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MACHINING PERFORMANCE WITH RESPECT TO CUTTING FORCES, VIBRATIONS AND SURFACE QUALITY IN DRILLING OF HYBRID ABACA AND GLASS FIBERS REINFORCED POLYMER COMPOSITE

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ABSTRACT: Initially, polymer composites utilized synthetic fibers as reinforcements due to their high strength and excellent water resistance. However, synthetic fibers are non-biodegradable, and their manufacturing process involves chemicals, rendering them environmentally unfriendly. Consequently, natural fibers began to be employed owing to their low production costs and inherent biodegradability. Nevertheless, natural fibers possess lower strength and non-uniform sizes, making them challenging to shape. Hybrid composites have been developed to address these limitations, combining synthetic and natural fibers to leverage their respective advantages and mitigate each other's shortcomings. As a result, hybrid composites are increasingly being adopted in various industries, including automotive, construction, sports, and electronics. During production, hybrid composite panels still require machining processes, such as milling to smooth the surface and drilling to create connecting holes, to become final products. Careful selection of machining parameters are needed to ensure product quality and minimize defects, including tool wear, fiber debonding, and delamination. Cutting forces and vibrations, critical factors influencing machining performance, can be regulated through optimized cutting conditions. This study examines the effects of cutting conditions on cutting forces and vibrations while drilling hybrid composites composed of abaca and glass fibers. Composite panels were fabricated using the compression molding method, consisting of 10% abaca fiber, 10% glass fiber, and 80% polyester resin with 1% hardener by weight. Drilling experiments were conducted using a two-flute high-speed steel (HSS) cutting tool under varying spindle speeds and feed rates. The results revealed that cutting parameters significantly influenced machining behaviour. Specifically, higher spindle speeds increased cutting forces by up to approximately 15%, whereas higher feed rates amplified vibration acceleration by up to 67.8%. These findings contribute to a deeper understanding of machining performance and provide valuable insights for optimizing drilling parameters to enhance machining efficiency and surface quality in hybrid natural–synthetic fiber composites.

ABSTRAK: Pada mulanya, komposit polimer menggunakan serat sintetik sebagai penguat kerana kekuatannya yang tinggi dan rintangan air terbaik. Walau bagaimanapun, serat sintetik tidak terbiodegradasi, dan proses pembuatannya melibatkan bahan kimia, menjadikannya tidak mesra alam. Akibatnya, serat semula jadi mula digunakan kerana kos pengeluarannya yang rendah dan kebolehbiodegradan. Namun begitu, serat semulajadi mempunyai kekuatan lebih rendah dan saiz tidak seragam, menjadikannya sukar dibentuk. Bagi menangani masalah ini, komposit hibrid dibangunkan, menggabungkan serat sintetik dan semulajadi bagi memanfaatkan kelebihan masing-masing dan mengurangkan kelemahan masing-masing. Hasilnya, komposit hibrid semakin diterima pakai dalam pelbagai industri, termasuk automotif, pembinaan, sukan dan elektronik. Semasa peringkat pengeluaran, panel komposit hibrid masih memerlukan proses pemesinan, seperti milling bagi melicinkan permukaan dan penggerudian bagi mencipta lubang penyambung, sebelum menjadi produk akhir. Pemilihan parameter pemesinan yang teliti diperlukan bagi memastikan kualiti produk dan meminimumkan kecacatan, termasuk haus alat, nyah ikatan gentian dan penyimpangan. Daya pemotongan dan getaran, yang merupakan faktor kritikal mempengaruhi prestasi pemesinan, dapat dikawal melalui keadaan pemotongan yang optimum. Kajian ini mengkaji kesan keadaan pemotongan ke atas daya pemotongan dan getaran semasa penggerudian komposit hibrid yang terdiri daripada serat abaka dan gentian kaca. Panel komposit telah difabrikasi menggunakan kaedah pengacuan mampatan, yang terdiri daripada 10% gentian abaka, 10% gentian kaca, dan 80% resin poliester dengan 1% pengeras mengikut berat. Eksperimen penggerudian telah dijalankan menggunakan alat pemotong keluli berkelajuan tinggi (HSS) dua mata di bawah kelajuan dan kadar suapan berbeza. Dapatan menunjukkan bahawa parameter pemotongan mempengaruhi tingkah laku pemesinan dengan ketara. Khususnya, kelajuan lebih tinggi menyebabkan daya pemotongan meningkat sehingga kira-kira 15%, manakala kadar suapan lebih tinggi menguatkan pecutan getaran sehingga 67.8%. Penemuan ini menyumbang kepada pemahaman yang lebih mendalam tentang prestasi pemesinan dan menyumbang pandangan berharga dalam mengoptimum parameter penggerudian bagi meningkatkan kecekapan pemesinan dan kualiti permukaan komposit serat semulajadi-sintetik hibrid.

KEYWORDS: *Hybrid Composite; Abaca and Glass Fiber; Drilling Process; Cutting Force; Vibration*

1. INTRODUCTION

The technical and economic advantages of Fiber Reinforced Polymer (FRP) composites stem from their properties differing from those of their individual constituent materials. The primary benefits of these composites include high strength, toughness, stiffness, low weight, and excellent creep resistance, which contribute to reduced risks of corrosion, wear, and fatigue compared to conventional materials. These characteristics highlight the remarkable versatility of FRP composites in meeting diverse industrial requirements across mechanical, electrical, magnetic, optical, and thermal properties, capabilities that monolithic materials cannot achieve. Consequently, these advantages make FRP composites highly desirable for various applications, from commercial aircraft development to sports equipment [1].

