Performance Evaluation of Drilling Al/CFRP/Ti Stacks using Textured Drills

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Abstract. This research paper focuses on extensive examination of the drilling process applied to hybrid Al/CFRP/Ti stacks, a crucial procedure in aerospace structure assembly. The intricate combination of aluminum alloy, carbon fiber-reinforced polymer (CFRP), and titanium alloy within the stack introduces critical material interactions during drilling. The primary objective of this study is to assess and compare the surface quality of holes drilled in the Al/CFRP/Ti stack using standard and micro-grooved drills under minimum quantity lubrication (MQL) conditions. The experimental investigation involves varying cutting parameters, such as cutting speed and feed. This study explores the influence of machining parameters and tool geometry (utilizing micro-grooved and standard drills) on thrust force under MQL conditions. Additionally, it sheds light on the significant impact of thrust force variations resulting from diverse material stacking on hole surface quality, including metallic phase induced CFRP delamination and surface roughness. The discoveries from this research provide valuable insights for optimizing the drilling process for hybrid Al/CFRP/Ti stacks in industries that rely on advanced materials and machining techniques.

Keywords: Al/CFRP/Ti; drilling; groove; MQL; circularity.

1 Introduction

Aircraft have evolved into indispensable assets in contemporary society, serving as pivotal conduits for the transportation of people, goods, and playing a crucial role in global defense strategies. These airborne marvels stand as a testament to human ingenuity, a feat made possible through the innovative amalgamation of hybrid materials, specifically the strategic combination of carbon fiber-reinforced plastics (CFRP) and titanium alloys. These chosen materials boast extraordinary attributes, including notable stiffness, resistance to corrosion, high specific stiffness, and an advantageous weight-to-strength ratio, resulting in a substantial reduction in fuel consumption.

In the ever-advancing aerospace sector, the integration of lightweight metals such as titanium alloys with multi-layer composite structures like CFRP has become a standard practice, particularly in the construction of an aircraft's fuselage. Furthermore, aluminum alloys, renowned for their ductility, strength, toughness, resistance to fatigue, corrosion resistance, and a favorable weight-to-strength ratio, are seamlessly incorporated within the intricate

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CFRP-titanium alloy arrangement. Pioneering aircraft models have already embraced these composite combinations, utilizing Aluminum, CFRP, and Titanium in various components, including wings and tails. At present, researchers are actively exploring the extensive application of these three-material composites throughout the entire aircraft fuselage, signifying a paradigm shift in aerospace engineering [1-2].

Despite their numerous merits, it is imperative to acknowledge that these materials also present challenges. For instance, the lower modulus and poor heat dissipation of titanium alloys [3], the abrasiveness of CFRP [4], and the ductile nature of aluminum alloys [5] contribute to complexities in the drilling process. These challenges manifest in terms of poor surface integrity and rapid tool wear, underscoring the need for innovative solutions in achieving efficient drilling operations for hybrid composite-metal stacks.

The utilization of modified drills emerges as a pivotal strategy to overcome these challenges and ensure the creation of high-quality holes in hybrid composite-metal stacks. These specialized tools play a crucial role in facilitating precise and controlled machining, effectively minimizing undesirable outcomes such as delamination, burrs, and material damage. The consistent quality of drilled holes not only enhances structural integrity but also plays a vital role in optimizing overall performance in aerospace applications, thereby ensuring the reliability of composite-metal hybrid components [6-7].

Numerous research endeavors have delved into the intricate process of drilling various aerospace materials, ranging from aluminum alloys and titanium alloys to Inconel 718 alloy and CFRP materials. Researchers have explored the efficacy of micro-grooved drills in the drilling of challenging materials like Inconel-718 alloy and titanium alloys. To enhance the performance of these drills, cutting-edge techniques such as laser surface technology and Wire-EDM have been employed to fabricate different patterns of micro-grooves on the rake faces of the cutting tools. This innovative approach, utilizing micro-texture on cutting tools, effectively minimizes cutting forces and reduces friction-induced temperatures during the machining process [8-9].

While past research has predominantly focused on drilling either CFRP/Ti or Ti/CFRP stacks, investigations into Al/CFRP/Ti hybrid stacks have been surprisingly scarce and typically limited to two materials.This research undertaking seeks to bridge this gap by thoroughly examining the drilling performance of three-material stacks using textured drills. Furthermore, the performance of the drilling tool is optimized under minimum quantity lubrication (MQL) conditions to achieve superior surface integrity in the drilled CFRP holes. This comprehensive study aims not only to address existing gaps in the literature but also to provide valuable insights that can potentially revolutionize drilling practices for hybrid composite-metal stacks in the aerospace industry.

