit.Drill.Bit https://en.wikipedia.org/wiki/Drill_bit

https://en.wikipedia.org/wiki/Speeds_and_feeds. (2024). *Speeds and feeds*. https://en.wikipedia.org/wiki/Speeds_and_feeds

https://global.toolstoday.com/learn/the-brad-point-boring-bit?glCountry=MY&glCurrency=MYR. (2024). *Brad Point Drill Bit– Rutlands Limited*. https://global.toolstoday.com/learn/the-bradpoint-boring-bit?glCountry=MY&glCurrency=MYR

https://industry.nikon.com/en-aom/products/optical-manual-m easuring/measuring-microscopes/mm-400-mm-800/. (2024). *MM-400N and MM-800N Series - Nikon Industrial Metrology*.

https://learn.toolingu.com/classes/drill-tool-geometry-371/. (2024). *Drill Tool Geometry 371*.

https://www.allied-material.co.jp/en/products/diamond/knowledge/cutting_formula.html. (2021).*Formula to calculate cutting process｜A.L.M.T. Corp.*

https://www.amazon.com/0-5mm-7mm-Carbide-Uncoated-Bright-Finish/dp/B0CNLH5ZWP (2024). *Amazon.com_ 0.5mm-7mm Solid Carbide Drill Bits Set, Uncoated Bright Finish Round Shank Spiral Flute Twist Drill Bit for Metal _ Industrial & Scientific*.

https://www.aptoolsltd.co.uk/product-category/drills-drill-reamers/dagger-drill-solid-carbide-gt50metric/. (2024). *Dagger Drill Solid Carbide Archives - AP Tools Ltd*. https://www.aptoolsltd.co.uk/product-category/drills-drill-reamers/dagger-drill-solid-carbidegt50-metric/

(2024). *10 Fun Facts About the 787 Boeing Dreamliner - Aversan*. https://www.aversan.com/10-fun-facts-about-the-787-boeing-dreamliner/

https://www.carbidedepot.com/formulas-drills-terms.htm. (2010). *Drills Term*. https://www.carbidedepot.com/formulas-drills-terms.htm

https://www.panamericantool.com/carbide-dagger-drills.html. (2024). *Carbide Dagger Drills*. https://www.panamericantool.com/carbide-dagger-drills.html tools.html?gad_source=1&gclid=CjwKCAjwyJqzBhBaEiwAWDRJVDbZRyOmWBciefAk18kVK35cG0umdl9maskOW-jCo3VwMdcUPFnXHhoCIYYQAvD_BwE. (2024). *Brad Point Drills*. https://www.panamericantool.com/composite

(2021). *Feed Rate vs Spindle Speed_ CNC Machining Quality*. https://www.rapiddirect.com/blog/difference-between-feed-rate-and-cutting-speed/

(2022). *Types of Machining Operations*. https://www.rapiddirect.com/blog/types-of-machining-operations/

(2022). *Drilling Machine Introdcution.PPT*. https://www.slideshare.net/slideshow/drilling-machine-ppt-88064601/88064601

Machining Time. 2021#:~:text=Machining%20time%20is%20the%20time,forward%20and%20making%20a%20 hole

https://www.velaction.com/machine-time/

Irina, M. M. W., Azmi, A. I., Tan, C. L., Lee, C. C., & Khalil, A. N. M. (2015). Evaluation of Mechanical Properties of Hybrid Fiber Reinforced Polymer Composites and their Architecture. *Procedia Manufacturing*, *2*, 236–240. https://doi.org/10.1016/j.promfg.2015.07.041

Jagadeesh, P., Mavinkere Rangappa, S., Suyambulingam, I., Siengchin, S., Puttegowda, M., Binoj, J. S., Gorbatyuk, S., Khan, A., Doddamani, M., Fiore, V., & Cuadrado, M. M. M. (2023). Drilling characteristics and properties analysis of fiber reinforced polymer composites: A comprehensive review. In *Heliyon* (Vol. 9, Issue 3). Elsevier Ltd. https://doi.org/10.1016/j.heliyon.2023.e14428

