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A REVIEW ON MECHANICAL MICRO DRILLING OF CFRP-TI6AL4V STACKED COMPOSITE

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ABSTRACT

A comparative study was conducted on the mechanical micro drilling of Ti6Al4V/CFRP stacked composites. It focused on the impact of point angle, spindle speed, feed rate, and Minimum Quantity Lubrication (MQL) on hole qualities, delamination, and tool life. The study reviews various aspects of mechanical micro drilling. This is crucial in meeting the increasing demands for aerospace, oil, defense, automobile, and biomedical science industries. Composites, in combination with aluminum and/or titanium, are widely used in aerospace applications, with Ti6Al4V/CFRP stacks also finding applications in engine cowlings, wing connections, wing panels, and nacelles. By optimizing parameters like point angle, spindle speed, feed rate, and implementing MQL, manufacturers can enhance hole quality, reduce delamination, and increase the lifespan of drilling tools. This caters to the surge in micro and nano levels of manufacturing and designing in different industries.

Keywords: Micro machining, Mechanical micro drilling, CFRP-Ti6Al4V, Composite

I. INTRODUCTION

Miniature drilling is a crucial machining technique that involves drilling holes with diameters ranging from 1 micron to 1 mm [1]. It finds extensive application in industries such as aerospace, electronics, semiconductors, die making, medical equipment, mold making, automotive, optical displays, and wireless technologies. In recent years, a composite material stack consisting of CFRP and titanium alloy has gained popularity, particularly in aerospace structures requiring high mechanical strength. For instance, wing and tail plane openings are typically created using multi-shot process that involves pre-drilling individual layers and subsequent deburring. The stack is then temporarily assembled mechanically before hole reaming. However, achieving the necessary tolerance levels can be challenging due to the differing mechanical properties of the workpieces. Prolonged production times often result from factors such as low cutting speeds during manual drilling and low feed rates. Additionally, CFRP and titanium drilling leads to high tool wear rates, further impacting process efficiency. This study investigates the effects of point angle, spindle speed, feed rate, and the implementation of Minimum Quantity Lubrication (MQL) on hole quality, delamination, and tool life. The goal is to optimize the micro drilling process for the double-layered composite stack, thereby improving hole quality, reducing delamination, and extending tool life, ultimately enhancing overall drilling efficiency.

II. LITERATURE REVIEW

Micro drilling on titanium

1. Hole quality

The quality of holes drilled in titanium (Ti) is evaluated based on parameters such as diameter of hole, cylindricity, burr formation, and surface roughness. Titanium is commonly used for parts which demands high reliability and wear resistance, requiring high hole quality. Increase in surface roughness may lead to fatigue issues, severe wear and reduction in corrosion resistance. However, machining operations often cause damage to the outer layer of titanium, resulting in phenomena such as micro cracks, plastic deformation, heat-affected zones, and tensile residual stresses [2].

Two fundamental criteria, namely hole diameter and cylindricity, are typically employed to assess the quality of hole in terms of size and shape. The diameter of hole must fall within the specified size range, represented by two concentric circles. Cylindricity refers to the extent of roundness throughout the hole length. The tolerance zone for cylindricity is defined by two concentric cylinders within which the machined hole should be located. Burr formation is common in titanium drilling, typically observed on both the surfaces(entry and exit).

However, the exit burr is generally larger and is particularly challenging in aerospace applications. It is approximated that around 30% of the cost of certain components can be attributed to deburring[3].

2. Tool wear/tool life

Machining titanium (Ti) poses challenges due to the tendency of chips to adhere to the cutting edges of the tool, leading to the formation of built-up edge (BUE). This BUE formation often results in chipping and premature tool failure. High cutting temperatures and strong adhesion between the tool and workpiece contribute to rapid tool wear in Ti machining. Additionally, the high stresses at the cutting edge can induce plastic deformation, further accelerating tool deterioration. The specific wear mechanisms observed during Ti drilling can vary depending on the combination of tool and workpiece materials. Common failure modes include indentation, non-uniform flank wear, hole wear, chipping, and catastrophic failure. Tool wear significantly impacts the cost of Ti drilling, necessitating lower cutting speeds to extend tool life. Drilling Ti typically requires more time compared to drilling steel.[2,3]

The choice of point angle plays a vital role in the drilling process. Extensive research and studies have been conducted by both researchers and manufacturers to identify the optimal tool point angle. Wong et al. discovered that reducing the point angle helps minimize the thrust force generated during drilling and prevents positional errors[4]. Heinemann et al. conducted experiments on miniature drills and determined that point angles B (120°) and C (130°) exhibit better performance in terms of higher tool life.[5]

