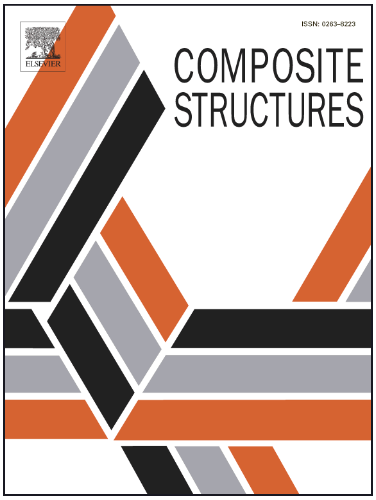

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PII: S0263-8223(19)34146-7
DOI: https://doi.org/10.1016/j.compstruct.2019.111727
Reference: COST 111727

To appear in: *Composite Structures*

Received Date: 30 October 2019
Revised Date: 19 November 2019
Accepted Date: 25 November 2019

Please cite this article as: Xu, J., Ji, M., Paulo Davim, J., Chen, M., Mansori, M.E., Krishnaraj, V., Comparative study of minimum quantity lubrication and dry drilling of CFRP/titanium stacks using TiAlN and diamond coated drills, *Composite Structures* (2019), doi: https://doi.org/10.1016/j.compstruct.2019.111727

# Comparative study of minimum quantity lubrication and dry drilling of CFRP/titanium stacks using TiAlN and diamond coated drills

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**Abstract:** Although minimum quantity lubrication (MQL) has been proved beneficial for the machinability improvement of metallic materials, it is still not well understood whether or not to use the MQL when machining the composite-titanium stacks and whether the MQL can achieve a comparable effect as it operates in the metal cutting processes. The current work is aimed at revealing the underlying mechanisms of the MQL drilling on the CFRP/Ti6Al4V stacks. Both the MQL and dry conditions were examined using the TiAlN-coated and diamond-coated carbide drills to quantify how the MQL operates when compared with the conventional dry machining. The effects of the MQL environment on the machinability of the composite-titanium stacks were quantified in terms of drilling thrust forces, delamination damage of the composite phase and tool wear signatures. A particular emphasis is put on the wettability testing of cut stack hole surfaces versus the minimum quantity lubricants in terms of contact angle. The results indicate that the machined composite surface shows a strong ability to absorb the lubricants under the MQL condition and fails to form a protective oil film at the drill-chip interface, resulting in an increase of thrust forces and delamination damage. Moreover, the MQL environment cannot prevent the drill bits from premature failures during the machining of CFRP/Ti6Al4V. It is indicated that the MQL fails to yield a comparable beneficial role as it operates in the machining of individual metal alloys in terms of the examined drilling responses.

***Keywords*:** CFRP/titanium stacks; MQL drilling; Wettability; Thrust forces; Delamination damage; Tool wear.

## 1. Introduction

Carbon fiber reinforced polymer (CFRP) is a new functional material featured by superior mechanical/physical properties including high specific strength, excellent corrosion resistance and superior fracture toughness [1-4]. In the aerospace industry, the CFRP composites are often employed in conjunction with metallic materials such as titanium and aluminum to form hybrid structures in order to obtain improved mechanical properties and enhanced structural functionalities not possessed by individual materials [5-8]. Multilayer sandwiches constituted by CFRP and Ti6Al4V are typical examples of hybrid composite stacks being widely used in the modern aerospace industry [9-11]. Prior to their final applications, mechanical drilling becomes necessary in order to create holes for riveting and bolting assembly of the composite/titanium stacks. Since the composite and the metallic materials possess different mechanical properties and cutting behaviors, drilling of CFRP/Ti6Al4V stacks has faced significant challenges. Particular issues are associated with the formation of severe drilling-induced damage, poor hole accuracy, rapid tool wear and high machining costs. In addition, thermal damage due to excessive drilling temperatures is non-negligible. This can be evidenced by the machining process of the titanium phase which generates a large amount of cutting heat transferred onto the composite surfaces, resulting in the thermal degradation or even the glass transition of the composite material. However, dry machining is still the most popular cutting strategy for such stacked materials in the modern aviation industry due to the economic reason. To alleviate the thermal and mechanical effects of the machining process of the composite/metal stacks, great endeavors have been sought to the cleaner and green manufacturing techniques. This comes out the emergence of the minimum quantity lubrication (MQL) being attracting due attention of researchers in both academia and industry. Taking the aviation industry for example, the Airbus Company has attempted to use the MQL technique in the machining processes of metallic alloys and fiber related laminates. The MQL refers to a green manufacturing process in which compressed gas and a minimal amount of lubricant (a flow rate of 50 to 500 ml/h) are mixed and sprayed into the cutting zone for effective lubrication [12]. The potentials of the MQL method lie in decreasing the environmental pollutions as compared with the conventional flood coolant technique [13, 14]. Additionally, the lubricating fluid can adhere to the tool-work interface and form a layer of protective film, which effectively reduces the friction coefficient between the cutting edges and the workpiece, resulting in lower temperatures of the machining area and longer tool life [15, 16].

To date, MQL has been extensively applied to the fields of various machining processes of titanium alloys, and hence a large number of scientific investigations have been conducted on the subject area. For instance, Behera et al. [17] discussed the tool wear characteristics of TiN coated carbide inserts in machining Ti6Al4V under dry and MQL conditions. It was found that the MQL mode provided less flank wear for machining Ti6Al4V at high cutting speed. Vazquez et al. [18] analyzed the effects of cooling and lubrication conditions in micro-milling of Ti6Al4V. The authors pointed out that the use of MQL could improve the surface finish and extend the tool life. Perçin et al. [19] addressed that the mean torque value obtained was at a minimum level in the micro-drilling process of Ti6Al4V under the MQL conditions. This means the friction at the tool-chip interface can be reduced, which leads to a better hole surface quality. Zeilmann and Weingaertner [20] compared the drilling temperature of Ti6Al4V under different MQL conditions. It was reported that the use of internally applied MQL could reduce the maximum temperature by 50% compared with external MQL. Pervaiz et al. [21] investigated the machinability of Ti6Al4V under different cutting environments in terms of surface finish, cutting forces, and tool life. The results showed that the MQL strategy had several potentials to replace the conventional flood cooling method.