Jagannatha, T. D., Bhaskar, H. B., Sheriff, Z. A., & Irfan, G. (2019). Optimization of machining parameters of hybrid fiber reinforced polymer composites using design of experiments. *AIP Conference Proceedings*, *2057*. https://doi.org/10.1063/1.5085579

Khashaba, U. A. (2013). Drilling of polymer matrix composites: A review. In *Journal of Composite Materials* (Vol. 47, Issue 15, pp. 1817–1832). https://doi.org/10.1177/0021998312451609

Khashaba, U. A., El-Sonbaty, I. A., Selmy, A. I., & Megahed, A. A. (2010). Machinability analysis in drilling woven GFR/epoxy composites: Part I - Effect of machining parameters. *Composites Part A: Applied Science and Manufacturing*, *41*(3), 391–400. https://doi.org/10.1016/j.compositesa.2009.11.006

Kinjawadekar, T. A., Patil, S., & Nayak, G. (2023). A Critical Review on Glass Fiber-Reinforced Polymer Bars as Reinforcement in Flexural Members. In *Journal of The Institution of Engineers (India): Series A* (Vol. 104, Issue 2, pp. 501–516). Springer. https://doi.org/10.1007/s40030-02300729-6

Koklu, U., Morkavuk, S., Featherston, C., Haddad, M., Sanders, D., Aamir, M., Danil, &, Pimenov, Y., & Giasin, K. (n.d.). *The effect of cryogenic machining of S2 glass fibre composite on the hole form and dimensional tolerances*. https://doi.org/10.1007/s00170-021-07150-y/Published

Krishnaraj, V., Prabukarthi, A., Ramanathan, A., Elanghovan, N., Kumar, M. S., Zitoune, R., & Davim, J. P. (2012). Optimization of machining parameters at high speed drilling of carbon fiber reinforced plastic (CFRP) laminates. *Composites Part B: Engineering*, *43*(4), 1791–1799. https://doi.org/10.1016/j.compositesb.2012.01.007

Lee, S. C., Jeong, S. T., Park, J. N., Kim, S. J., & Cho, G. J. (2008). Study on drilling characteristics and mechanical properties of CFRP composites. *Acta Mechanica Solida Sinica*, *21*(4), 364–368. https://doi.org/10.1007/s10338-008-0844-z

Linbo, Z., Lijiang, W., & Xin, W. (2003). *Study on vibration drilling of fiber reinforced plastics with hybrid variation parameters method*. www.elsevier.com/locate/compositesa

Liu, D. F., Tang, Y. J., & Cong, W. L. (2012). A review of mechanical drilling for composite laminates. In *Composite Structures* (Vol. 94, Issue 4, pp. 1265–1279). https://doi.org/10.1016/j.compstruct.2011.11.024

López De Lacalle, L. N., Pérez-Bilbatua, J., Sánchez, J. A., Llorente, J. I., Gutiérrez, A., & Albóniga, J. (2000b). Using High Pressure Coolant in the Drilling and Turning of Low Machinability Alloys. In *Int J Adv Manuf Technol*.
http://doi.org/10.1007/s001700050012

Mallick, P. (2015). *Fiber Reinforced Composites Materials, Manufacturing, and Design*.
Maoinser, M. A., Ahmad, F., Sharif, S., & Keong, W. T. (n.d.). *Minimizing Drilling Thrust Force for HFRP Composite by Optimizing Process Parameters using Combination of ANOVA Approach and S/N Ratios Analysis*. https://doi.org/10.1051/C

Maoinser, M. A., Ahmad, F., Sharif, S., & Keong, W. T. (2016). *Minimizing Drilling Thrust Force for HFRP Composite by Optimizing Process Parameters using Combination of ANOVA Approach and S/N Ratios Analysis*. https://doi.org/10.1051/C

Maoinser, M. A., Ahmad, F., Shariff, S., & Woo, T. K. (2014). Effects of twist drill point angle on thrust force and delamination factor in hybrid fiber composites drilling. *Applied Mechanics and Materials*, *564*, 501–506. https://doi.org/10.4028/www.scientific.net/AMM.564.501