Micro drilling on CFRP

Carbon fiber reinforced plastic (CFRP) composites gained extensive usage in different engineering applications, like automobiles, aircraft, spacecraft, and marine vehicles, primarily because of their remarkable advantages compared to other materials. These composites offer high strength and stiffness, exceptional corrosion resistance, lightweight construction, low thermal conductivity, high fatigue strength, fire resistance, and resistance to chemical and microbiological attacks. As a result, advanced composite materials account for approximately 50% of the structural weight of Boeing 787 and Airbus A350XWB aircraft.Mechanical drilling operations using conventional or specialized drill bits are commonly employed for drilling composite laminates. The drilling process and the quality of the resulting hole are significantly influenced by factors such as cutting parameters, tool geometries, tool materials, thrust force, and torque. These factors play a vital role in achieving desired drilling outcomes and ensuring the CFRP laminates integrity [6].

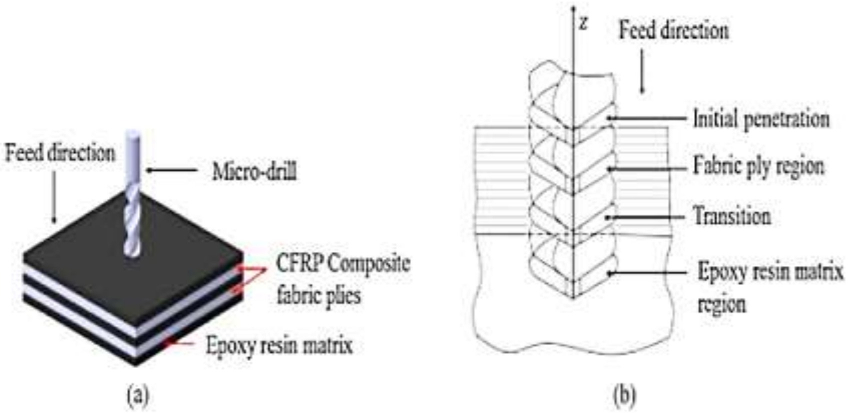

Figure 1. Micro drilling of CFRP material [7]

1. Hole quality

Assessing drilling performance in terms of hole quality is crucial as it directly affects the service life of composite parts after assembly. M. Rammulu et al. proposed a method to evaluate hole quality by categorizing commonly observed defects associated with drilled holes in fiber-reinforced plastics (FRPs) [8]. In a similar vein, Saad Waqar et al. investigated the primary defects in hole quality encountered during CFRP drilling, which include surface delamination, fiber/resin pullout, and insufficient surface roughness [9]. Ensuring high-quality holes without these defects is paramount to maintain the integrity and longevity of composite components.

2. Effect of Drilling Factors on Surface roughness and Delamination

Cutting parameters, like spindle speed and feed rate, have a notable impact on cutting force and delamination in drilling of CFRP laminates. Higher cutting speeds generally result in lower cutting forces, while increasing feed rate and drill size leads to higher cutting forces. Bellam Venkatesh et al. carried out research on factors influencing delamination during CFRP drilling and found that drill diameter had the greatest influence (88.39%) on delamination. Experiments were conducted to investigate whether varying the feed rate and spindle speed could reduce delamination [6].

Wei Y et al. conducted experiments on CFRP and Ti alloy stacks, revealing that drilling forces increased with higher feed rates but had uncertain relationships with cutting speed. Delamination area could be reduced by using lower feed rates, but delamination increased significantly once the feed rate exceeded a critical value [10]. Krishnaraj et al. experimented on thin CFRP using a K20 carbide drill, varying various input parameters and optimizing them using a genetic algorithm [11].

Optimum values for spindle speed and feed rate were determined to be 12,000 RPM and 0.137 mm/rev, respectively. Experimental and simulation results showed that thrust force and torque improved with higher feed rates and decreased with higher spindle speeds. Additionally, delamination was found to increase with higher feed rates and decrease with spindle speed, with delamination increasing significantly when the feed rate exceeded 500 mm/min. Furthermore, it was observed that drills with a double point angle exhibited less delamination compared to twist drills [12].

Delamination is the most frequent and significant form of damage that occurs during the drilling of composite materials, and it is regarded as the primary constraint in FRP drilling. Delamination refers to the separation of adjacent layers in the composite and is identified by the development of cracks between the layers of the material.Peel-up delamination occurs at the hole entrance (Fig 2. a) due to cutting forces pushing and peeling the material at the surface. Push-down delamination (Fig 2. b) occurs in the inter-laminar regions and is influenced not only by the nature of the fibers but also by the properties of the resin type. This damage is caused by the compressive thrust force exerted by the drill bit edge on the uncut laminate plies.