Fibers used as reinforcement in polymer composites are classified into two types: synthetic fibers and natural fibers. Synthetic fibers are produced through chemical processes using non-natural materials, typically derived from petrochemical polymers. These fibers exhibit excellent mechanical and physical properties; however, their manufacturing process generates chemical waste and may cause skin irritation in workers and users. Additionally, synthetic fibers are non-biodegradable, posing potential environmental concerns [1].

In contrast, natural fibers originate from renewable sources such as plants, animals, or minerals and are produced without synthetic chemicals or artificial processes. Commonly used natural fibers in industrial applications include cotton, hemp, jute, abaca, wool, silk, and cashmere. These fibers offer significant environmental advantages: they are renewable, biodegradable, and recyclable. However, natural fibers generally have lower resistance to extreme weather conditions, humidity, and UV radiation, making them more susceptible to degradation or mold growth under certain conditions. Furthermore, they tend to be less dimensionally stable, as they may shrink or stretch after washing [2].

Researchers have developed hybrid composites to address this issue by combining two types of fibers. Typically, one fiber in a hybrid composite has a lower modulus or cost, such as glass or Kevlar fiber. In comparison, other fibers, such as boron or carbon fiber, possess a higher modulus or cost. This combination optimizes the material's mechanical properties and cost-effectiveness. Consequently, natural fibers used as reinforcements in polymer composites can be combined with synthetic fibers, such as hemp and glass fibers [3], jute and Kevlar [4], or carbon and hemp [5].

Abaca fiber is a cellulose-based fiber obtained from the pseudostem of the abaca (Musa textilis) or banana plant. One of the key economic advantages of the abaca plant is its ability to grow without requiring fertilizers, pesticides, or large amounts of water [6]. Abaca fiber is widely recognized for its high strength, resistance to saltwater, and durability. Its long-term resilience and flexibility make it suitable for various applications. Additionally, abaca fiber is classified as a lightweight natural fiber, contributing to product strength without adding significant weight. Moreover, abaca fiber is environmentally friendly due to its biodegradability, which prevents environmental pollution. However, despite its advantages, abaca fiber has limitations in terms of thickness and length variation, which may result in unevenness and reduced resistance to sudden impacts or pressure [7].

Glass fiber is produced by drawing molten glass into thin threads that can be spun. It is widely utilized in various industries for manufacturing products such as automobile bodies, aircraft, and ships. Glass fiber exhibits high tensile strength, making it an excellent reinforcing material in composite structures. Despite its strength, it remains relatively lightweight, which helps reduce the overall weight of the final product. Additionally, glass fiber exhibits resistance to corrosion, chemicals, and moisture, which contributes to its durability. It also possesses excellent thermal and electrical insulation properties and can withstand high temperatures. The ability to be molded into various sizes and shapes, along with its recyclability, enhances its appeal as an environmentally friendly material. However, glass fiber has certain limitations. It is less impact-resistant and may crack or break when subjected to sudden force or pressure. Moreover, its rough texture can cause discomfort upon direct skin contact, limiting its application in consumer products that require frequent handling. The glass fiber manufacturing process is energy-intensive, which impacts both production costs and environmental sustainability. Compared to certain synthetic fibers, such as carbon fiber, glass fiber is more brittle and less resistant to fatigue or long-term structural degradation [8, 9].

Utilizing hybrid composites involves integrating two types of fibers within a single composite structure. A particularly advantageous approach is the combination of natural and synthetic fibers, as this can result in composite materials that are strong, cost-effective, and environmentally friendly. By incorporating abaca fibers and glass fibers, the composite's specific mechanical and physical properties can be enhanced, leading to improved product quality and a more efficient manufacturing process [10].

Raj et al. [11] investigated the mechanical properties of hybrid composites reinforced with abaca-glass and abaca-Kevlar fibers. The results revealed that incorporating glass and Kevlar fibers significantly enhanced the tensile, flexural, and impact strengths, rendering the hybrid composites superior to the abaca composite alone. Although the abaca-Kevlar hybrid composite exhibited greater stability, the abaca-glass hybrid composite proved more efficient, as its strength was only marginally lower than that of the glass composite alone. Prakash et al. [12] investigated the abrasive wear behavior of abaca-glass fiber hybrid composites using a pin-on-disc tribo-test. They reported that the hybridization of glass fibers into abaca fibers and an epoxy matrix significantly enhanced the wear properties, making it a qualified high-wear-resistance polymer composite. Qahhar et al. [13] studied the vibration in the milling of abaca-glass fiber hybrid composites. They found that cutting parameters, such as spindle speed, feed rate, and depth of cut, significantly affected the vibration. The study concluded that vibration can be controlled by selecting appropriate cutting conditions, reducing the tool wear rate, and maintaining surface quality.

In general, composites are not final products; additional processing steps are required, such as cutting to achieve the desired shape and size and drilling to create holes for assembly purposes. However, drilling composite materials presents several challenges, including 'delamination', which occurs when composite layers separate during machining [14]; 'tool wear', which shortens tool lifespan and increases production costs [15]; and 'excessive heat generation', which can degrade the polymer matrix, cause thermal damage, and reduce the mechanical properties of the composite [16]. Additionally, sudden variations in cutting force can lead to process instability and unpredictability [17], while excessive vibration may result in rough surfaces, reduced precision, and lower cutting accuracy and quality [18, 19]. These factors can hinder the attainment of optimal machining results for composite materials.

To mitigate these issues, it is essential to optimize cutting conditions by selecting appropriate cutting parameters, using sharp and suitable cutting tools for composite materials, and ensuring adequate cooling to prevent excessive heat buildup. Proper techniques like cutting in the correct direction or using lubricants can help minimize tool wear and avoid delamination. Moreover, routine maintenance of cutting equipment plays a crucial role in maintaining cutting efficiency and accuracy. By applying these strategies, cutting quality can be enhanced, and potential machining issues can be minimized, ensuring that the final composite product remains high in quality and performance [20-22].