2 Materials and methods

2.1 Materials

The top layer of the multi-stack in this investigation comprises a 6mm-thick Aluminum 7075 alloy with a T6 grade. Recognized for its elevated strength, this alloy lacks the same corrosion resistance and weldability found in more common alloys. However, its remarkable resistance to stress and strain renders it particularly valuable in aerospace applications, contributing to weight reduction strategies. For the middle layer, a T700-M21 grade of CFRP material with a 4mm thickness was chosen. This CFRP composite, incorporating a unidirectional laminas, underwent curing using an autoclave. The lay-up sequence for the CFRP laminate adopted the pattern $[90/-45/0/45]_{2s}$. This selection is based on the material's suitability for the intended purpose and the advantageous characteristics it offers. The bottom layer of the multi-stack features a 6mm-thick grade-5 Ti-6Al-4V alloy. This titanium alloy is known for its strength and is a fitting choice for the structural integrity of the composite material. The combination of these distinct materials in the multi-stack aims to harness their individual strengths and properties.

In the drilling process, two types of 6mm tungsten carbide drills were employed—standard twist drills and drills engraved with laser-imposed microgrooves. The microgrooves, arranged in a parallel pattern on the rake and flank faces of the drill, as illustrated in Fig.1, serve the purpose of minimizing friction and retaining lubricants during drilling, especially under Minimum Quantity Lubrication (MQL) conditions [10]. Essentially, these microgrooves function as miniature reservoirs, mitigating heat and friction generated during the drilling operation [11]. The specific dimensions of the microgrooves in this study include a diameter of 50μm, a pitch of 100μm, and a depth of 40μm. This meticulous approach to the fabrication of microgrooves is intended to optimize their performance and ensure their effectiveness in enhancing the drilling process. Overall, this multi-material stack combined with advanced drilling techniques represents a comprehensive exploration of materials and methodologies for aerospace applications, offering potential advancements in weight savings and performance efficiency.

2.2 Experimentation

The experimental setup involved conducting tests with varying cutting speeds ranging from 20 m/min to 35 m/min and feed rates from 0.03 mm/rev to 0.09 mm/rev. Four levels within these speed and feed rate limits were explored, resulting in a total of 16 set of experiments, as per the full factorial design. To measure thrust force during the drilling process, the Al/CFRP/Ti stacks were securely clamped onto the KISTLER dynamometer, as illustrated in Fig.2.