Despite the extensive well-performed research works, very limited studies have been reported so far to deal with the MQL machining of fibrous composites and their related stacks. Iskandar et al. [22] evaluated the performance of the air, flood, dry, and MQL conditions when milling CFRPs in terms of tool wear and hole geometrical accuracy. The best tool life and dimensional accuracy were obtained when milling with MQL, especially in the combination of maximum air flow rate and minimum oil flow rate, which was due to the smaller droplet size, higher droplet velocity, and lower vorticity. Iskandar et al. [23] conducted a comparative study between the dry and MQL conditions when slotting CFRP laminates. The authors found that lower flank wear and higher process temperatures were obtained under the MQL condition. Brinksmeier and Janssen [24] carried out a preliminary investigation on the machining of multilayer stacks made of aluminum alloys, CFRP and titanium alloys in terms of cutting forces, tool wear, hole quality, and chip formation. The authors suggested the use of MQL with an internal supply when drilling the multilayer materials. Meshreki et al. [25] made a more in-depth inspection of the MQL effects when drilling CFRP/Al stacks, and revealed that the MQL might also cause several drawbacks in machining. For example, although MQL could reduce the forces in the Al phase, an elevation of forces was found for the CFRP phase. In addition, the MQL conditions were found to increase the surface roughness for both phases of the multilayer stack. Compared with the CFRP/Al sandwiches, drilling CFRP/Ti6Al4V stacks is a more challenging task that leads to a large amount of cutting heat and rapid tool wear. Senthilkumar et al. [26] were among the earliest to study the hole quality issues when drilling CFRP/Ti6Al4V stacks under the MQL conditions, and a series of drilling tests were conducted with varying flow rates. The experimental results showed that a lower flow rate was beneficial to the improvement of the stack hole quality. However, the authors did not verify whether the MQL conditions are superior or inferior to the conventional dry machining for the composite/titanium stacks. Additionally, even though the operating mechanisms of MQL are to reduce the friction coefficient at the tool-chip interface, the cut surfaces of the composites are much rough which makes it rather difficult to form an effective oil film at the tool-chip contact surface. As such, it remains unknown whether the use of the MQL conditions can improve the drilling machinability of the CFRP/titanium stacks.

The present paper is thus aimed at identifying the feasibility and operating mechanisms of the MQL conditions in drilling CFRP/Ti6Al4V stacks. To realize this goal, a series of drilling tests were conducted on multilayer stacks constituted by T700/FRD-YZR-03 CFRP laminates and Ti6Al4V alloys using TiAlN-coated and diamond-coated drill bits. The mechanical effects of dry and MQL strategies on the drilling characteristics of CFRP/Ti6Al4V stacks were rigorously investigated. Aspects including drilling forces, delamination damage of the composite phase and wear signatures of drill bits were studied. A particular focus is put on the wettability testing of cut stack hole surfaces versus the minimum quantity lubricants in terms of contact angle in order to clarify the different abilities of the stacked composite and metallic surfaces to form lubricating oil films. The results discussed in this paper contribute to the scientific understanding of the impact of the MQL on the machinability of CFRP/Ti6Al4V stacks and allow several technical guidance for the machining of this multilayer stack.

## 2. Experimental procedures

### 2.1. Workpiece specimens and drill bits

In the present work, the multilayer stacks constituted by the carbon/epoxy composite laminates and the titanium alloy plates were selected as the workpiece specimen. The CFRP laminate was an epoxy-based (FRD-YZR-03) thermosetting plastic reinforced by the T700 carbon fibers subjected to the $[0^{\circ}/-45^{\circ}/45^{\circ}/90^{\circ})_4]_s$ layup sequence. The composition and physical properties of the CFRP laminate are summarized in Tables 1 and 2, respectively. The metallic phase is a duplex alpha-beta Ti6Al4V alloy, and the chemical composition and the physical properties of the Ti6Al4V alloys are given in Tables 3 and 4, respectively. The stack specimen was in the shape of a rectangular plate having a total size of 200 mm (width) × 300 mm (length) × 12.88 mm (thickness) (6.60 mm thickness for the CFRP board and 6.28 mm thickness for the Ti6Al4V sheet), as depicted in Fig.1.

**Table 1** Composition of the used composite laminate.

| Reinforcing fibers | Resin | Density | Fiber volume fraction | Fiber bundle |
|---|---|---|---|---|
| T700 | FRD-YZR-03 | 1.6 g/cm$^3$ | 60% | 7μm, 12K |

**Table 2** Physical properties of the used composite laminate.

| Properties | Value | Properties | Value |
|---|---|---|---|
| Tensile modulus/GPa | 240 | Flexural modulus/GPa | 210 |
| Tensile strength/MPa | 4900 | Flexural strength/MPa | 1500 |
| Poisson’s ratio | 0.3 | Glass transition temperature/℃ | 125~135 |

**Table 3** Chemical composition of the Ti6Al4V alloy.

| Element | Ti | Al | V | Fe | O | C | N | H |
|---|---|---|---|---|---|---|---|---|
| *wt*.% | Base | 5.50-6.75 | 3.50-4.50 | <0.30 | <0.20 | <0.08 | <0.05 | <0.015 |

**Table 4** Physical properties of the Ti6Al4V alloy.

| Properties | Value | Properties | Value |
|---|---|---|---|
| Density/(kg/m$^3$) | 4430 | Thermal conductivity/(W/(m•K)) | 7.3 |
| Poisson’s ratio | 0.342 | Tensile strength/MPa | 960-1270 |
| Elongation/% | 8.0 | Specific heat/(J/(kg/℃)) | 526 |
| Melting point/℃ | 1650 | Yield strength/MPa | 820 |
| Hardness/HV | 360 | Young’s modulus/GPa | 113.8 |