This study investigates the cutting force and vibration generated during drilling a hybrid composite composed of abaca fiber and glass fiber. The composite was fabricated using the press molding method, with polyester resin as the matrix and abaca and glass fibers as the reinforcing materials. Drilling was performed using a two-flute high-speed steel (HSS) cutting tool with a 12 mm diameter, while varying the cutting parameters, specifically spindle speed and feed rate.

2. RESEARCH METHODS

2.1.Preparation of the materials

The specimen mold was constructed from a steel plate featuring a square pocket measuring 200 mm on each side with a thickness of 5 mm. Abaca fibers, obtained from CV Naturi, Aceh, Indonesia, were combed to obtain a uniform maximum diameter of 1 mm, then rinsed with water and dried in the sun, and finally cut into uniform lengths of 20 mm. The glass fiber (chopped strand mat type 120E, procured from Chemposite Store, Surabaya, Indonesia) was cut into 200 mm × 200 mm squares. Each piece of glass fiber with this dimension weighed 10 grams. The fabrication of the hybrid abaca-glass fiber composite panel is illustrated in Figure 1, following these steps.

Polyester resin and hardener (Yukalac 157 BQTN-EX Series, manufactured by Justus, Indonesia) were mixed in a ratio of 100:1 (Figure 1a). A layer of wax was applied to the bottom surface of the mold to prevent the composite panel from adhering to the mold. The polyester resin was poured evenly into the mold (Figure 1b). Next, 10 grams of abaca fiber were randomly distributed within the mold (Figure 1c), followed by another uniform layer of polyester resin. Two layers of glass fiber, weighing 20 grams, were placed over the abaca fiber (Figure 1d), and another layer of polyester resin was poured uniformly onto the glass fiber. As the final layer, 10 grams of abaca fiber were randomly distributed over the glass fiber (Figure 1e), and a final coating of polyester resin was applied.

A steel plate was placed on top of the mold (Figure 1f), and the mold was then positioned in a press machine, where pressure was applied until the steel plate and mold were securely locked in place (Figure 1g). The mold remained closed for four hours, allowing sufficient time for the natural curing process. Once cured, the composite panel was removed from the mold and prepared for drilling (Figure 1h). The total weight of the composite panel was 201 grams, resulting in a fiber-to-matrix weight ratio of 20:80.

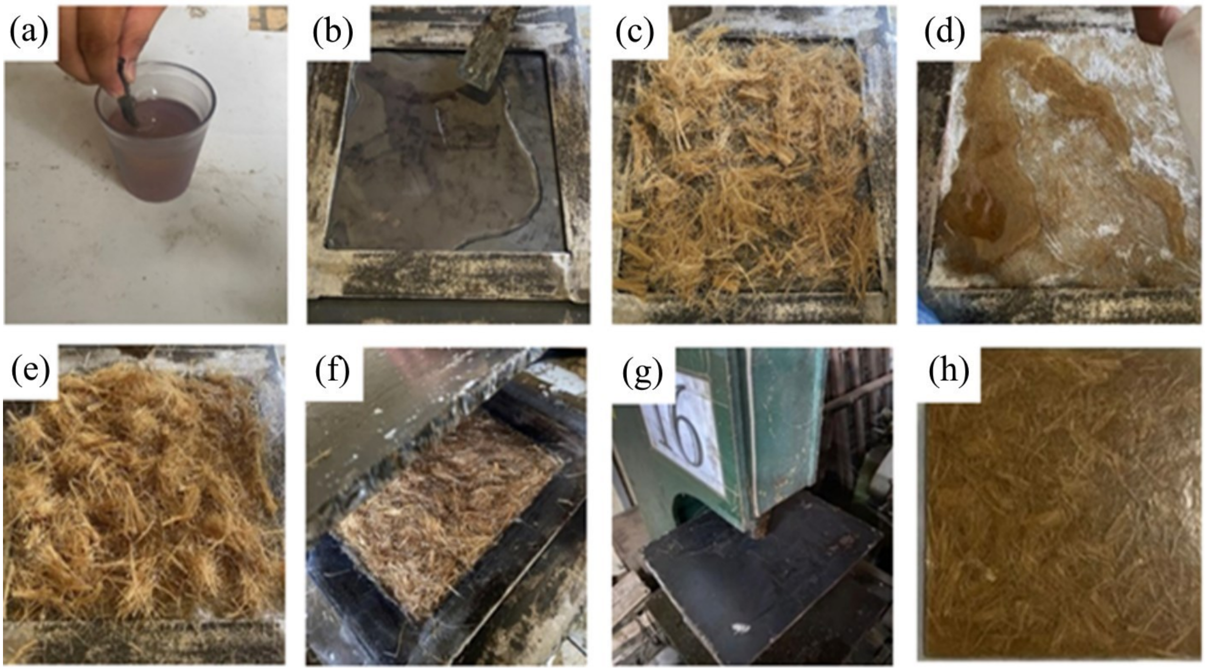

Figure 1. The Fabrication process of the composite panel: (a) mixing polyester resin with hardener, (b) pouring the polyester resin into the mold, (c) placing abaca fibers for the first layer, (d) placement of glass fiber, (e) placing abaca fibers for the final layer, (f) placement of the steel mold, (g) application of pressure load and (h) the composite panel.

