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Investigating Twist Drill Design Influence on Thrust Force and Surface Roughness in Drilling AFRP/ Al7075-T6 Stacks Materials

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ABSTRACT

Drilling Aramid Fiber-Reinforced Plastic (AFRP) presents unique challenges when compared to drilling other composite panels. These difficulties arise from the high-toughness characteristics of aramid fibers, which exhibit a tendency for ductile deformation during the drilling process. This research explores the influence of drill bit design on the drilling process stack-up materials, which comprise Aramid Fiber Reinforced Plastic Composite Laminates (AFRP) and Aluminum Al7075-T6. Three distinct bit designs were employed in the experiment, conducted on a Computer Numerical Control (CNC) machine operating at a spindle speed of 2000 rev/min and a feed rate of 0.05 mm/rev. To measure thrust force during drilling, a dynamometer was integrated into the setup. Subsequently, a roughness tester was utilized to assess the hole surface roughness of the stack-up materials. For AFRP materials, the w-point drill design emerged as the optimal choice, reducing thrust force by approximately 5% to 13% compared to other drill bit designs. Conversely, for Al7075-T6 panels, the tapered web drill design demonstrated exceptional results, lowering thrust force by approximately 21% and 50% in comparison to burnishing and w-point drill bits, respectively. In terms of hole surface roughness, the burnishing drill type consistently produced the smoothest surfaces, boasting significant improvements of 44% and 82% when compared to the tapered web and w-point drill bits for AFRP panels. Similarly, for Al7075-T6 panels, the burnishing drill type consistently outperformed the tapered web and w-point drill bits by 74% and 88%, respectively, in achieving a superior hole surface finish. These findings underscore the critical importance of selecting the appropriate drill bit design to optimize thrust force reduction and hole surface quality when working with stack-up materials.

Keywords: *Twist drill design, hole surface roughness, thrust force, stack-up material*

1. INTRODUCTION

Aramid composites hold significant importance across diverse sectors, spanning aircraft, automotive, and military applications. Within these industries, the drilling process assumes a paramount role, with outcomes dependent on factors encompassing drill bit design, drilling parameters, and the inherent properties of the workpiece [1],[2]. As composite materials continue to gain prominence in engineering, comprehending the intricacies of drilling within these materials becomes a pressing necessity. The significance of composites is notably underscored in aviation applications, driven by their multifaceted advantages. Composites offer an enticing blend of attributes: lightweight properties bolster fuel efficiency, inherent strength suits load-bearing tasks, durability withstands demanding stress levels, resistance to corrosion extends component lifespan, and the inherent flexibility allows for tailored properties [3],[4].

These properties empower engineers to fine-tune aircraft component performance, adapting to the dynamic demands of the industry. This pairing imbues AFRP laminates with a potent combination of strength, lightweight nature, and resistance to high temperatures [5]. Aramid fibers contribute to structural strength and rigidity, while the polymer matrix offers adhesion and toughness [6]. As a result, AFRP laminates are well-suited for an array of applications, encompassing aircraft, defence, and construction [7]. Key to understanding AFRP's versatility is recognizing its composition of aramid fibres and polymer resin. These materials exhibit a balance of robustness and flexibility, allowing them to deform without fracturing [8],[9]. A meticulous production process involves layering aramid fibres, followed by high-temperature and high-pressure curing, yielding materials resilient against dynamic impacts [10]. However, drilling in AFRP can trigger delamination—a process that significantly jeopardizes material strength [11]. Existing delamination models fall short in capturing contact conditions due to their simplified load summation approach [12]. The intricate structure of AFRP materials demands careful drilling. Despite their inherent strength, drilling can introduce defects such as fuzzing, ripping, and delamination [12]. Delamination emerges as a critical concern, undermining component integrity and fatigue life, thus rendering them unsuitable for extended use.