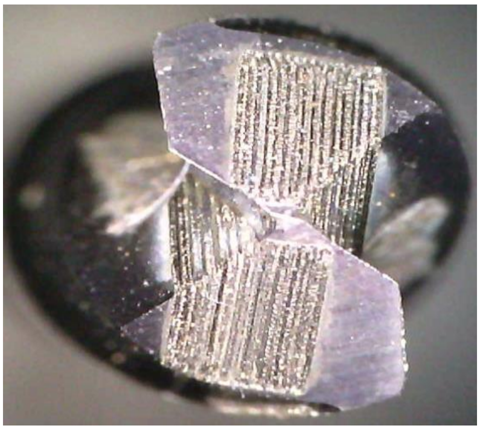

Fig.1. Grooved Drill

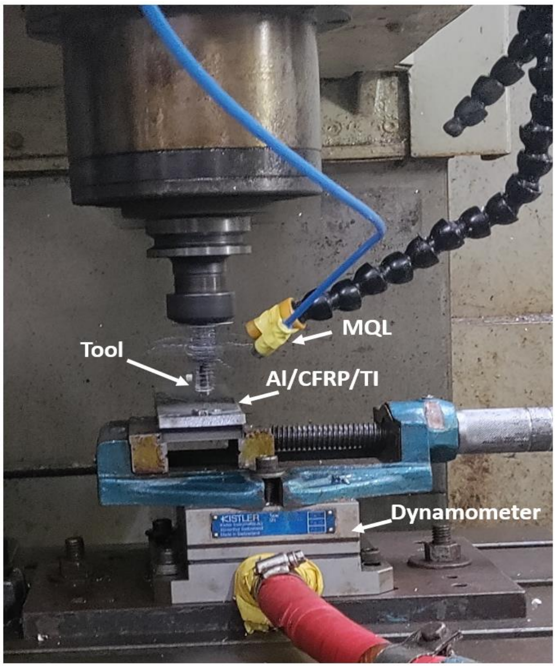

Fig.2. Experimental setup

This dynamometer played a crucial role in capturing the data essential for analyzing the drilling performance. The experiments were conducted under Minimum Quantity Lubrication (MQL) conditions. The aim was to reduce friction and heat during drilling while ensuring the efficiency of the process. Initially, standard drills were employed for the experiments, and subsequently, the same set of experiments was repeated using micro-grooved drills. The micro-grooves, engraved on the drill surfaces, aimed to minimize friction and store lubricants during the drilling process under MQL conditions. This approach was expected to enhance the overall drilling efficiency.

3 Results and discussions

3.1 Analysis on Thrust Forces

The generation of thrust forces in the drilling process is primarily attributed to the drill tool exerting pressure against the work materials to remove unwanted material. These thrust forces are crucial parameters in determining the machinability characteristics of various materials and multi-stack configurations, influencing the surface integrity of drilled holes and the tool's lifespan [12]. In Figure 3(a-b), the variations of thrust forces during the drilling of Al/CFRP/Ti stacks with standard and grooved drills are depicted. Figure 3(a) illustrates the thrust force fluctuations in Al/CFRP/Ti stacks using a micro-grooved drill. The graph reveals three distinct regions.

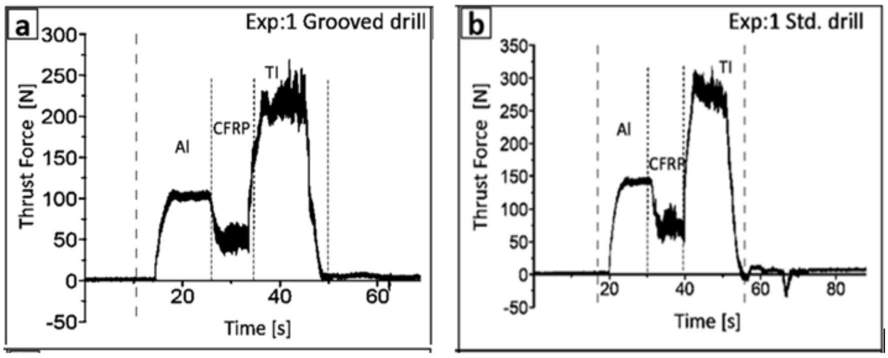

Fig.3. Three stages of thrust force variations

These variations in thrust forces are attributed to the distinct mechanical characteristics of the different materials within the stack. Notably, these variations are significantly higher when using a standard twist drill for the same experiment. Figure 3(b) details the thrust force variations when drilling with grooved drill. This variation indicates an approximate increase of 50N in thrust forces for the entire Al/CFRP/Ti stack. Observations from Figure 3(a) underscore the significant role of micro-grooves in reducing thrust forces, serving as micro-pool reservoirs to store lubricants and contribute to the overall efficiency of the drilling process. The integration of grooves appears to play a pivotal role in minimizing thrust forces and optimizing the drilling performance, particularly in the challenging context of multi-material stacks.

Figure 4-a, b & c depicts the comparison of thrust forces measured from both types of tools, focusing on the Al-7075 phase, CFRP phase, and TI-6Al-4V phase, respectively. Notably, an elevation in feed rate corresponds to an increase in thrust force. This rise is attributed to augmented chip-thickness and heightened cutting resistance encountered at higher feed rates. Particularly pronounced is the surge in thrust force during the drilling of the titanium alloy phase, primarily due to the elevated hardness, leading to increased cutting pressure. Moreover, the escalation in feed rate contributes to a higher Material Removal Rate (MRR) in this phase [3].