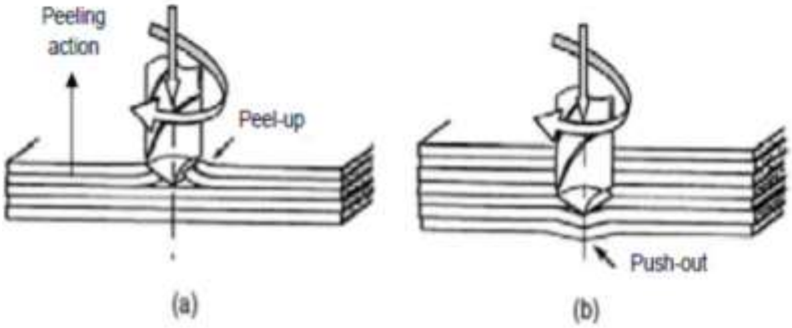

Figure 2. Delamination Mechanisms:

A) Peel – Up Delamination at Entrance

B) Push – Down Delamination at Exit

[6] M. Lair et al. [13] utilized a combination of Taguchi experimental analysis and a multi-objective optimization approach to determine the optimal drilling parameters for achieving desirable outcomes in terms of delamination, surface roughness, and thrust force. The researchers observed that to obtain delamination-free holes with a satisfactory surface finish, it was necessary to employ high cutting speeds and low feed rates. These parameters were identified as crucial factors to achieve the desired drilling performance. By applying their approach, Lair et al. were able to identify the preferred drilling parameters that would result in improved hole quality and overall drilling efficiency.

3. Tool wear/tool life

In metal cutting, the commonly used criterion to determine the end of tool life is maximum flank wear and it typically falls within the range of 0.3 - 0.6 mm. However, when it comes to cutting FRP composites, there is no established tool wear criterion. While drilling CFRP, both flank wear and chisel edge wear are observed, and their rates of increase are influenced by the number of drilled holes. Pecat O. et al. conducted experiments on drilling 4 mm thick CFRP plates and found that carbide drills exhibited negligible wear compared to HSS (High-Speed Steel) tools. The HSS tools produced a wear scar of 0.012 mm after only a few holes [14]. Thus, establishing a specific tool wear criterion for cutting FRP composites remains an area of ongoing research and development

Micro drilling on CFRP-Ti6Al4V stack composite

To enhance productivity and reduce costs in drilling CFRP-Ti6Al4V stacks, effective control of wear progression and management of hole quality are crucial for stack acceptance and post-assembly performance. However, limited research has been conducted to understand the relationships between cutting parameters, hole quality, and drill wear mechanisms. In the machining of CFRP-Ti6Al4V stacks using TiAlN coated tools, it was observed that increasing feed rates led to higher levels of delamination, burrs, and surface roughness on the drilled hole surfaces. Conversely, increasing cutting speeds resulted in decreased delamination, burrs, and surface roughness. Compared to machining isolated materials, the drill life was significantly reduced when drilling multi-layer stacks due to the cumulative effect of drill wear [7]. SenthilKumar et al. examined the wear behavior of drills with different geometric features, such as chisel edge thickness and point angle, during the machining of CFRP/Ti6Al4V stacks. They found that drills with a 130° point angle, characterized by a smaller chisel edge thickness and a larger point angle, exhibited lower wear levels and better chip ejection capability [15] Prabukarthi et al. utilized an acoustic emission technique to evaluate the drilling performance of various modified twist drills when machining CFRP-Ti6Al4V stacks. They determined that the helix and point angles significantly influenced tool performance, and drills with the highest helix angle and the lowest point angle generated the least thrust forces during drilling. Additionally, aside from process parameters, the choice of tool materials and geometries, as well as drilling techniques such as vibration-assisted drilling and rotary ultrasonic machining, can also have a significant impact on the machinability of composite/metal sandwiches and the resulting drill wear signatures. Pecat and Brinksmeier demonstrated that low-frequency vibration-assisted drilling reduced flank wear and adhesion while drilling CFRP-Ti6Al4V stacks, resulting in a threefold increase in tool life compared to conventional twist drilling, attributed to improved metallic chip ejection [14].

Furthermore, Cong et al. emphasized that the use of ultrasonic vibration-assisted (UVA) drilling for CFRP-Ti6Al4V stacks highly improves the machinability of these composites. UVA drilling reduces drilling forces, cutting temperatures, surface roughness, and hole damage compared to conventional twist drilling [17]. These findings highlight the potential of advanced drilling techniques to enhance the machining process and improve the performance of CFRP-Ti6Al4V stacks.