In aviation applications, composite materials envelop metal structures as protective skins, interconnected through drilled holes to facilitate rivet or bolt assemblies [13]. For successful drilling outcomes, a profound grasp of AFRP's properties is indispensable. Manipulating tool geometry and material properties, such as cemented carbides or PCD, alongside optimizing machining parameters, significantly enhances the drilling process

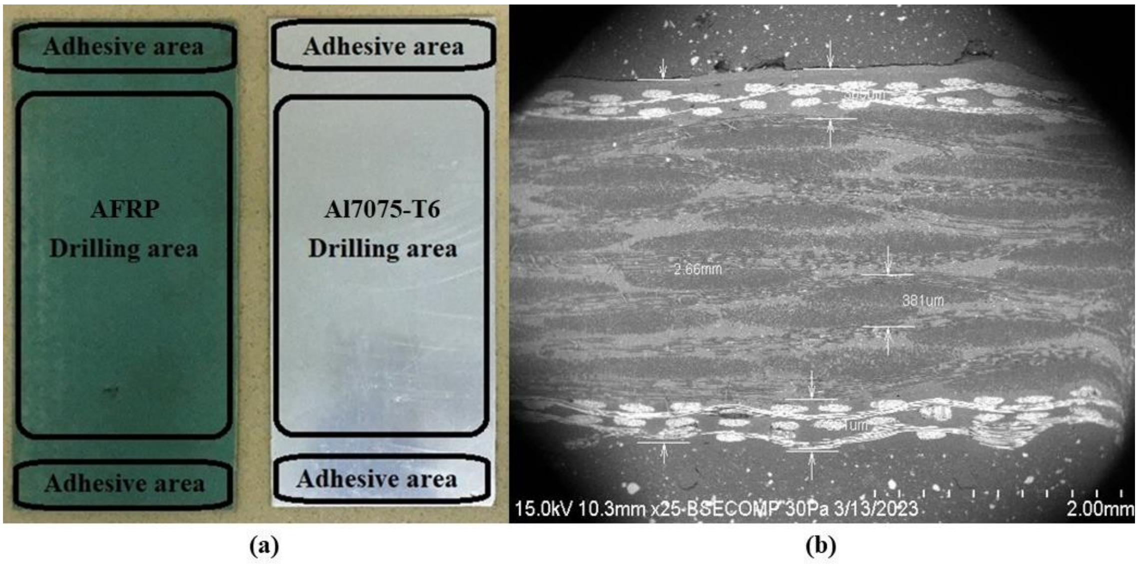
[14]. The application of composites and aluminium in aviation is driven by their fatigue crack resistance and damage tolerance, reinforcing the pivotal role of drilling in rivet and bolt assembly [15]. In the metalworking industry, drill bit materials span a spectrum from high-carbon steels to ceramics and diamonds, each tailored to distinct properties and applications. The discovery of carbide as a cutting tool material during World War I, prompted by diamond shortages, heralded a revolution in machining practices [16]. High-Speed Steel (HSS) drill bits, alloyed with carbon, chromium, molybdenum, tungsten, and vanadium, epitomize heightened hardness, heat resistance, and durability compared to standard steel bits [17]. HSS drill bits excel in drilling materials ranging from cast iron and steel to non-ferrous metals and stainless steel [18],[19]. Polycrystalline Diamond (PCD) drill bits, characterized by diamond particle-infused cutting edges bound by metal, shine in demanding tasks. Their hardness and abrasion resistance make them ideal for tough materials like concrete, masonry, and selected metals [20],[21]. Though pricier than carbide alternatives, PCD drill bits prove invaluable for drilling composites and metals [22].

The primary objective of this research is to explore the impact of twist drill designs on the quality of drilled holes in single-shot drilling for AFRP/Al7075-T6 stack-up composite panels. Twist drills have demonstrated their superiority compared to specialized geometries like w-point or dagger drills, commonly used exclusively for drilling composite panels. This superiority can be attributed to the twist drill's low helix angle, which significantly enhances chip evacuation efficiency, especially when dealing with metal components. The low helix angle minimizes the tendency for metal chips to become trapped, thereby avoiding any detrimental effects on the drilled hole's surface quality. Essentially, the research meticulously examines both the thrust force exerted during drilling and the resultant hole quality, characterized by surface roughness, for both AFRP and Al7075-T6 material panels. The study delves into the effects of different drill types on thrust force and identifies variations in hole quality, specifically in terms of surface roughness under constant parameters: 2000 rev/min speed and a feed rate of 0.05 mm/rev.