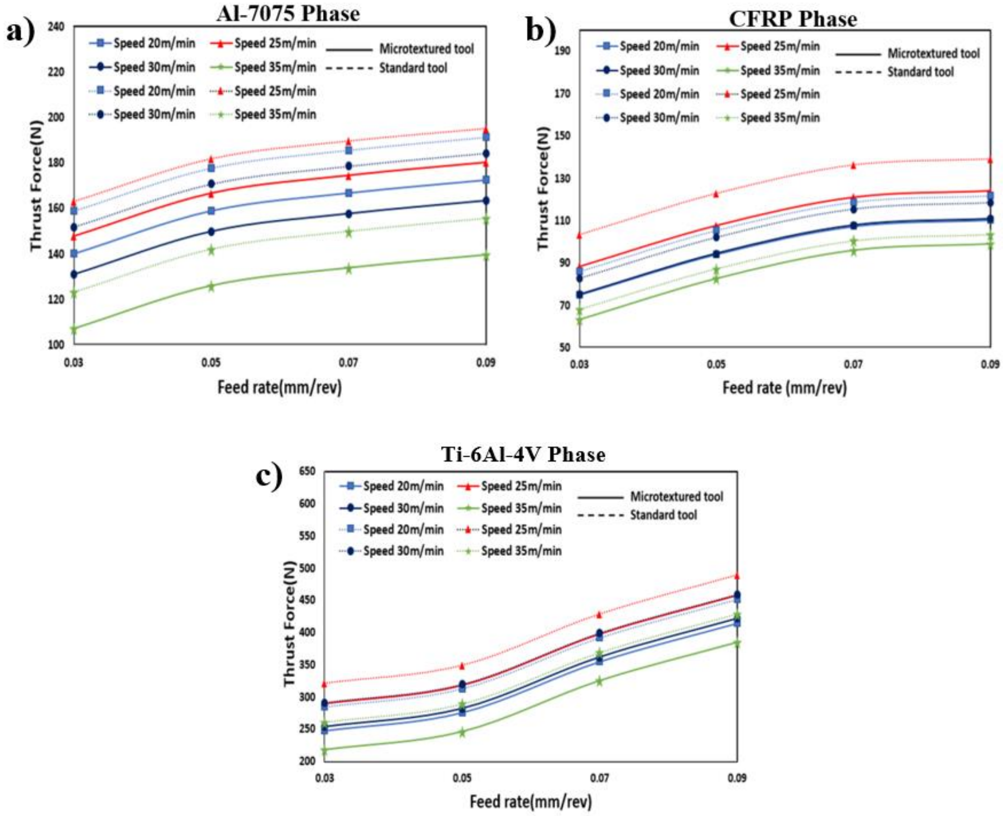

Fig.4. Compartive analysis on thrust force variations

The subsequent increase in thrust is observed in the Al alloy and CFRP material phases. Through careful examination, it is evident that the thrust forces generated by the micro-grooved drill are consistently lower than those produced by the un-grooved drill. This observation underscores the efficacy of micro-grooves in mitigating thrust forces during the drilling process. The diminished thrust forces associated with the micro-grooved drill can be attributed to its ability to reduce friction and act as micro-reservoirs for lubricants. This contributes to an overall improvement in the drilling performance, as depicted by the comparative analysis of thrust forces across different material phases. Both drill geometries exhibit improved performance at maximum cutting speeds, with the most notable outcomes observed at 35 m/min, where a minimum thrust force is recorded for both.

3.2 Analysis on Delamination Factor

In this study the comparative analysis on the delamination of drilled CFRP holes were performed by dismantling the CFRP, Al and Ti alloy after the drilling of hybrid stacks. The delamination factor (Fd) serves as a critical metric for assessing delamination related damages in CFRP composites. This study excludes the discussion of delamination damages at the drill exit regions, as it's minimal due to titanium alloy support beneath the CFRP. The Figure 5 compare delamination in the drill entry regions, showing improved performance of the groove at higher speeds. Delamination damage increases linearly with higher feed rates due to increased thrust force. Grooved drills notably reduces the peel-up delamination, especially at maximum speeds.

The research findings reveal a noteworthy disparity in delamination occurrences during the drilling of Al/CFRP/Ti stacks when employing a grooved drill, particularly under lower speed conditions. The heightened incidence of delamination appears to be linked to the compromised chip breakability and the protracted chip removal process prevalent at lower speeds. In stark contrast to the conventional drill, the grooved drill exhibits minimal push-out delamination failure, particularly noticeable at elevated speeds used in this study. This discrepancy is attributable to the reduced thrust force and heightened chip breakability associated with the grooved drill in comparison to the standard drill at higher speeds. The experimental evidence underscores the intricate interplay between drilling parameters and delamination tendencies, with grooved drills demonstrating distinct advantages in mitigating delamination failures, especially under dynamic speed conditions.