2.2.Experimental Setup

The configuration of the drilling process and the equipment used to measure cutting force and acceleration is shown in the experimental setup (Figure 2). The hybrid abaca-glass fiber composite panel was securely clamped on top of the dynamometer (semiconductor stationary dynamometer with force sensing and piezoresistive strain sensors) using a jig and fixture [23]. An accelerometer sensor (PCB Piezotronics, model 352C33) was attached to the test object. Data acquisition was performed by connecting the system to a computer, where the Neo-MoMac software was used: National Instruments NI 9237 for recording the cutting force signal and National Instruments NI 9520 for capturing the vibration signal generated during the drilling process.

This research investigates the effect of cutting parameters on cutting force and vibration during the drilling of hybrid abaca-glass fiber composites. The cutting parameters considered in this study were spindle speed and feed rate, which are crucial in determining process efficiency and drilling quality. Variations in spindle speed and feed rate were applied to analyze their influence on cutting forces, cutting vibrations, drill hole surface quality, and overall drilling performance. Three levels of each parameter were defined based on the tool catalog recommendations for drilling composite materials using an HSS tool, as shown in Table 1.

The experiment was designed using a complete factorial configuration. The Design of Experiment (DOE) resulted in nine cutting conditions for two variables with three levels each. Five drillings were performed for each condition, and the average value was taken as the final measurement. The distances between the holes in the composite panel were 20 mm and 37 mm, resulting in 15 holes per panel. Three composite panels were prepared, each used to drill five holes for each of the nine cutting conditions.

The drilling was performed using an Agma A-8 CNC machine with a 12 mm, 2-flute HSS drill tool (Nachi, type L/N 500, procured from Sumber Teknik Mandiri, Jakarta, Indonesia). Cutting force and vibration signals were recorded from when the cutting tool made contact with the composite surface until it retracted after penetration, and the cutting process stopped. The measurement results were displayed graphically on the computer screen and exported to a Microsoft Excel file.

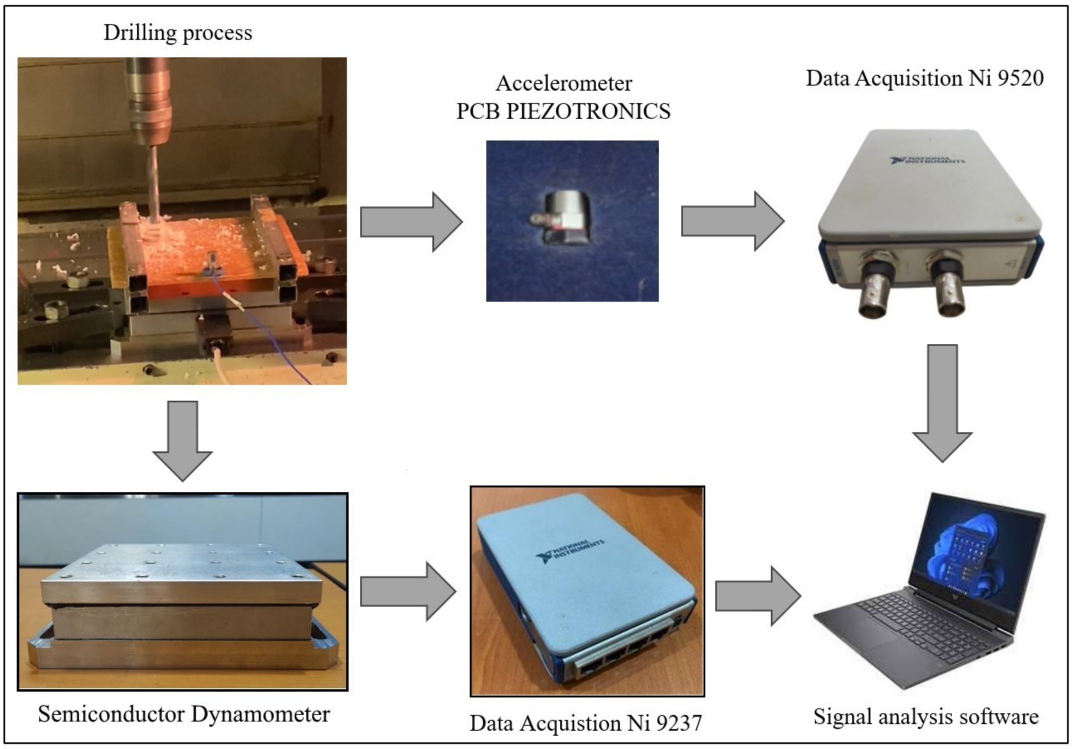

Figure 2. The experimental setup.

Table 1. Experimental parameters

No.	Level	Spindle Speed, N (rpm)	Feed Rate, F (mm/rev)
1	-1	1000	0.10
2	0	1500	0.15
3	1	2000	0.20

3. RESULTS AND DISCUSSION

3.1.The drilling process and data collection

Figure 3 shows the abaca-glass fiber hybrid composite panels after the drilling process. During the drilling process, the cutting forces were measured using the dynamometer and recorded in volts by the NI 9237 data acquisition system. The recorded data were then converted to Newtons by multiplying them by the corresponding sensitivity values. The sensitivity values were 2.365 for the x-axis, 2.279 for the y-axis, and 3.806 for the z-axis. The cutting force signals (in Newtons) were then plotted using MATLAB, as shown in Figure 4.