2. MATERIAL AND METHODS

2.1. Stack-Up Preparation

The materials used in this study are a combination of aramid fiber reinforced plastic (AFRP) and aluminum alloy (Al7075-T6). The AFRP and Al7075-T6 materials have dimensions of 86 mm x 185 mm and a thickness of 3.30 mm, while the AFRP composite panel measures 84 mm x 185 mm with a thickness of 2.66 mm. To bond these materials, a 3-ton epoxy adhesive with a resin-to-hardener ratio of 1:1 will be applied at the adhesive region, as depicted in Figure 1.



(a) (b)

Figure 1. (a) AFRP composite panels and Aluminum Al7075-T6 (b) AFRP's detail layer by Scanning Electron Microscope.

2.2. Drill Bit Preparation

A sintered tungsten carbide rod with a diameter of 6.35mm was fabricated at Gandtrack Asia Sdn Bhd using a CNC grinding center, namely the Walter Helitronic Mini Power machine. This machining process involved the use of diamond wheels, specifically the Castle Tech wheels with D64 and D91 grit, attached to the machine. The CNC grinding machine consists of five degrees of freedom: three axes in translation (x-axis, y-axis, and z-axis) and two in rotation (a-axis and c-axis). During the manufacturing of the drill bits, three-wheel types were used, each with specially designed geometry. The process of shaping the drill bit tool comprised four significant machining steps: (i) fluting, (ii) heel grinding, (iii) gashing out, and (iv) pointing for the tip clearance. In this study, there are three types of twist drill design was proposed which compass of w-point, burnishing and tapered web drill bit. All the bits were drilled with five holes and the average data of the hole is presented. The drill bit used in this experiment is illustrated in Figure 2.

Figure 2. (i) w-point (ii) tapered web (iii) burnishing.

2.3. Drilling Stack-Up Materials

The drilling of stack-up materials was carried out using a Computer Numerical Control (CNC) machine, specifically the Fanuc Robodrill α-T21iFLb. This CNC machine is equipped with a variable spindle speed capable of reaching up to 10,000 revolutions per minute, and it is powered by a 3.7 kW spindle drive motor. The feed rate used during drilling ranged from 1 to 30,000 millimeters per minute for standard operations and 48 meters per minute for rapid transverse movements. The drilling process was performed as a single-shot operation, commencing with the AFRP material, and concluding with the Al7075-T6 panel. Figure 3 provides a visual representation of the CNC machine utilized and details the workpiece setup during the drilling process. Stacked panels were inserted into the fixture and securely clamped in place throughout the drilling procedure.

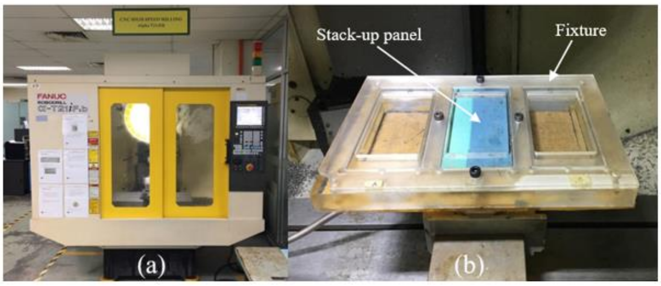


Figure 3. (a) CNC machine (b) Stack-up panels in the fixture.