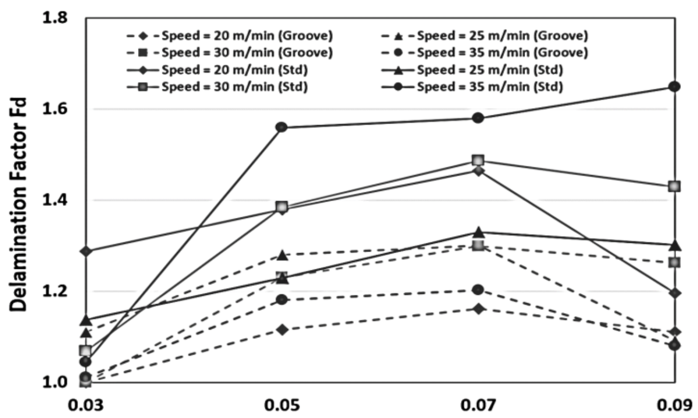

Fig.5. Analysis on delamination

3.3 Analysis on Surface Quality of CFRP

Evaluating Carbon Fiber Reinforced Plastic (CFRP) surface integrity is crucial in composite stacks with alloys. Unlike metals, CFRP is sensitive to irregularities, impacting bonding and fatigue resistance. This research focuses on surface quality parameters such as roughness, circularity, and hole diameter variations in CFRP, which is essential for optimizing mechanical characteristics. The emphasis lies on understanding CFRP's unique behavior in composite stacks, highlighting its distinct considerations compared to metals

Figure 6-a, b & c provides insights into the impact of cutting speed on the surface quality (roundness, roughness &hole diameter error)of the CFRP hole walls. The observations reveal a noteworthy trend: as cutting speed increases, there is a discernible reduction in roundness errors. This phenomenon can be attributed to the elevated temperatures generated at higher speeds, leading to a more effective resin smearing process across the CFRP hole wall. Interestingly, this effect is particularly pronounced at low feed rates and high-speed

conditions. The interplay between speed and feed rates becomes a crucial factor in influencing the quality of the machined holes.