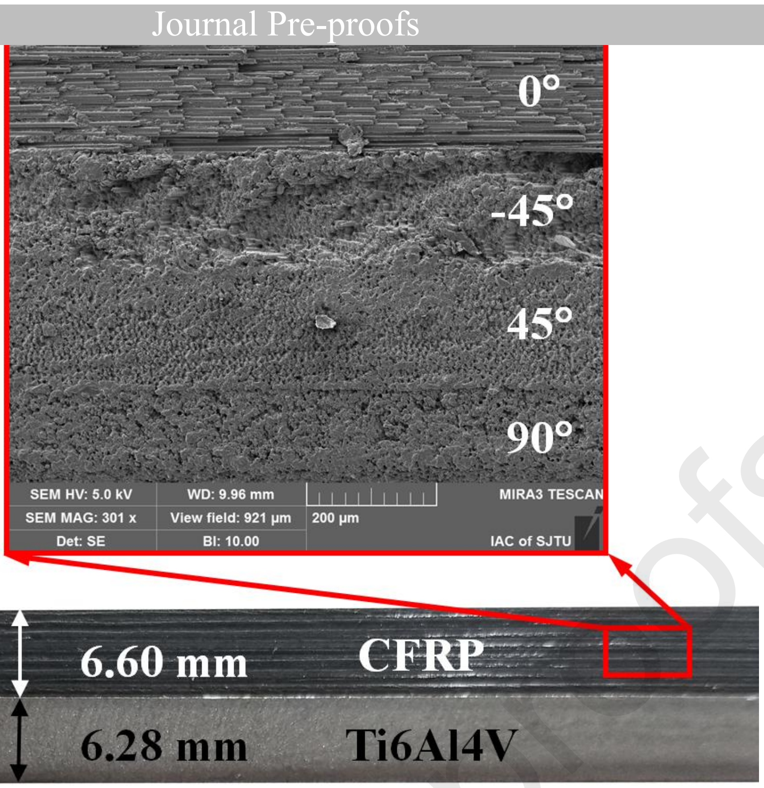

**Fig.1.** Morphologies of the used CFRP/Ti6Al4V specimen.

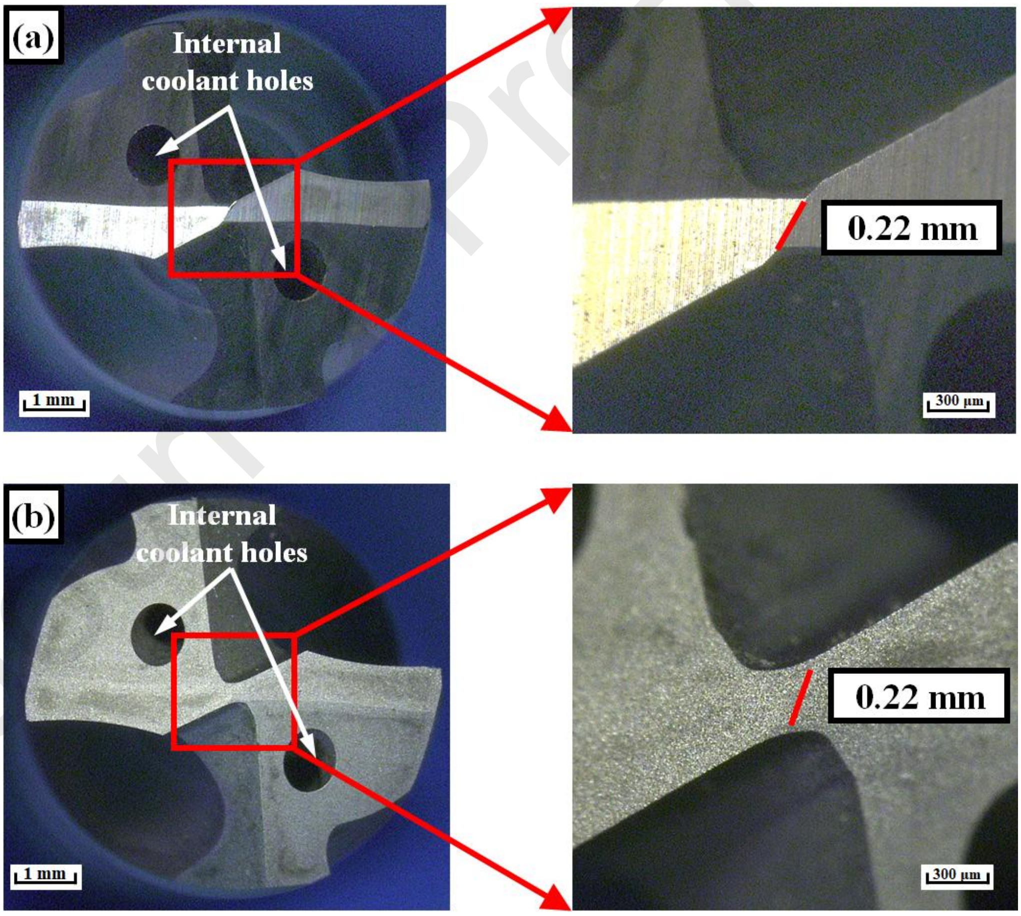

**Fig.2.** Morphologies of (a) the TiAlN-coated drill and (b) the diamond-coated drill.

Two types of tools including the PVD TiAlN-coated and the CVD diamond-coated tungsten carbide drills were used in the experiments, which were specially designed by the ITF Company for the machining of composite/metal stacks. Note that the diamond coating has a thickness of 10 μm while the TiAlN coating has a thickness of 3~4 μm. Both drills have the identical geometrical angles and are characterized by a double land structure that can disperse the cutting force and enhance the secondary trimming effects on the hole walls, thus ensuring the consistency of cut hole diameters. Moreover, each drill has two coolant holes so that an internal supply of MQL can direct into the cutting zone while drilling the hybrid composite stacks. The morphologies of the used two types of drill bits are shown in Fig.2 and their geometrical parameters are summarized in Table 5.

**Table 5** Details of the used drill bits.

| **Manufacturer** | **Coating type** | **Drill bit** |
|---|---|---|
| ITF Company | PVD TiAlN |  |
| ITF Company | CVD diamond |  |

| **Parameters** | **Value** | **Parameters** | **Value** |
|---|---|---|---|
| Diameter/(mm) | 6 | Helix angle/deg | 30 |
| Point angle/deg | 140 | Length of chisel edge/mm | 0.22 |
| Length of cutting edge/mm | 25 | Land width/mm | 0.8 |
| Total length/mm | 70 | Rake angle/deg | 10 |
| First clearance angle/deg | 12 | Second clearance angle/deg | 20 |

### *2.2. Experimental setup*

The drilling tests were conducted under both the dry and MQL conditions on a HURCO VMX42 CNC machining center which has a maximum spindle speed of 12000 rpm, a maximum power of 17.9 kW, and a positioning accuracy of 0.01 mm. Each hole of the multilayer composite/titanium specimen was drilled out in one-shot pass instead of drilling each composite and titanium material separately in order to minimize the positional errors and to obtain tight tolerance for the post mechanical assembly using bolts or rivets [5, 7]. The spindle system of the machining center has an inner-coolant function, which enables the connection of a high-pressure minimum quantity lubrication system (ARMORINE IMQL 252IE) having a compressed air pressure ranging from 0.5 to 0.8 MPa and a flow rate ranging from 5 to 50 ml/h with the drill bit. For the MQL drilling, as indicated by Iskander et al. [22] and Meshreki et al. [25], a combination of high air pressure and low oil flow rate is beneficial to obtain higher machining quality, so the compressed air pressure was set at 0.6 MPa and the oil flow rate was set at 15 ml/h in the experiments. Additionally, the lubricant used for the MQL machining was vegetable-based micro-cutting oil (MICROLUBE 2000). Specimens of the composite/metal stacks were firmly clamped by a specially-designed fixture upon a KISTLER dynamometer (type 9272) connected with a multichannel charge amplifier (KISTLER 5070A) and a data acquisition system to capture *in-situ* the force signals generated during the stack machining. An overview of the experimental setup for the drilling of CFRP/Ti6Al4V stacks is shown in Fig.3. The drilling experiments under the dry and MQL conditions were implemented following a full factorial trial design including the cutting speeds ($V_c$) of 15, 30, 45, and 60 m/min and the feed rates ($f$) of 0.025, 0.050, 0.075, and 0.100 mm/rev as summarized in Table 6. Each set of cutting parameters was repeated three times and the average value of the three results was used as the experimental data for the subsequent analysis. After the drilling tests, additional wear experiments were conducted to compare the wear signatures of drills under the two different cutting environments.