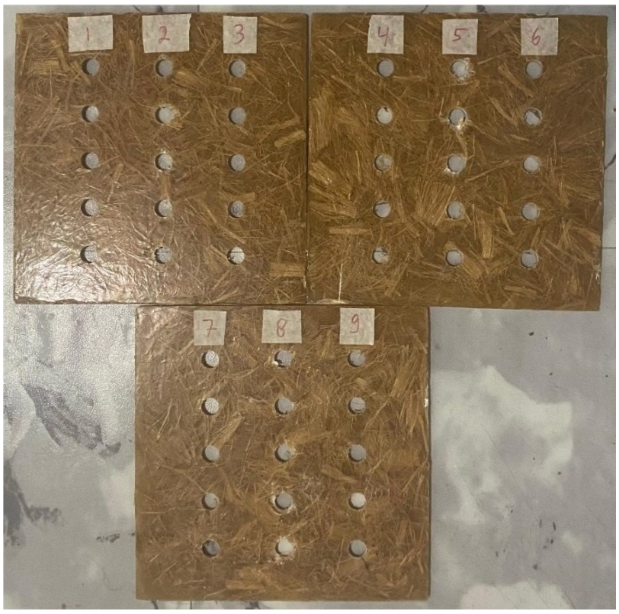

Figure 3. The abaca-glass fiber hybrid composite panels after the drilling process.

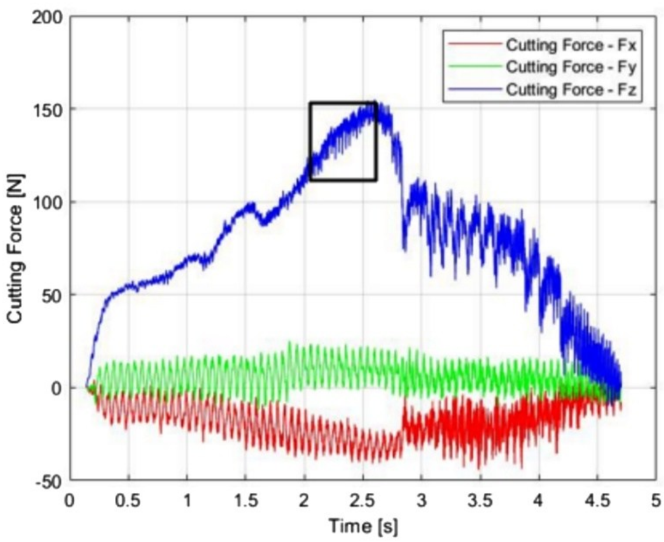

Figure 4. The cutting force signals.

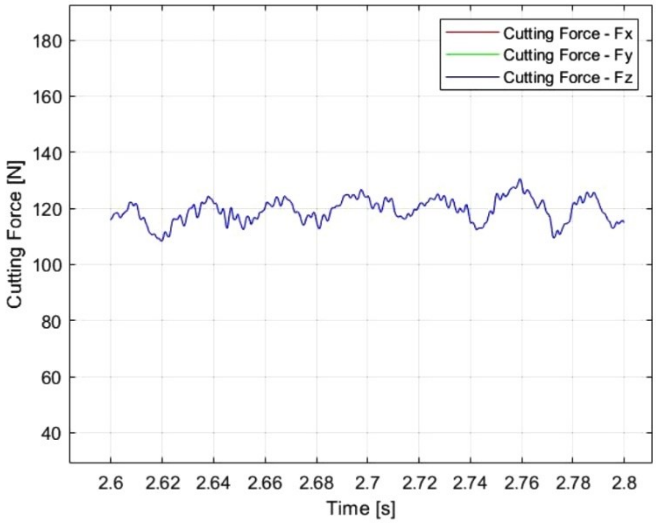

Figure 5. Cutting force signals after being processed.

As shown in Figure 4, the dominant cutting force was Fz (represented by the blue signal), which corresponds to the z-axis direction, or the axial/vertical direction of the cutting tool. The cutting force signal appeared when the drill bit first made contact with the surface of the composite panel and increased as the tool continued to penetrate the material. When the entire cutting edge of the drill was in complete contact with the composite surface, the force signal reached its maximum level. As the drill bit exited the opposite side of the composite panel, the force signal gradually decreased. The cutting force value was determined by averaging the uniform signal at the maximum level, as shown in Figure 5.

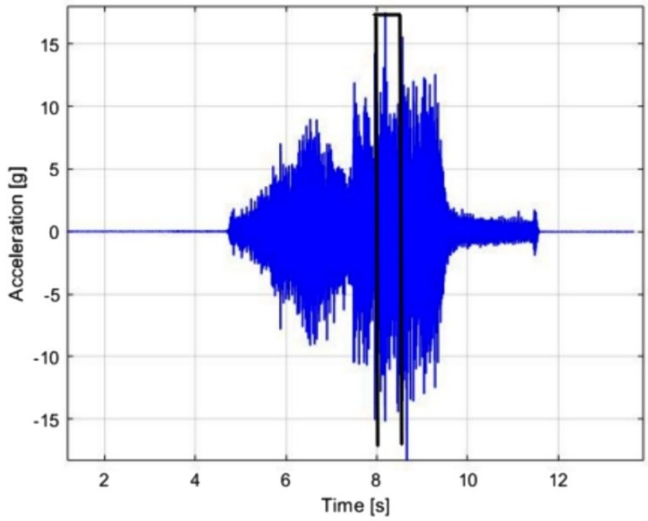

Figure 6. The recorded vibration signal.

The vibration signal was recorded from the moment the drill bit made contact with the surface of the composite panel until it exited the drilled hole, as shown in Figure 6. The maximum vibration signal occurred when the drill bit was in complete contact with the inner surface of the hole in the composite panel. The vibration data were obtained by averaging the signal at this maximum level.

After drilling, the vibration signal was measured to evaluate changes resulting from the interaction between the drill bit and the composite panel. This measurement aimed to analyze the vibration acceleration level after drilling and identify patterns that might indicate imbalances or irregularities in the process. The obtained data were processed using MATLAB to visualize the vibration characteristics more clearly. Figure 7 presents the recorded vibration signal after the drilling process.