Figure 3. The photograph showing the used Ti6Al4V and T800/X850 CFRP specimens. [7]

1. **Effect of spindle speed on hole characteristics**

   Increasing the spindle speed improves the stiffness of the drill, enhancing its self-piloting nature and stability, resulting in better circular holes and reducing the circularity error [13]. Higher spindle speeds also minimize the tendency for delamination, reducing the impact of vibrations on the drill bit and machine. However, in micro drilling operations, heat generated during the process poses challenges in heat dissipation. This heat accumulation on the cutting surface of Ti6Al4V material leads to thermal expansion and increased material removal during drilling. Lower spindle speeds result in larger cutting thickness, increased cutting force, and plastic deformation of the cutting tool, leading to the formation of larger burrs at the entrance and larger hole diameters [7, 11, 13].

2. Effect of feed rate on hole diameter

The circularity of the drilled holes is defined by a tolerance range between two concentric circles. It is influenced by the feed rate during drilling of CFRP and Ti6Al4V alloy. A lower feed rate results in a smaller circularity error, while an increase in feed rate leads to a gradual increase in circularity error. This can be attributed to the higher force required to fracture the CFRP fibres at higher feed rates. When drilling CFRP/Ti6Al4V stacks, the transport of Ti6Al4V chips through the CFRP material can cause severe erosion, posing a significant quality issue [18].

A higher feed rate triggers elevated dynamic vibrations in the machining zone. As a result, the length of the uncut chip thickness rises, causing amplified ploughing action between the tool and the workpiece, thereby augmenting the circularity error. On the other hand, increasing the spindle speed and drill diameter reduces delamination and circularity error.

In contrast, an increase in feed rate increases delamination, which adversely affects the structural integrity of the drilled samples. The optimal process parameter for minimizing the delamination factor is the spindle speed. Increasing the spindle speed and drill diameter also minimizes cylindricity by reducing the effect of vibrations on the drill bit and machine. However, an increase in feed rate contributes to a higher circularity error due to the lower material removal rate [7, 19, 20].

3. Effect of MQL flow rate on hole diameter

The utilization of a wet lubrication system has been found to be more effective in reducing circularity errors compared to a near-dry system. In this regard, palm oil is employed as a lubricant to effectively remove debris from the machining zone, preventing the formation of BUE. Additionally, palm oil efficiently dissipates heat, thereby avoiding any thermal softening effects [21].During high-speed micro-scale drilling operations, it has been observed that the flow rate and air pressure have a negligible impact on cutting forces. An MQL (Minimum Quantity Lubrication) flow rate of 60ml/hr at an air pressure of 3bar has been found to reduce cutting forces. This reduction is attributed to the rapid evaporation of the MQL coolant during drilling, which provides lubrication at the tool circumference while rotating. It has been observed that MQL is particularly effective on the upper surface of the workpiece, where the cutting tool circumference is exposed. Furthermore, increasing air pressure has an influence on micro-drill pressure, torque, and vibrations at the micro-scale [21].

4. Effect of point angle on hole characteristics

It might increase hole diameter at a lower point angle of 135 degrees than at a higher point angle of 145 degrees. It is observed that higher point angle produces minimum hole exit delamination than small point angle [9]. Material is deformed during micro drilling operation due to the effect of point angle. According to Johnson Cook model for strain and strain rate, shown point angle effect on yield strength of material [22].

It is observed that small drill diameter and high ratio of chisel edge length to diameter reduces strain due to material flow volume conservation principal. Therefore, strain at radial location reduces material flow caused by deformation of material in term of burr.

III. CONCLUSIONS

Hole Quality - Higher feed rate induce higher dynamic vibrations in the machining zone. Due to the length of the uncut chip, the thickness of the chip increased, which in turn increased the ploughing component of the cutting force.The cicularity error is increased by this expanded ploughing part. Tool Wear - Smaller drill bits always face a problem of dissipating heat slower than larger drill bits. At substantial speeds, there was a possibility of very high temperature development.

It generated microcracks and heightened tool deterioration. The delamination factor declined as the feed rate decreased. This occurred due to the impact of the micro-drilling size phenomenon, where the specific cutting forces exhibited a non-linear increase when reducing the feed in CFRP-Ti6Al4V composite material. There is a lack of research on micro drilling of CFRP-Ti6Al4V Stack Composite. Micro drilling tool profile work is not performing on stack material with 0.1mm diameter of tool.

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