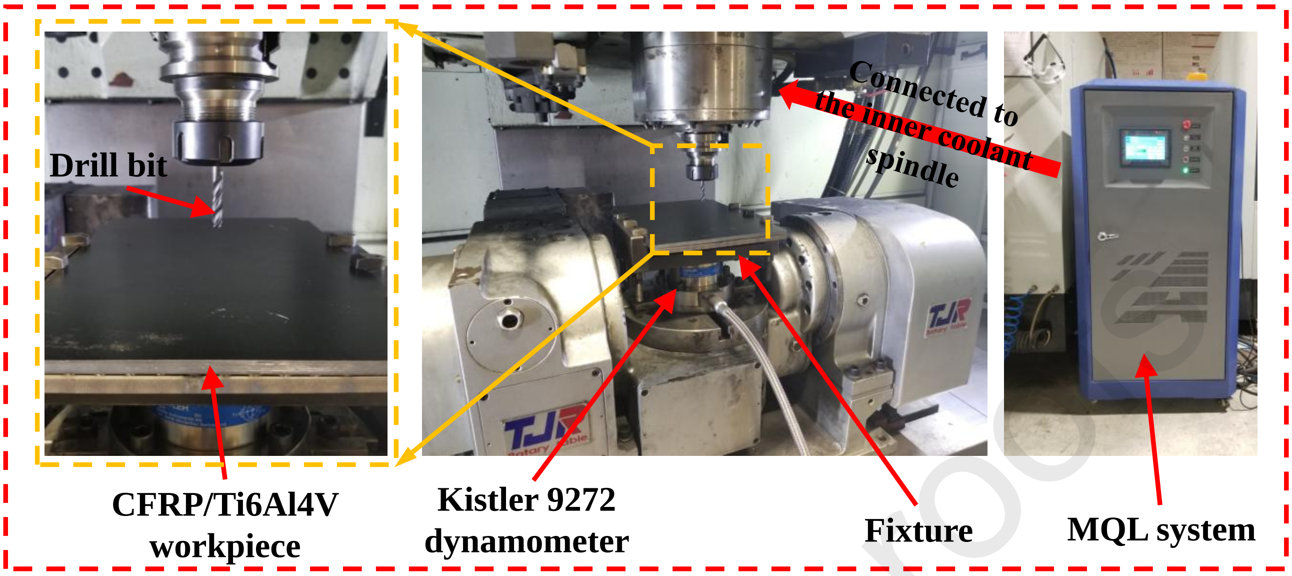

**Fig.3.** Experimental setup for the drilling of CFRP/Ti6Al4V stacks.

**Table 6** Cutting parameters used for the drilling of CFRP/Ti6Al4V stacks.

| Test no. | Cutting speed, $V_c$ [m/min] | Feed rate, $f$ [mm/rev] | Drilling environment | Drill bit |
|---|---|---|---|---|
| 1 - 4 | 15 | 0.025, 0.050, 0.075 and 0.100 | Dry condition | TiAlN-coated drill<br>Diamond-coated drill |
| 5 - 8 | 30 | | | |
| 9 - 12 | 45 | | | |
| 13 - 16 | 60 | | | |
| 1 - 4 | 15 | 0.025, 0.050, 0.075 and 0.100 | MQL condition | TiAlN-coated drill<br>Diamond-coated drill |
| 5 - 8 | 30 | | | |
| 9 - 12 | 45 | | | |
| 13 - 16 | 60 | | | |

### *2.3. Post-process analysis*

After the completion of the drilling tests, delamination damage occurring inside the CFRP laminate under different cutting environments was characterized and evaluated using a KSI v-400E scanning acoustic microscope (SAM). A photograph depicting the process setup of the *in-situ* delamination detection of a drilled CFRP specimen is given in Fig.4. Based on the greyscale image recorded by the KSI v-400E, an image processing software called KSI-VISION was used to color the damaged area red and to calculate the delaminated area of each layer by means of the analysis of pixel number. In this paper, the CFRP holes were scanned layer by layer. To quantify accurately the severity of interlaminar delamination damage occurring inside the CFRP composite laminates, a new delamination assessment criterion, namely, the three-dimensional delamination factor ($F_V$) proposed by Xu et al. [27] was adopted in the present work. The $F_V$ is defined as the ratio of the cumulative volume ($V_{del}$) to the nominal hole volume ($V_{nom}$) of the delaminated CFRP layers, which considers the interlaminar delamination modes produced at the inner of the composite layers and presents a much higher accuracy for quantification of the delamination extents in comparison with the conventional one-dimensional and two-dimensional delamination factors [28]. Regarding the full details of the measuring and calculating procedures of the three-dimensional delamination factor, readers are directed to the work done by Xu et al. [27]. In order to figure out the interacting mechanisms between the lubricant and the machined CFRP/Ti6Al4V surfaces, the wettability of two stacked phases were examined in terms of the contact angle using a drop shape analyzer (type DSA100). The liquid droplets used were the vegetable oil originated from the MQL supply and the volume of each droplet was set as 5 μL. Finally, signatures of the worn drills were examined using the TESCAN VEGA3 XMU and MIRA3 SEM to characterize the frictional contacts at the tool-work interface and the wear modes of drills when changing the cutting environment.