2.4. Thrust Force Measurement

A dynamometer was used to capture the thrust force signature during a drilling process. The Kistler 5019B Force Dynamometer was affixed to the worktable of the CNC machine, and the resulting force signal was transmitted to the data acquisition system. This signal was subsequently amplified and displayed on the computer as a thrust force signature plotted against cutting time. The data acquisition system was comprised of a multichannel charge amplifier along with Kistler DynoWare software. The charge signal originating from the dynamometer underwent conversion to voltage through the multichannel charge amplifier and was then further transformed into force values using the calibrated data within the software. For a visual representation of the actual setup and an example thrust force signal over time during the drilling of stack-up materials and the result was represented according to Figure 4.

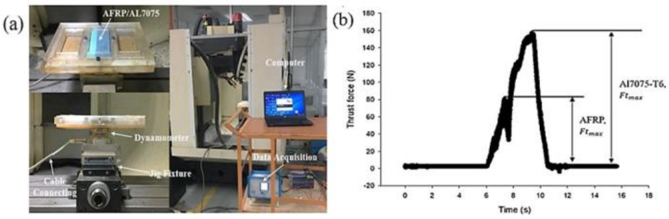
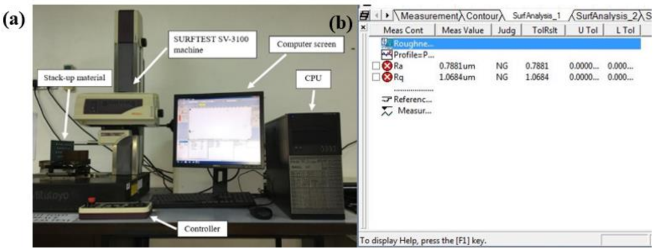


Figure 4. (a) Actual setup (b) Example thrust force signal versus time-history curve.

2.5. Hole Surface Roughness Measurement

The surface roughness of the hole was measured using a contact roughness tester machine model SURFTEST SV-3100. This machine utilizes a stylus to trace the surface of the hole and measure the height of the peaks and valleys. The FORMTRACEPAK software was employed to support the system, providing a graphical interface for viewing and analysing the measurement data. The setup for measuring the hole surface roughness is illustrated in Figure 5(a). The FORMTRACEPAK software offers several features that can be used to analyse measurement data. These features include the ability to view the measurement data as a graphical plot, calculate various roughness parameters, and compare the measurement data to standard values. One of these parameters is the average roughness (Ra), which measures the smoothness of a hole's surface. It is calculated as the average height of the peaks and valleys in the surface roughness profile. The example of the hole surface roughness results was illustrated in Figure 5(b).



Meas Cont	Meas Value	Judg	TolRslt	U Tol	L Tol
Ra	0.7881um	NG	0.7881	0.0000...	0.000...
Rq	1.0684um	NG	1.0684	0.0000...	0.000...

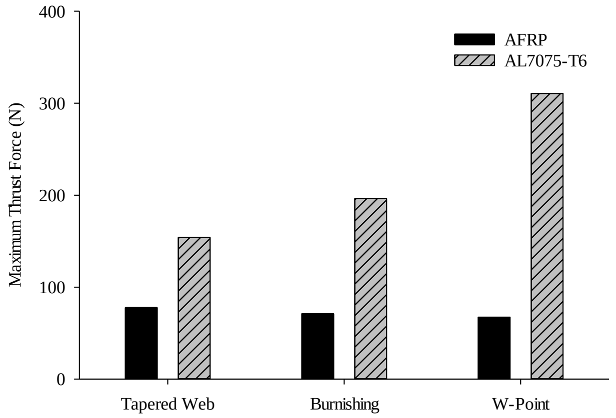
To display Help, press the [F1] key.

Figure 5. (a) Setup of measuring hole surface roughness (b) Ra value in FORMTRACEPAK software.