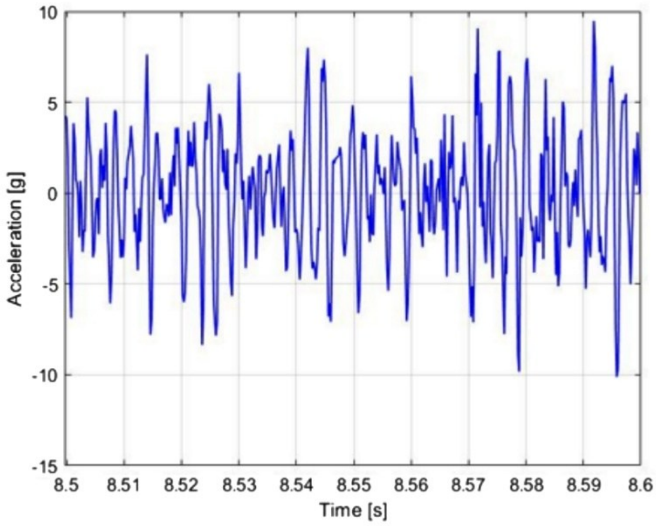

Figure 7. The vibration signal after processing.

Table 2. Result of the experiment

Diameter tools			12 mm	
No.	**Spindle Speed N (rpm)**	**Feed Rate F (mm/rev)**	**Cutting Force (Fz, N)**	**Acceleration (m/s^2)**
1	1000	0.1	154.60	0.028
2	1000	0.15	191.67	0.047
3	1000	0.2	233.95	0.038
4	1500	0.1	151.62	0.032
5	1500	0.15	161.97	0.05
6	1500	0.2	224.33	0.041
7	2000	0.1	187.85	0.04
8	2000	0.15	191.75	0.06
9	2000	0.2	248.51	0.054

The experimental results are presented in Table 2. Each cutting condition was tested five times, measuring cutting force and vibration simultaneously. The final result was obtained by averaging the five recorded values.

3.2. The Effect of Spindle Speed on Cutting Force

Figure 8 illustrates the effect of spindle rotation speed on cutting force at different feed rates. When the spindle speed increased from 1000 to 1500 rpm, the cutting force decreased across all feed rate levels. However, the reduction was minimal at feed rates of 0.1 mm/rev and 0.2 mm/rev. In contrast, at a feed rate of 0.15 mm/rev, there was a significant decrease of 18.6%, from 191.67 N to 161.97 N. Conversely, when the spindle speed increased from 1500 rpm to 2000 rpm, the cutting force increased uniformly across all feed rate levels by approximately 15%.

As shown in Figure 8, spindle speed has a significant impact on cutting force. In many drilling operations, higher spindle speeds produce smaller chip sizes, reducing the cutting force required for material removal. However, increased spindle speed generates more heat due to friction between the cutting tool and the workpiece. Excessive heat can accelerate tool wear, alter the cutting geometry, and increase the cutting force.

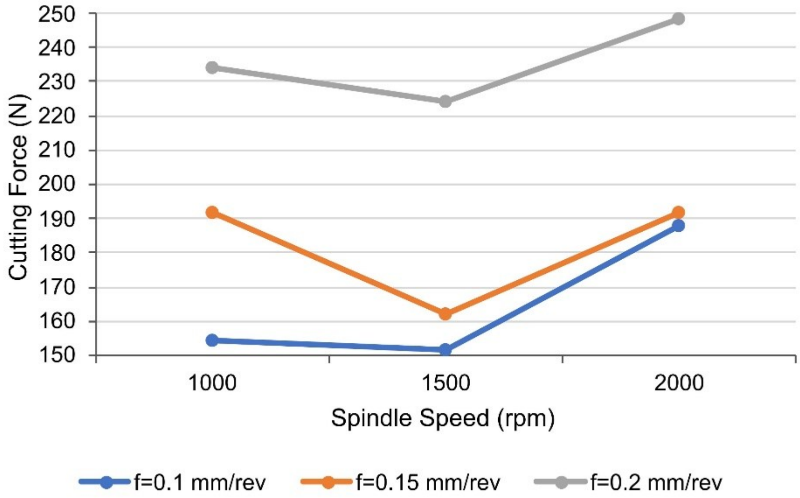

Figure 8. The Effect of Spindle Speed on Cutting Force.

3.3. The Effect of Feed Rate on Cutting Force

The impact of feed rate on cutting force at different spindle speeds is shown in Figure 9. The cutting force increased at all spindle speed levels when the feed rate was raised from 0.1 mm/rev to 0.15 mm/rev. However, the increase was negligible at spindle speeds of 1500 rpm and 2000 rpm. At a spindle speed of 1000 rpm, there was a significant rise of 24%, from 154.60 N to 191.67 N. When the feed rate was further increased from 0.15 mm/rev to 0.2 mm/rev, the cutting force increased sharply across all spindle speed levels, reaching up to 39%.

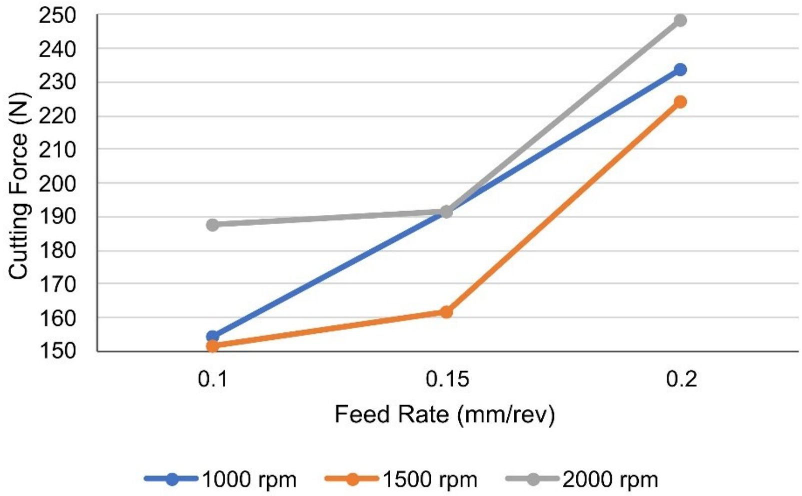

Figure 9. The Effect of Feed Rate on Cutting Force.