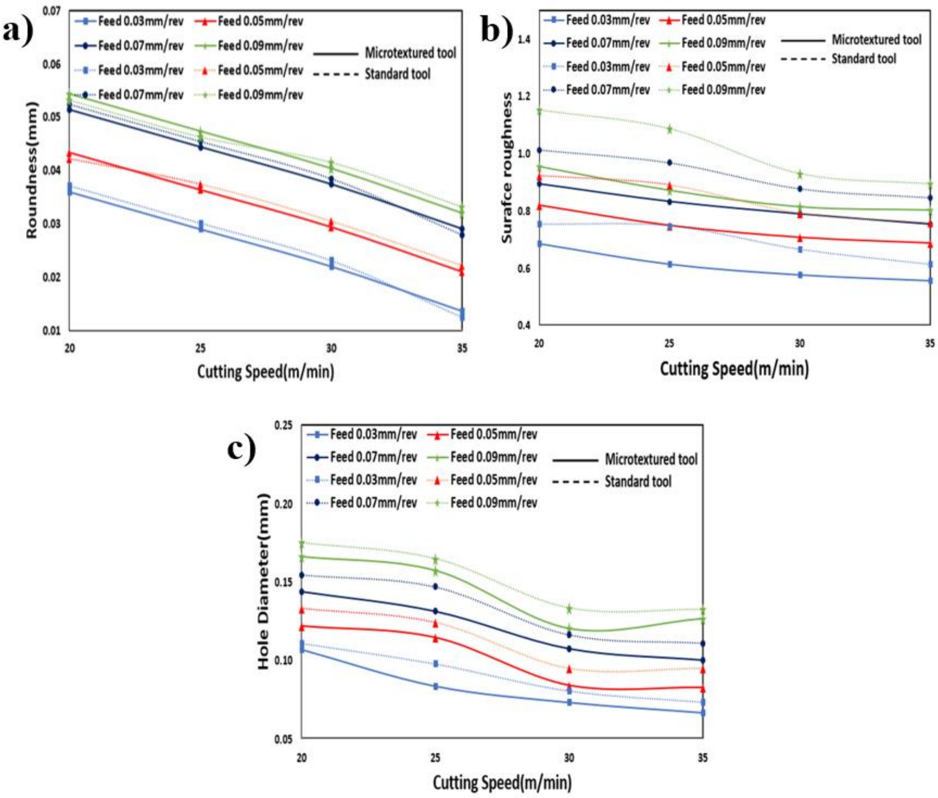

Fig.6. Analysis on thesurface quality of CFRP

Moreover, a fascinating aspect is the minimal effect of microgrooves on roundness across various speed and feed conditions. Despite their presence, these grooves do not significantly alter the roundness of the CFRP hole walls. This finding highlights the robustness of the machining process against certain variations in tool design. Moving on to the variations in surface roughness and holediameter error, increasing cutting speed during CFRP drilling demonstrates a clear trend: a notable reduction in surface roughness and diameter errors. This trend is particularly pronounced when dealing with metallic stacks such as Al/CFRP/Ti. The rationale behind this improvement lies in the ability of higher cutting speeds to minimize material deformation, resulting in cleaner and smoother holes. The dynamic interaction between the drill and the composite material, combined with the higher velocities, enhances hole quality through a continuous wiping action across the CFRP hole wall surfaces [17-18].

Crucially, the findings suggest that the machining quality of CFRP is optimized at specific combinations of cutting speed and feed rate. Experimental run 13, characterized by higher speed (35 m/min) and lower feed rate (0.03 mm/rev), stands out as particularly effective in achieving superior surface quality. In this scenario, reduced magnitudes of thrust contribute to the improved machining efficiency of CFRP. The holistic analysis of machining parameters underscores the significance of tailoring speed and feed rate combinations to achieve optimal surface quality in CFRP machining processes. Furthermore the scanning electron microscopic images of CFRP hole wall drilled with modified and unmodified drill is shown in Figure 7, which clearly depicts the better quality of CFRP hole wall with textured drill. These insights are vital for refining machining strategies and advancing the efficiency of CFRP drilling in practical applications.

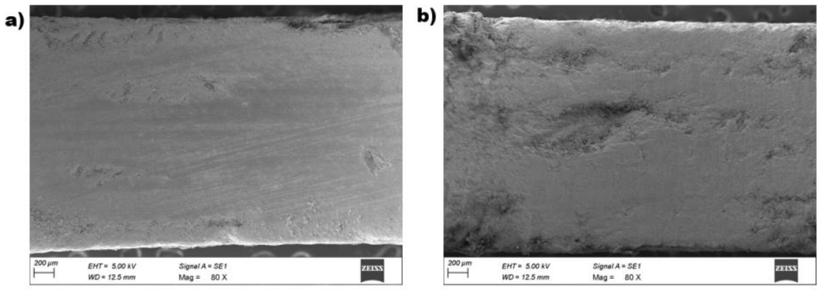

Fig.7. SEM images of CFRP hole wall a) textured drill b) Std. drill

3.4 Analysis on the Surface Roughness and Chip formation of Al and Ti alloys

When drilling aluminum, an escalation in feed rate can lead to an increase in surface roughness, influenced by various factors. One primary reason is the accelerated removal of a larger volume of material from the workpiece within a shorter timeframe. This heightened material removal raises the risk of vibration and chatter, phenomena that cause the cutting tool to bounce against the workpiece, resulting in a rougher surface finish.

Figure 8(a) illustrates the impact of feed rate on roughness values for both microtextured and standard tools.Another contributing factor to heightened surface roughness at higher feed rates is the formation of a built-up edge (BUE) on the cutting tool. BUE occurs when material from the workpiece adheres to the cutting edge, dulling the tool's effectiveness. This, in turn, leads to increased cutting forces and a coarser surface finish. Remarkably, the microtextured tool prevents the formation of BUE, resulting in improved roughness and a smoother finish compared to the standard tool.