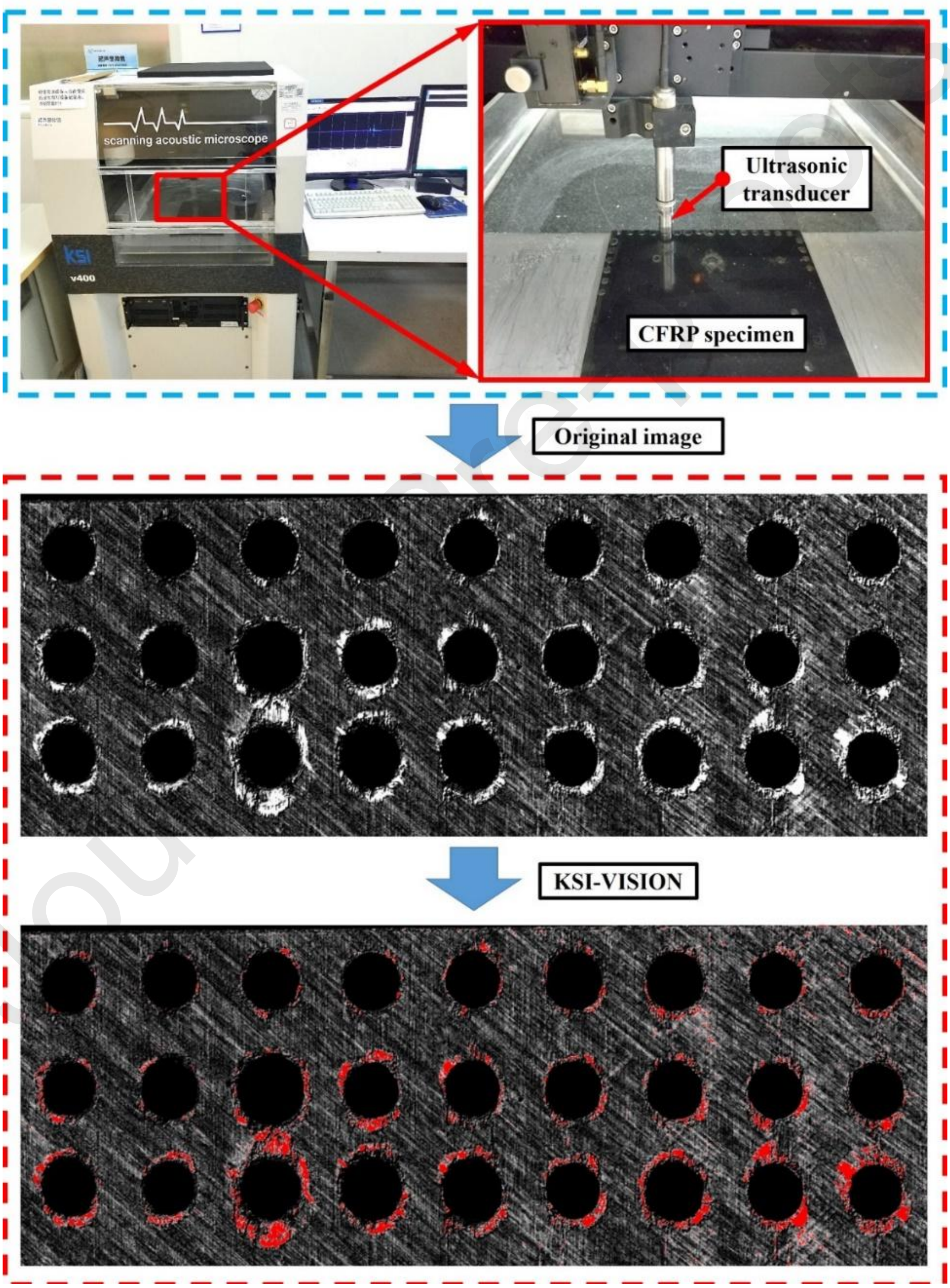

**Fig.4.** Process setup of the delamination detection of a drilled CFRP specimen using the KSI v-400E SAM.

## 3. Results and discussion

### 3.1. Drilling forces

The cutting force in the machining process is produced due to the sliding of the cutting tool against the workpiece in order to remove the material from the workpiece. In drilling operations, thrust force is considered as one of the fundamental indicators used to evaluate machinability and power consumption of various composites or composite/metal stacks as it influences the quality of holes and the resulting tool wear [29-32]. Additionally, the most critical damage type, namely, the drilling-induced delamination is firmly associated with the drilling thrust forces. Analysis of the thrust force is of critical importance to figure out the activated mechanisms of the MQL condition on the composite/titanium stack machining. Fig.5 shows the measured thrust forces for the two drill bits in terms of the CFRP phase machining under the dry and MQL conditions. It is noticeable that for the TiAlN-coated drill bits, the thrust forces increase with increasing the feed rate and decrease with increasing the cutting speed under both cutting environments. The varying trends of the CFRP thrust forces with the drilling parameters agree well with those reported in the scientific literature [33, 34]. The phenomenon is attributed to the enlarged cross-sectional area of un-deformed chips as the feed rate increases, which leads to a higher drilling resistance force. In contrast, increasing the cutting speed tends to enlarge the frictional work consumed at the drill-work interface and thus promotes higher machining temperatures, which leads to the softening of the workpieces and hence the reduction of the thrust force. The results given in Fig.5 (b) reveal that the thrust forces promoted by the diamond-coated drills generally depict a similar varying trend as those for the TiAlN-coated drills particularly under the dry cutting condition. However, in the case of the MQL condition, the correlation between the thrust force and the cutting speed for the diamond-coated drill differs from that for the TiAlN-coated one. Additionally, the MQL machining is found to promote much higher magnitudes of CFRP thrust forces than the conventional dry condition for both drills. This observation is consistent with the findings of Meshreki et al. [25] when drilling CFRP/Al stacks under the MQL condition. However, the phenomenon conflicts with the observations reported in the fields of machining metal alloys. This is attributed to the different operating mechanisms of MQL when machining the composite phase. On the one hand, the cooling effects arising from the supply of MQL oil prevent the softening and plasticizing of the composite polymer matrix, which retains the brittle properties of the carbon/epoxy system. The higher thrust forces obtained when using the MQL condition indicate that the CFRP phase does not soften and thus opposes a higher mechanical resistance to the drill cutting edges and particularly to the chisel edge [35]. On the other hand, as shown in Fig.6, the cut surfaces of composites are featured by fiber fractures which take place below the machined surface, and then the vegetable oil sprayed under the MQL condition tends to flow inside the surface cavities and fails to form a protective lubricating film. In contrast, the chip removal of the metallic phase is governed by elastoplastic deformation, which inclines to generate a much smoother cut surfaces favoring the formation of protective lubricating films as illustrated in Fig.6(c). Moreover, the lubricant has an ability to moisten and soak the powdery composite chips, which makes the composite chips stick together and adhere onto the tool surface. Thus, the frictional behavior at the tool-chip interface was deteriorated instead of being improved, which leads to the increase of the thrust force. Moreover, the thrust forces generated by the diamond-coated drills are much higher than those gained by the TiAlN-coated drills under the MQL condition. The phenomenon is consist with the findings of Braga et al. [36] when drilling the aluminum-silicon alloys. Braga et al. [36] found that larger cutting forces were produced under the MQL condition when using the diamond-coated drills compared with the uncoated drills. The reason lies on the fact that the use of MQL increases the humidity at the cutting zone. The tribological behaviors of diamond coatings are very sensitive to the humidity, and the friction coefficient of the diamond coating tends to be elevated when the humidity increases, which thereby leads to a larger cutting force [37].

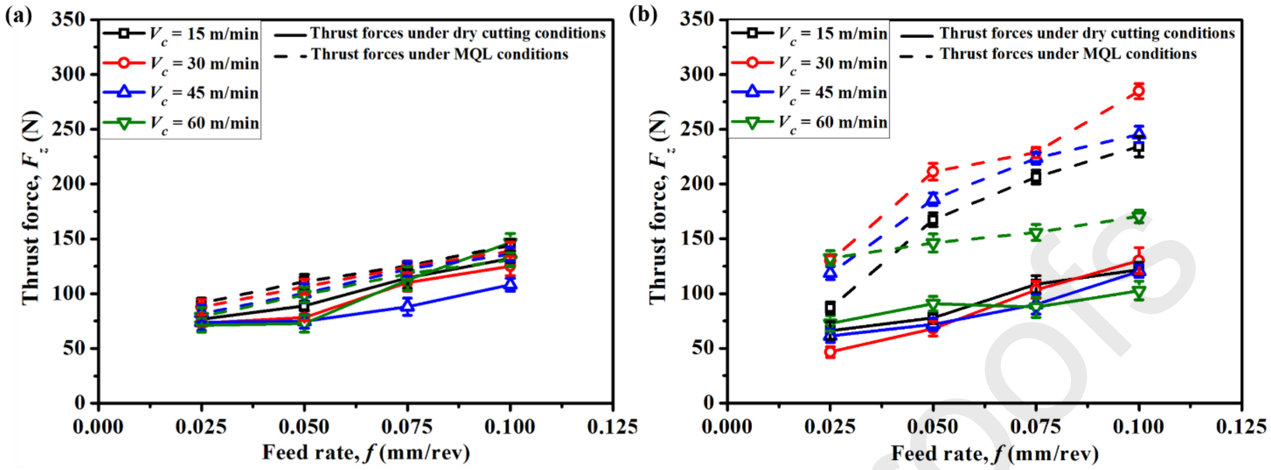

**Fig.5.** Comparison of the thrust forces for the CFRP phase under two cutting environments with (a) TiAlN-coated drills and (b) diamond-coated drills.