Figure 9 demonstrates that cutting force is directly proportional to the feed rate. As the feed rate increases, the drill bit engages with a larger volume of material during each rotation, requiring greater force to cut through the material. At higher feed rates, the cutting edge of the drill bit encounters increased resistance due to the greater material removal per pass, leading to higher thrust and radial forces.

3.4. The Effect of Spindle Speed on Acceleration Vibration

Figure 10 illustrates the effect of spindle speed on acceleration vibration at different feed rates. As the spindle speed increased from 100 rpm to 1500 rpm and then to 2000 rpm, the acceleration increased slightly across all feed rate levels. However, the increase was more pronounced when the spindle speed rose from 1500 rpm to 2000 rpm compared to the increment from 1000 rpm to 1500 rpm.

The graph in Figure 10 demonstrates that spindle speed plays a crucial role in influencing vibrations. An increase in spindle speed leads to higher vibration frequency and amplitude at certain speeds due to resonance effects. As observed in previous results, higher spindle speeds generate larger cutting forces, which may increase vibration frequency and amplitude.

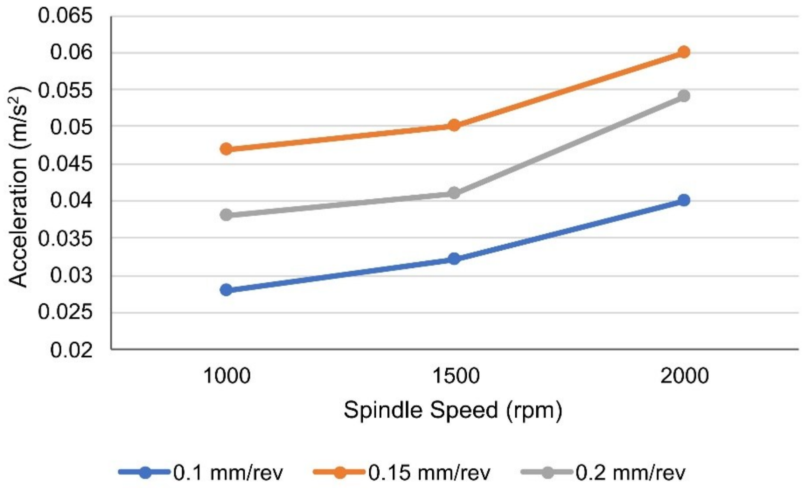

Figure 10. The Effect of spindle speed on acceleration.

3.5. The Effect of Feed Rate on Acceleration Vibration

The impact of feed rate on acceleration vibration at varying spindle speeds is illustrated in Figure 11. The acceleration increased sharply at each spindle speed level when the feed rate was raised from 0.1 to 0.15 mm/rev. A maximum increase of 67.8% was observed at a spindle speed of 1000 rpm, followed by 56.25% at 1500 rpm and 50% at 2000 rpm. However, when the feed rate increased from 0.15 mm/rev to 0.2 mm/rev, the acceleration decreased across all spindle speed levels. The reduction reached 19% at 1000 rpm, 18% at 1500 rpm, and 10% at 2000 rpm.

The results indicate that the feed rate significantly influences vibration during the drilling of hybrid composite panels. However, the relationship is not linear. In this case, lower acceleration vibration can be achieved by applying either a low feed rate (0.1 mm/rev) or a high feed rate (0.2 mm/rev).

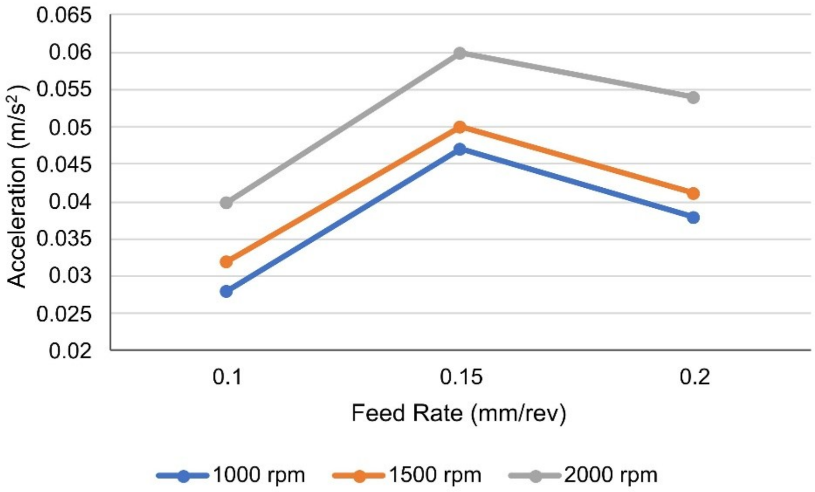

Figure 11. The Effect of Feed Rate on Acceleration.

3.6. The Influence of Hole Drilling Parameters on Hole Quality

Figure 12 shows the quality of holes in each test based on the hole quality images from the drilling process. The hole quality was assessed through visual inspection, either directly on the hole surface or from images captured by a digital camera. No measuring equipment was used in this evaluation. A hole with a smooth surface was considered good quality, whereas a hole with a rough surface was classified as poor quality.