3. RESULTS AND DISCUSSIONS

3.1. Effect of Drill Types to The Maximum Thrust Force

Figure 6 illustrates the maximum thrust force (N) for each bit design on the stack-up materials, as extracted from Figure 4(b). In general, the maximum thrust force for AFRP remains relatively slightly different across all bit designs. The lowest maximum thrust force is achieved with the w-point drill type, registering at 67.53 N, which is approximately 6 % and 15 % better than the burnishing and tapered web designs, respectively. The w-point bit's pointed and narrow tip design contributes to reduced friction during drilling. Consequently, when drilling through the AFRP panel, less friction results in reduced effort required to penetrate the material, leading to lower thrust forces. Additionally, the sharp point of the w-point bit enables clean and precise cutting, a critical factor for creating accurate holes in composite materials like Aramid fibre. This feature minimizes the risk of splintering, tearing, or delamination during the drilling process.



F_{tmax}, N	Tapered web	Burnishing	W-point
AFRP, N	77.87	71.28	67.53
AL-7075, N	154.07	196.36	310.63

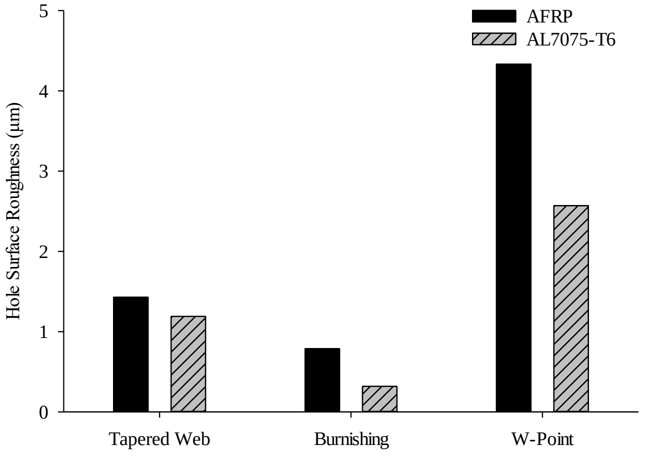
Figure 6. Maximum thrust force in drilling of AFRP/AL7076-T6 stacks material at 2000 rev/min and 0.05 mm/rev.

In the case of the Al7075-T6 panel, the tapered web drill bit performed exceptionally well by achieving a maximum thrust force of 154.07 N. This represents a substantial improvement of approximately 21% and 50% compared to the burnishing and w-point drill bits, respectively. Both the tapered web and w-point drill bits feature a faster helix design when compared to the burnishing drill type, as shown in Figure 2. A faster helix angle in drill bit design can be advantageous for soft metals like Al7075-T6. It helps evacuate chips more efficiently by lifting and removing them from the cutting area effectively [13]. This aids in preventing chip congestion and subsequently lowers the thrust force required for drilling. However, it's important to note that the w-point drill bit faced a challenge when drilling metal due to chip clogging at the tip. This occurred because the w-point's negative point angle design is more suitable for drilling materials that produce fine chips like composite, rather than long chips typical of metal. In the case of metal, these long chips tend to get stuck in the flute of the drill bit instead of smoothly flowing out. In the investigation conducted by Hassan et al. on composite stacked materials, experiments employing a tungsten carbide twist drill bit unveiled thrust force results for CFRP that spanned from 87.69N to 126.18N. In contrast, Al7075-T6 exhibited variations ranging between 218.21N and 375.54N [23]. Given the recognized higher hardness and wear rate of CFRP compared to AFRP, it is crucial to achieve a lower maximum thrust force for drilling AFRP, observed to be within the range of 67.54N to 77.87N in this experiment. An intriguing aspect arises from the use of the same grade of aluminum material (Al7075-T6) in both study and this experiment [23]. This prompts a meaningful examination of the disparities in maximum thrust force when drilling aluminum. Surprisingly, the observed maximum thrust force range in the results for aluminum is 154.07N to 310.63N, notably less than the former.