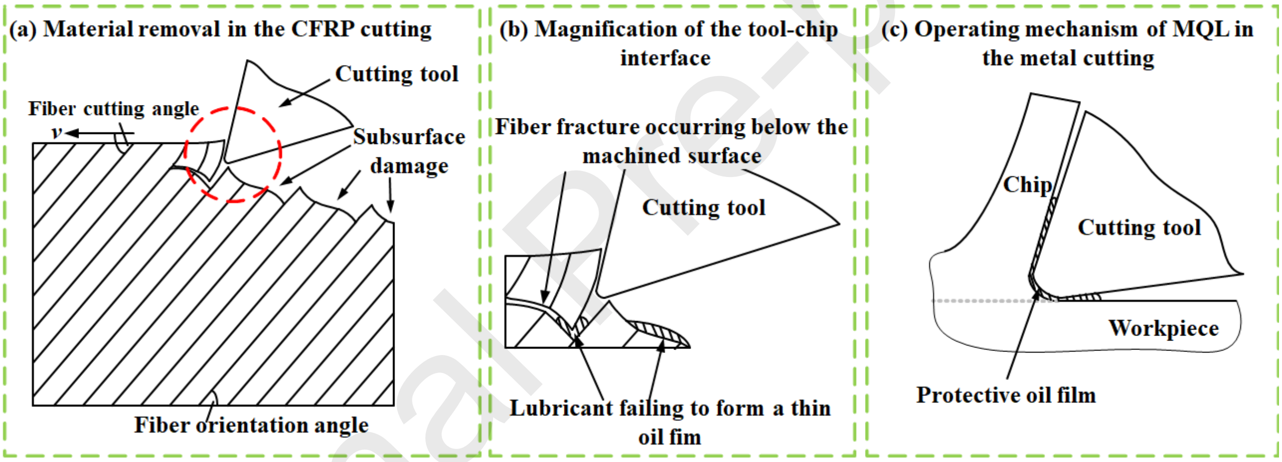

**Fig.6.** Schematic illustrations of the different operating mechanisms of MQL in (a)-(b) the CFRP cutting, and (c) the metal cutting.

Fig.7 shows the comparison of the dry and MQL effects on the titanium thrust forces under varying drilling parameters when using TiAlN and diamond-coated drills. By analyzing Figs.5 and 7, it is noted that machining the Ti6Al4V phase generally entails much higher magnitudes of thrust forces than the CFRP phase irrespective of the used drill bits. The phenomena are attributed to the disparate chip removal mechanisms of the composite and the metallic materials. As depicted in Fig.8 (a) when machining the titanium alloy, the chips are separated in terms of elastoplastic deformation and are in the form of continuous and serrated shapes, which thereby creates much higher mechanical resistance and hence higher force magnitudes [38, 39]. In contrast, the CFRP phase is governed by the brittle fracture chip removal mode, resulting in the powdery chip formation (Ref. Fig.8 (b)), which thus produces much lower magnitudes of thrust forces. Additionally, the thrust forces for both drills increase with increasing the feed rate. The observation agrees well with the findings of Wu et al. [40] when drilling individual Ti6Al4V alloys. This is because the increase of the feed rate will simultaneously lead to an increased chip thickness and a decrease of the deformation coefficient. Consequently, the combination of the two effects results in the elevated thrust force. Besides, the magnitudes of the thrust force under the MQL condition appear to be greater than those gained by the dry cutting condition. The higher thrust force observed for the metallic phase conflicts with the results reported by Meshreki et al. [25] who stated that the average thrust force of the metallic phase was lower when drilling CFRP/aluminum stacks under the MQL condition. The reason is due to two factors that may account for this phenomenon. Firstly, the titanium alloy is a typical hard-to-machine material compared with the Al alloy, the use of MQL reduces the temperature of the cutting zone, which simultaneously weakens the effect of thermal softening and causes a cooling effect among chips ejected from the drilled hole, so the friction between each chip and the hole wall is greater. Secondly, for the titanium alloy, the cutting edge should be as sharp as possible, but the adhered CFRP chips induced by the vegetable oil cause a significant cutting edge rounding and aggravate the abrasive wear of the drill bit, which is quite unfavorable for drilling the tough titanium alloy, resulting in higher magnitudes of the cutting load. For the TiAlN-coated drill, the thrust force is found to decrease as the cutting speed increases, the observation of which agrees with the findings of Sushinder et at. [41] when drilling individual Ti6Al4V alloys. The phenomenon is due to the fact that the cutting temperature increases sharply with the elevation of the cutting speed, thus generating a thermal softening effect, which in turn, reduces the thrust force. With respect to the diamond-coated drill, its situation becomes more complicated under the MQL condition. Fig.9 depicts the correlation between the thrust forces for the diamond-coated drills and the cutting speed. It is noted that the thrust force increases initially and then decreases with the increase of the cutting speed for both the CFRP and the titanium layers, and the maximum thrust magnitudes are obtained under the 30 m/min cutting speed. The photograph of the experimental scene also shows that a phenomenon of severe chip congestion occurs along the drill bit, which consequently results in a significant increase of the drilling thrust. With the further increase of the cutting speed, the centrifugal force of the titanium chips gets larger and larger, then the chips become easy to break and the cutting force tends to decrease accordingly.

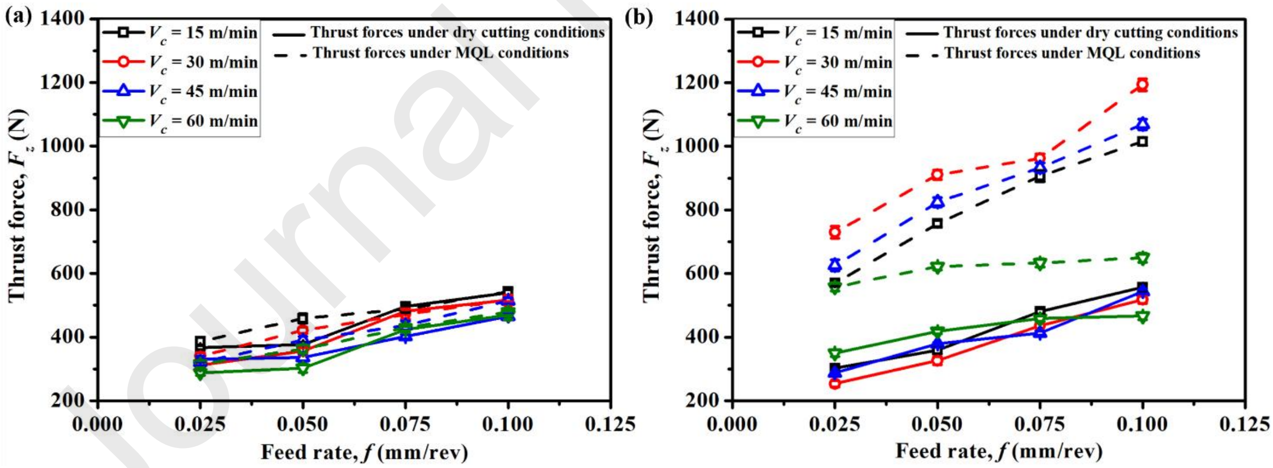

**Fig.7.** Comparison of the thrust forces for the titanium phase under two cutting environments with (a) TiAlN-coated drills and (b) diamond-coated drills.