Maria, M. (2013). Advanced composite materials of the future in aerospace industry. *INCAS BULLETIN*, *5*(3), 139–150. https://doi.org/10.13111/2066-8201.2013.5.3.14

Mazumdar, S. K. (2002). *Composites manufacturing : materials, product, and process engineering*. CRC Press.
Mishra, R., Malik, J., & Singh, I. (2010). Prediction of drilling-induced damage in unidirectional glass-fibre-reinforced plastic laminates using an artificial neural network. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, *224*(5), 733– 738. https://doi.org/10.1243/09544054JEM1760

Mouritz, A. P. (2012). *Introduction to aerospace materials*. American Institute of Aeronautics and Astronautics.
N.A Azalina. (2024). *Investigation of the effects of tool geometry features to minimize the damages during trimming of hybrid fiber reinforced polymer(HFRP) Material-Aerostructural component*.

Nargis, T., Shahabaz, S. M., Acharya, S., Shetty, N., Malghan, R. L., & Shetty, S. D. (2024). A Comprehensive Study on the Optimization of Drilling Performance in Hybrid Nano-Composites and Neat CFRP Composites Using Statistical and Machine Learning Approaches. *Journal of Manufacturing and Materials Processing*, *8*(2). https://doi.org/10.3390/jmmp8020067

Natarajan, E., Markandan, K., Sekar, S. M., Varadaraju, K., Nesappan, S., Albert Selvaraj, A. D., Lim, W. H., & Franz, G. (2022). Drilling-Induced Damages in Hybrid Carbon and Glass Fiber-Reinforced Composite Laminate and Optimized Drilling Parameters. *Journal of Composites Science*, *6*(10). https://doi.org/10.3390/jcs6100310

NitPro Composites. (2023). *Important usus of Carbon Fiber Sheets*. https://medium.com/@nitprocomposites/5-important-uses-of-carbon-fiber-sheets-ec81a672b1b3

Professor, A., Shunmugesh, K., Aravind, S., & Pramodkumar, M. (2017). Optimization of Drilling Characteristics using Grey Relational Analysis (GRA) in Glass Fiber Reinforced Polymer (GFRP). In *Materials Today: Proceedings* (Vol. 4). www.sciencedirect.comwww.materialstoday.com/proceedings

Quilter, A. (n.d.). *Composites in Aerospace Applications*.
R Rodrigues, L. L., Brn, M., Rodrigues, L. L., & Devineni, A. (2012). Process Parameters Optimization in GFRP Drilling through Integration of Taguchi and Response Surface Methodology. In *Research Journal of Recent Sciences* (Vol. 1, Issue 6). https://www.researchgate.net/publication/267424855

Rakesh, P. K., Singh, I., & Kumar, D. (2012). Drilling of composite laminates with solid and hollow drill point geometries. *Journal of Composite Materials*, *46*(25), 3173–3180. https://doi.org/10.1177/0021998312436997

Rampal, Kumar, G., Rangappa, S. M., Siengchin, S., & Zafar, S. (2022). A review of recent advancements in drilling of fiber-reinforced polymer composites. In *Composites Part C: Open Access* (Vol. 9). Elsevier B.V. https://doi.org/10.1016/j.jcomc.2022.100312

Ramulu, 2016. (2016). *MACHINABILITY OF TITANIUM/GRAPHITE HYBRID COMPOSITES IN DRILLING*. https://www.researchgate.net/publication/279571612

Sambhav, K., Dhande, S. G., & Tandon, P. (2010). CAD Based Mechanistic Modeling of Forces for Generic Drill Point Geometry. *Computer-Aided Design and Applications*, *7*(6), 809–819. https://doi.org/10.3722/cadaps.2010.809-819

Sambhav, K., Tandon, P., & Dhande, S. G. (2012). Geometric modeling and validation of twist drills with a generic point profile. *Applied Mathematical Modelling*, *36*(6), 2384–2403. https://doi.org/10.1016/j.apm.2011.08.034