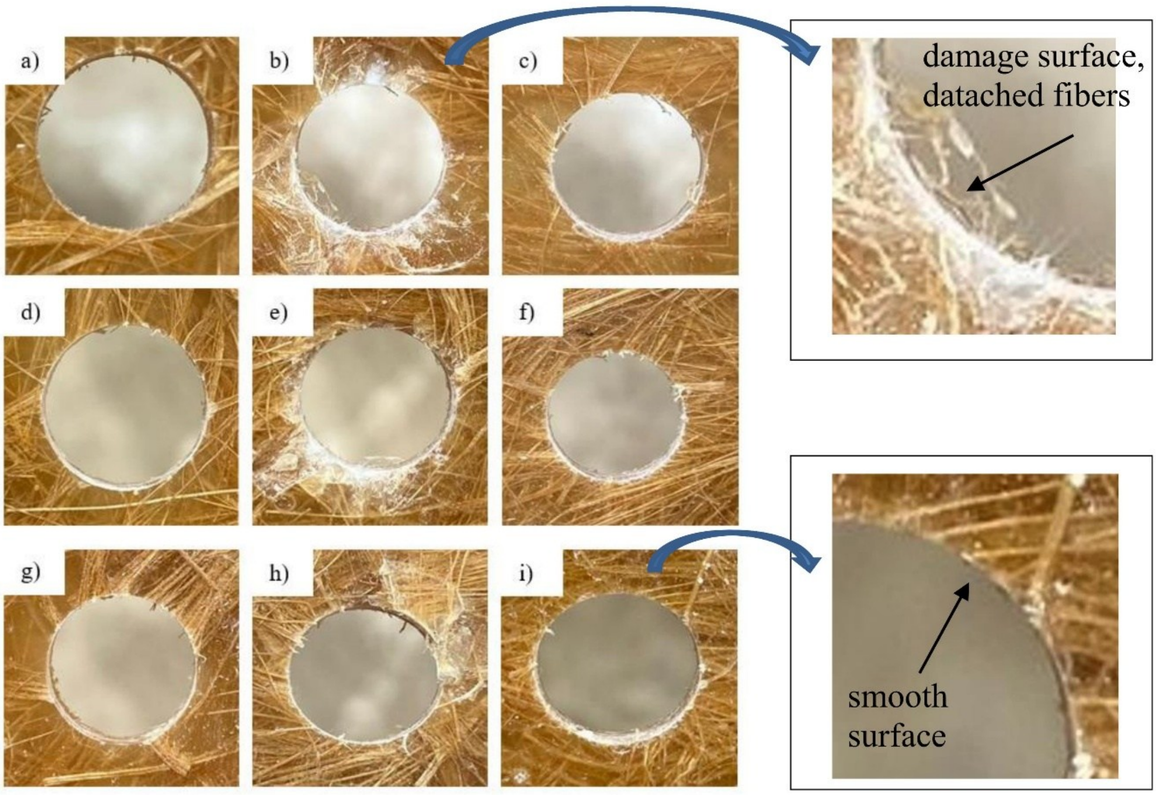

Figure 12. Data on cutting results related to hole quality: spindle speed at 1000 rpm (a) f=0.1 mm/rev, (b) f=0.15 mm/rev, (c) f=0.2 mm/rev, spindle speed at 1500 rpm (d) f=0.1 mm/rev, (e) f=0.15 mm/rev, (f) f=0.2 mm/rev, and spindle speed at 2000 rpm (g) f=0.1 mm/rev, (h) f=0.15 mm/rev, (i) f=0.2 mm/rev.

Figure 12 shows that increased spindle rotation speed results in better hole quality. The best hole quality was achieved at a spindle speed of 2000 RPM with a feed rate of 0.2 mm/rev, as shown in Figure 12.(i), where the hole surface appeared smooth and uniform. In contrast, the poorest hole quality was observed at a spindle speed of 1000 RPM with a feed rate of 0.15 mm/rev, as shown in Figure 12.(b), where some parts of the surface were damaged, and some fibers were detached from the panel.

Higher spindle speeds can increase cutting efficiency, reducing the fiber pull-out and matrix cracking, which can cause rough surfaces. Additionally, the cutting tool can cut fibers more effectively, reducing fiber breakage and resulting in a smoother surface. Furthermore, the cutting tool can penetrate the composite panel more smoothly, reducing the material layer separation risk and minimizing delamination [14, 15]. However, it is worth noting that excessively high spindle speeds can generate excessive heat, leading to matrix degradation and tool wear. Therefore, optimizing spindle speed is crucial to achieving a smooth surface when drilling composite panels.

4. CONCLUSION

The research findings indicate that higher spindle speed and feed rate result in increased cutting force and vibration levels, with the maximum cutting force of 248.515 N observed at 2000 RPM and 0.2 mm/rev, and the minimum cutting force of 151.619 N recorded at 1500 RPM and 0.1 mm/rev. Similarly, vibration levels peaked at 0.06 m/s² at 2000 RPM and 0.15 mm/rev, while the lowest vibration level of 0.028 m/s² was recorded at 1000 RPM and 0.1 mm/rev. Cutting conditions also affected hole quality, where the best results were achieved at 2000 RPM and 0.2 mm/rev, and the poorest quality at 1000 RPM and 0.15 mm/rev. These outcomes contribute valuable insights to composite machining and can guide the industry toward more efficient and higher-quality drilling practices. However, this study was limited to cutting force, vibration, and surface quality, and future work should investigate tool wear, as some conditions that reduce cutting force and vibration while improving surface finish may also accelerate tool degradation. Moreover, optimization studies are recommended to establish cutting conditions that balance surface quality, cost, and machining time.

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