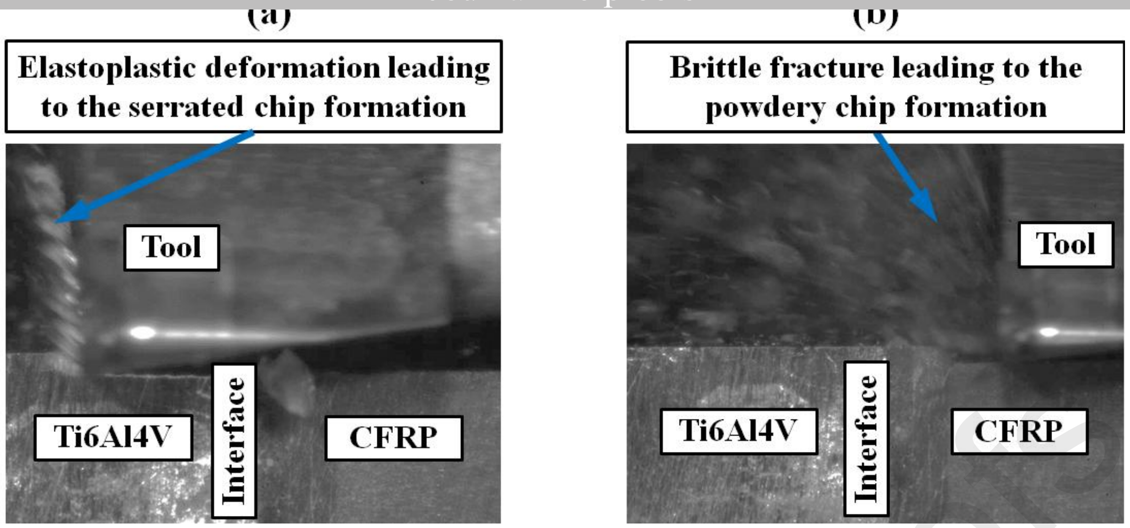

**Fig.8.** In-situ documented images showing the chip separation of CFRP/Ti6Al4V stacks: (a) machining the Ti6Al4V phase and (b) machining the CFRP phase [38, 39].

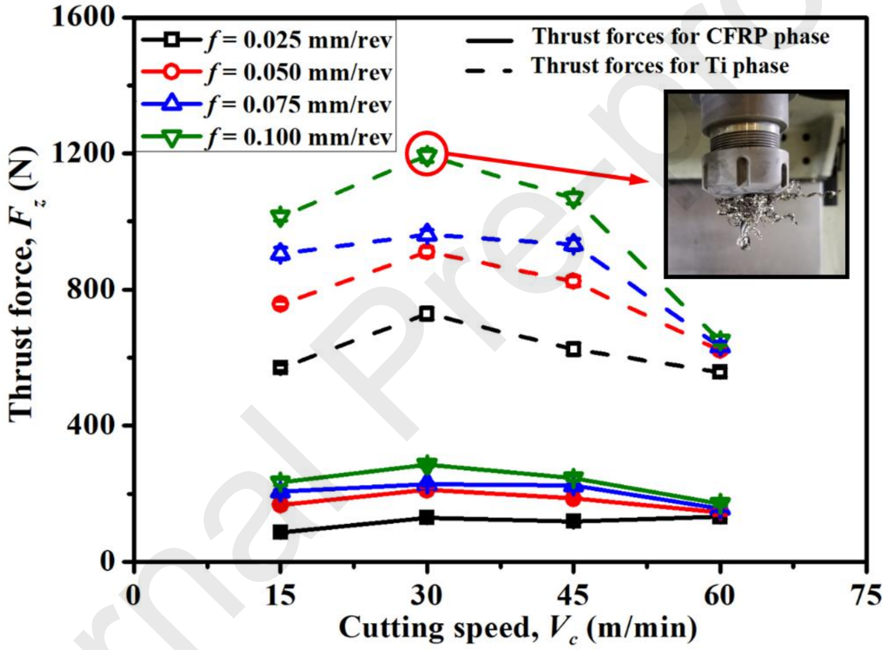

**Fig.9.** The thrust forces for each stacked phase under the MQL condition with diamond-coated drill bits.

To figure out the interacting mechanisms of the minimum quantity lubricants acting on the stack surfaces during the chip removal process, there is a need to conduct the wettability testing of the two stacked material layers. As such, measurements of the contact angle at the machined surfaces of the composite and metallic layers were performed. Note that the contact angle signifies the angle at which a liquid/vapor interface meets the solid surface, which can be used to verify the hydrophilic/hydrophobic abilities of a treated surface to be wetted by liquids. The liquid droplets used in the tests are the vegetable oil being originated from the minimum quantity lubricants applied in the drilling tests. The spreading process of lubricants on the composite and titanium surfaces is shown in Fig.10. For the metallic phase, the titanium is acting as a super-hydrophilic material possessing a contact angle of 26.2°~28.8° as depicted in Fig.10 (a). With the extension of the contact time, the contact angle gradually decreases and stabilizes at about 20°. This indicates that the lubricant becomes easy to stretch out on the metallic surface and to form a thin oil film which can reduce the frictional work at the drill-chip interface, resulting in a decrease of the titanium cutting forces. This phenomenon also explains why the MQL environment gains remarkable benefits in the metal cutting process. With respect to the CFRP phase, when the lubricant first drops on the machined carbon/epoxy surface, the contact angles is approximately in the range of 32.5°~40.1° (Ref. Fig.10 (d)). Although the CFRP is a material featured by a low surface energy (about 43 mJ/m$^2$ ~ 47 mJ/m$^2$ [42]), the surface tension of the vegetable oil is smaller than that of the distilled water, so it inclines to form a lower contact angle at the composite surface, resulting in a hydrophilic behavior. However, the contact angle of the lubricant droplets decreases rapidly in time, and the lubricant is completely absorbed by the material very rapidly as shown in Fig.10 (e) and (f). The phenomenon is due to the fact that on the one hand, the matrix of the composite phase is epoxy resin which possesses a strong ability to absorb liquids. On the other hand, the cut composite surface is constituted by quantities of micro cavities due to the removal of fractured fibers and the loss of epoxy matrix resulting from the debonding of the carbon/epoxy interface as depicted in Fig.11, which favors the absorption of minimum quantity lubricants sprayed from the inner drill holes and reduces the possibilities of forming lubricating films at the drill-composite interface during the chip removal process. As a consequence, the MQL fails to reduce the friction between the cut composite hole surface and the drill edge surface and does not play an effect in decreasing the drilling forces of the composite phase.

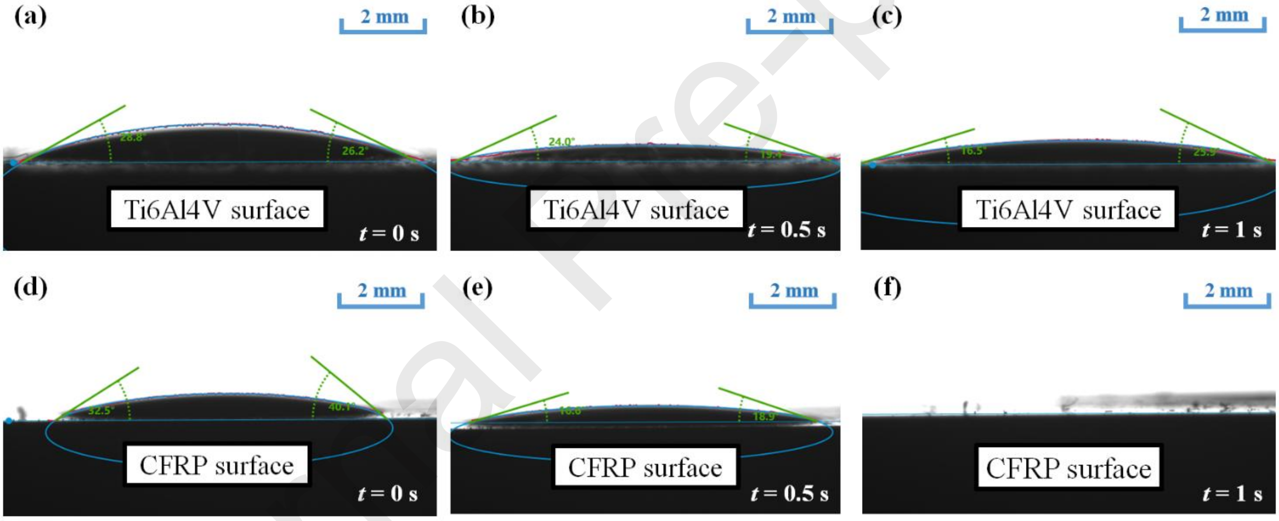

**Fig.10.** The spreading process of the minimum quantity lubricant droplets on the machined stack surface in terms of the contact time: (a)-(c) the Ti6Al4V surface; (d)-(f) the CFRP surface.