3.2. Effect of Drill Types to the Hole Surface Roughness

Figure 7 shows the hole surface roughness of the holes in the stack-up materials for each drill bit design. Generally, the hole surface roughness of AFRP holes is consistently higher than that of Al7075-T6 for all drill bits. This discrepancy is linked to the chip formation process when drilling the aluminum panel in a single-shot procedure. The quality of chip produced during drilling directly impacts hole surface roughness. Chips generated during the drilling process can significantly influence tool performance. If longer chips are produced, they have tendency to accumulate around the tool, leading to congestion. In subsequent drilling operations, these chips can cause damage and directly impact the surface roughness of the holes. When the formation of larger chips occurs, it is evident that a relatively high surface roughness follows. By selecting conditions that yield smaller chips (less than 2.5 mg), the roughness seems to be largely a random phenomenon, independent of chip size [24]. Finer chips result in improved surface roughness. Reducing friction on the drill panels is facilitated by the generation of finer chips. This, in turn, minimizes tool wear, preserving the sharpness of the cutting edge and enhancing overall tool performance during hole drilling. The easy evacuation of finer chips from the holes significantly reduces congestion, leading to a more consistent and smoother surface finish for the holes. Desirable chips in drilling processes are small and well-broken. Larger chips face difficulties moving through the flutes, leading to heightened torque requirements and elevated temperatures. This situation can potentially result in drill breakage and contribute to a rougher surface roughness [25].

In this study, the lowest hole surface roughness for the AFRP panel is achieved with the burnishing drill type, measuring 0.7881µm. A lower surface roughness achieved by burnishing drill is Due to the lower helix angle in burnishing compared to the other two drill bits. In a study conducted by Jaafar et al., various helix angles (0°, 5.5°, and 11°) were examined to drill CFRP/Al stack materials, and revealing that a helix angle of 5.5° exhibited the lowest thrust force during drilling, with 0° and 11° following in ascending order. The underlying concept of cutting force concerning the helix angle encompasses both axial and radial force components, significantly influencing thrust force generation. The study's observation suggests that with an increase in the helix angle, there is a more pronounced proportion of axial force exerted by the cutting tool. Furthermore, the finding is attributed to the anisotropy in composite material (CFRPs), primarily stemming from the orientation of reinforcing fibers within the polymer matrix. Consequently, a lower helix angle in the cutting tool resulted in the production of better-quality drilled holes [26].



R_a, µm	Tapered web	Burnishing	W-point
AFRP	1.4281	0.7881	4.3322
AL-7075	1.1891	0.3172	2.5692

Figure 7. Hole surface roughness of AFRP/AL7076-T6 stacks material at 2000 rev/min and 0.05 mm/rev.

This represents a significant improvement of 44% and 82% compared to the tapered web and w-point drill bits, respectively. The specific geometry of the chisel edge angle in the burnishing drill type enables the production of smaller, finer chips when drilling the aluminum panel. These fine chips are less likely to affect the surface of the AFRP panel during the chip evacuation process.

For Al7075-T6 panel, it's worth noting that the burnishing drill type consistently yielded the lowest hole surface roughness, measuring at 0.3172µm. This remarkable result represents a substantial improvement of 74% and 88% when compared to the tapered web and w-point drill bits, respectively. The higher surface roughness associated with the w-point drill type in drilling metal part can be attributed to its sharp-pointed tip [21]. This sharp point tends to engage in a shearing mechanism rather than a cutting mechanism when drilling metal materials. Consequently, this shearing mechanism leads to the formation of wider and longer chips, which not only affects the efficiency of the cutting process but also tends to negatively impact the quality of the hole surface.

4. CONCLUSION

In this study, the choice of drill bit design significantly influenced the maximum thrust force experienced during the drilling process. For AFRP materials, the w-point drill design demonstrated superior performance, reducing thrust force by approximately 5% to 13% compared to other drill bit designs. However, for Al7075-T6 panels, the tapered web drill design exhibited exceptional results, lowering thrust force by around 21% and 50% compared to burnishing and w-point drill bits, respectively. For the hole surface roughness, the burnishing drill type yielded the lowest surface roughness, with a remarkable improvement of 44% and 82% compared to the tapered web and w-point drill bits, respectively for AFRP panel. Similarly, for Al7075-T6 panels, the burnishing drill type consistently achieved the smoothest surface finish, outperforming the tapered web and w-point drill bits by 74% and 88%, respectively.

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