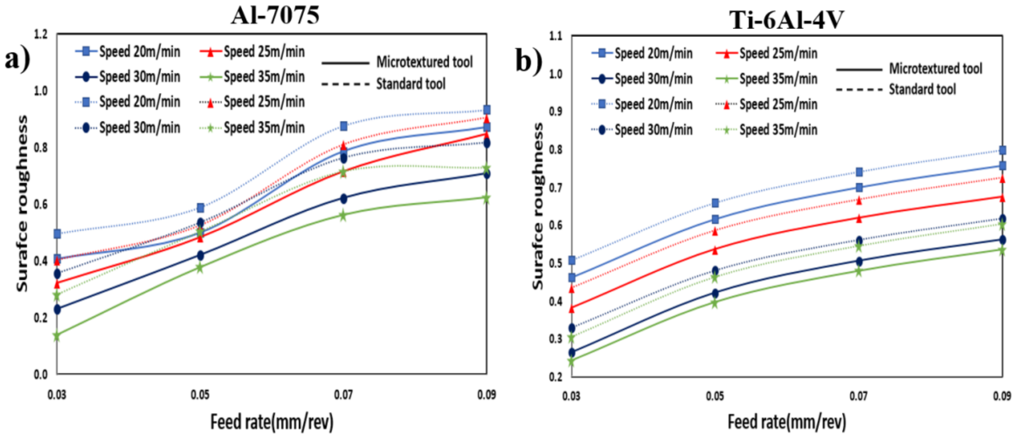

Fig.8. Effect of machining parameters on the surface roughness-Metallic phases

The absence of BUE in the micro-textured tool highlights its efficacy in maintaining a smoother surface finish during aluminum drilling. The micro-textured tool's design mitigates the challenges associated with high feed rates, promoting a more controlled and efficient machining process. This nuanced understanding of the interplay between feed rates, tool design, and surface roughness contributes to optimizing aluminum drilling procedures, ensuring enhanced quality and efficiency in metalworking applications.

Drilling titanium introduces several factors influencing material surface roughness, including cutting speed, feed rate and drill bit geometry. Notably, an elevated feed rate during titanium drilling is associated with an increase in surface roughness as shown in Figure 8(b). This relationship stems from the feed rate dictating the pace at which the cutting tool advances into the material. Higher feed rates result in the cutting tool engaging a larger workpiece area, leading to heightened cutting forces and heat generation. Consequently, material deformation occurs, contributing to a rough surface finish. Additionally, higher feed rates lead to the production of thicker chips during drilling, complicating their evacuation from the cutting zone. This can result in chip packing and accelerated tool wear [19-20], causing the drill bit to rub against the workpiece rather than cut, further exacerbating surface roughness. In contrast, lower feed rates facilitate the cutting tool engaging with a smaller workpiece area, reducing cutting forces and heat generation. This enables a cleaner cut, yielding a smoother surface finish. Microtextured tool performed well by giving improved surface finish when compared standard tool.

During drilling of titanium and aluminum alloys, various chip types are formed [3]. Continuous chips result from efficient cutting conditions, exhibiting long, unbroken ribbons. Conversely, segmented chips arise from interrupted cutting, characterized by shorter, fragmented pieces. Additionally, discontinuous chips can form under inadequate cutting parameters, producing irregular, small-sized chips. Proper tool selection and cutting conditions are crucial to control chip formation [20], ensuring efficient machining of Ti alloys in aerospace and industrial applications. In this study the drilling the Al/CFRP/Ti stack sequence, the machining dynamics exhibit intriguing variations across the different material phases. During the drilling of the Al alloy phase, the formation of continuous spiral chips is prominent, indicative of its relatively low shear strength and high ductility. This behavior contrasts with the drilling of the Ti alloy phase, where a dual chip formation phenomenon emerges [20]. While spiral chips persist due to the Ti alloy's moderate ductility, partially ribbon-shaped chips also manifest, suggesting influences of higher shear strength and work hardening tendencies. These observations underscore the complexity inherent in multi-material stack drilling, where distinct material properties interact with cutting conditions and tool geometry to shape chip formation. Understanding such nuances is pivotal for optimizing machining processes and enhancing efficiency and precision in aerospace and automotive applications where Al/CFRP/Ti stacks are prevalent.

4 Conclusions

The utilization of the micro-textured tool, in conjunction with the Minimum Quantity Lubrication (MQL) setup, significantly enhances the reachability of cutting fluids to the machining zone during drilling. This innovative approach results in a noteworthy reduction of 12–17% in the total thrust force when compared to the standard tool, showcasing the tool's effectiveness in optimizing fluid delivery for improved machining performance.

Through a comprehensive drilling study, it is evident that a strategic combination of low feed rate and high cutting speed, specifically a feed rate of 0.03 mm/rev paired with a cutting speed of 35 m/min, can effectively minimize the thrust force.

The surface integrity analysis of CFRP holes reveals that the micro-textured tool outperforms in terms of delamination factor, roundness, and roughness. This superior performance is attributed to the enhanced flow of lubricants facilitated by the micro-textured tool during the drilling operation. The findings underscore the significant role played by lubrication in achieving superior surface quality in CFRP hole drilling.

These findings collectively emphasize the instrumental role of the micro-textured tool, coupled with strategic drilling parameters, in enhancing machining performance, reducing thrust force, and improving surface integrity in CFRP hole drilling applications.

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