Sedlacek, J., & Slany, M. (2019). *ANALYSIS OF DELAMINATION IN DRILLING OF COMPOSITE MATERIALS*.
Srinivasan, T., Palanikumar, K., & Rajagopal, K. (2014). Influence of Thrust Force in Drilling of Glass Fiber Reinforced Polycarbonate (GFR/PC) Thermoplastic Matrix Composites Using Boxbehnken Design. *Procedia Materials Science*, *5*, 2152–2158. https://doi.org/10.1016/j.mspro.2014.07.419

Stone, R., & Krishnamurthy, K. (1996). A NEURAL NETWORK THRUST FORCE CONTROLLER TO MINIMIZE DELAMINATION DURING DRILLING OF GRAPHITE-EPOXY LAMINATES. In *Tools Manure* (Vol. 36, Issue 9).
Suresh Kumar, B., Baskar, N., & Rajaguru, K. (2020). Drilling operation: A review. *Materials Today: Proceedings*, *21*, 926–933. https://doi.org/10.1016/j.matpr.2019.08.160

Tan, C. L., Azmi, A. I., & Muhammad, N. (2015). Surface Roughness Analysis of Carbon/Glass Hybrid Polymer Composites in Drilling Process Based on Taguchi and Response Surface Methodology. *Advanced Materials Research*, *1119*, 622–627. https://doi.org/10.4028/www.scientific.net/amr.1119.622

Teimouri, R., & Amini, S. (2019). Analytical and experimental approaches to study elastic deflection of thin strip in ultrasonic-assisted drilling process. *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering*, *233*(1), 21–34. https://doi.org/10.1177/0954408917739453

Thomas, J. (2005). optimizing drilling parameters of GFRP using Grey Relation Analysis. In *IJRET: International Journal of Research in Engineering and Technology*. http://www.ijret.org

Trzepieciński, T., Najm, S. M., Sbayti, M., Belhadjsalah, H., Szpunar, M., & Lemu, H. G. (2021). New advances and future possibilities in forming technology of hybrid metal–polymer composites used in aerospace applications. In *Journal of Composites Science* (Vol. 5, Issue 8). MDPI AG. https://doi.org/10.3390/jcs5080217

Turnad, L. G., & Bambang, A. (2014). Cutting force and temperature variation in bone drilling - A review. *Advanced Materials Research*, *845*, 934–938. https://doi.org/10.4028/www.scientific.net/AMR.845.934

Upputuri, H. B., & Nimmagadda, V. S. (2020). Optimization of drilling process parameters used in machining of glass fiber reinforced epoxy composite. *Materials Today: Proceedings*, *23*, 594– 599. https://doi.org/10.1016/j.matpr.2019.05.415

Yi, X. S. (2015). Development of multifunctional composites for aerospace application. In *Multifunctionality of Polymer Composites: Challenges and New Solutions* (pp. 367–418). Elsevier Inc. https://doi.org/10.1016/B978-0-323-26434-1.00011-8

Zhang, G., To, S., & Zhang, S. (2016). Evaluation for tool flank wear and its influences on surface roughness in ultra-precision raster fly cutting. *International Journal of Mechanical Sciences*, *118*, 125–134. https://doi.org/10.1016/j.ijmecsci.2016.09.013

APPENDICES

APPENDIX A GUN CHART for PSM 2

Task/Planning	WEEK													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
PSM 2: PROJECT BRIEFING	■													
Drrilling HFRP		■												
Get data for Roundness			■											
Get data for Thrust Force				■										
Get data for Tool wear					■									
Get data for Delamination						■								
CHAPTER 4: RESULT & DISCUSSION														
- Report Writing							■	■	■	■	■	■		
CHAPTER 5: CONCLUSION														
- Report Writing											■	■	■	
OTHERS PREPARATION														
Format Thesis													■	
Gantt Chart	■	■	■	■	■	■	■	■	■	■	■	■	■	
Poster Presentation Preparation													■	
Presentation														■
Submit Final PSM 2 Report													■	

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