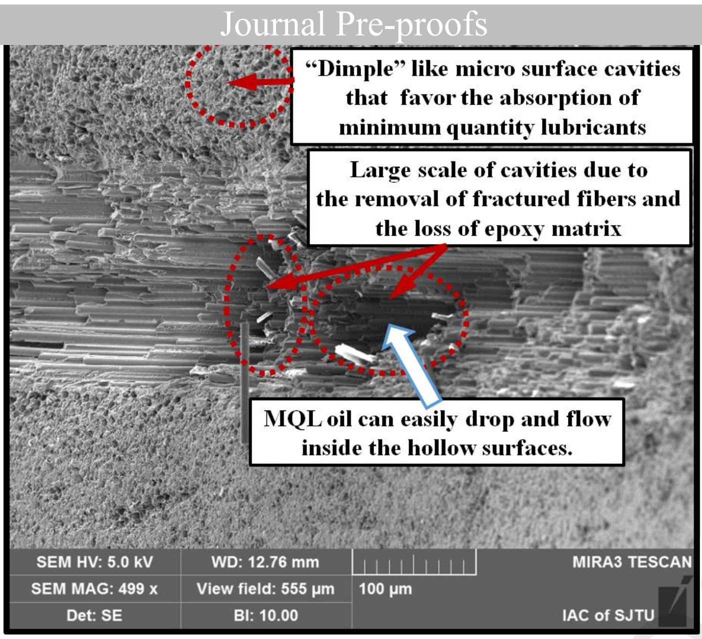

**Fig.11.** A SEM micrograph showing the typical morphologies of a drilled composite surface.

### *3.2. Delamination damage of drilled composite holes*

Assessment of delamination in drilling is of critical importance for improving the service performance of the composite-made components. Delamination, which refers to the interlaminar debonding occurring inside the adjacent layers of a composite, is recognized as the most critical damage as it affects adversely the assembly performance and the fatigue life of composite laminates [28, 43, 44]. It takes place as a result of bending stresses between the drill bit and the material contact point [45]. Additionally, under the working conditions of alternating loads, delamination will further expand and eventually lead to the early termination of the service life of the composite-made components. The present work uses the three-dimensional delamination factor ($F_V$) to quantify the severity of the delamination damage while drilling the CFRP/Ti6Al4V stacks. The $F_v$ is defined as the ratio of the cumulative volume ($V_{del}$) to the nominal hole volume ($V_{nom}$) of the delaminated CFRP layers [27].

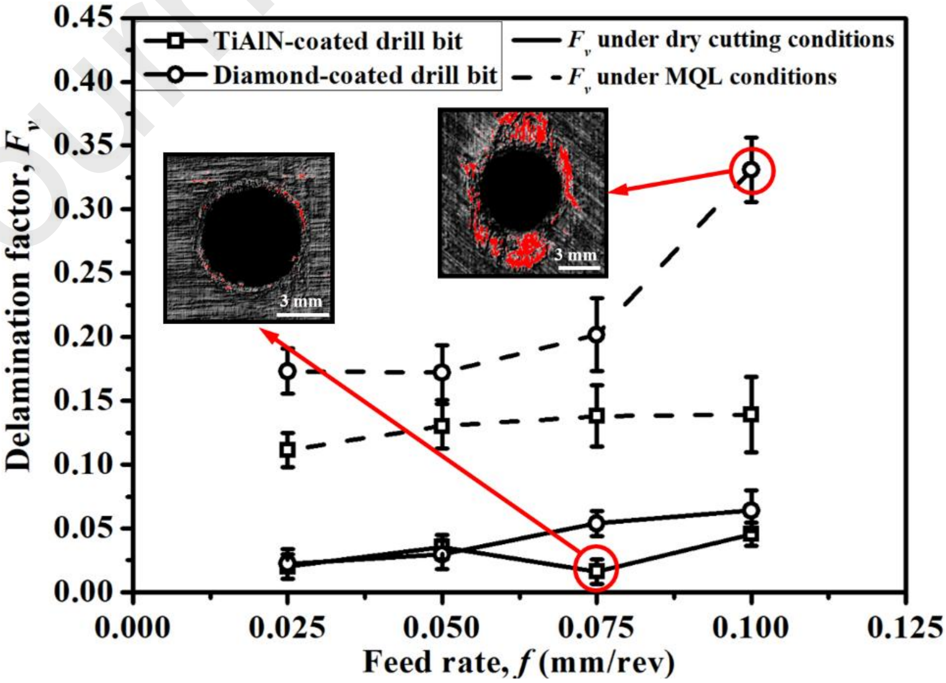

**Fig.12.** Evolution of delamination factors ($F_V$ = three-dimensional delamination factor) under two cutting environments when using the TiAlN-coated and diamond-coated drills ($V_c$ = 30 m/min).

Fig.12 shows the evolution of the calculated three-dimensional delamination factor ($F_V$) versus the feed rate under two cutting environments ($V_c$ = 30 m/min). The delamination factor ($F_V$) basically shows an increasing trend with the feed rate for each cutting environment, which agrees with the findings of Sorrentino et al. [46] and Gaitonde et al. [47] when drilling individual FRP laminates. The phenomenon is associated with the formation mechanisms of delamination damage. This is because delamination is mainly caused by the thrust force of a drilling process that creates interlaminar debonding among adjacent plies of a composite, leading to the push-out delamination at the exit of the composite hole. The larger the thrust force, the more severe the delamination damage becomes. The phenomenon also explains why the delamination factors appear much larger under the MQL condition than those gained under the dry cutting condition. As mentioned earlier, the MQL drilling often promotes higher magnitudes of the CFRP thrust forces for both drill bits, which thereby leads to larger extents of the composite delamination damage. When increasing the feed rate to the maximum value of 0.100 mm/rev, the delamination factor produced by the diamond-coated drills reaches the largest magnitude due to the fact that the thrust force of the composite phase attains the maximum level (Ref. Fig.5), the phenomenon of which can be evidenced by the SAM image shown in Fig.12 that the delamination area under such a condition develops along the radial direction and extends to a large surrounding region. In view of delamination damage, the MQL condition seems unsuitable for the drilling of CFRP/Ti6Al4V stacks.

### *3.3. Wear signatures of drills*

Tool wear is one of the most important criteria in machining processes, which directly affects the tool life, surface quality, and production cost [48]. Tool wear in machining CFRP/Ti6Al4V stacks occurs due to the rubbing of the cutting tool edge with the hard carbon fibers as well as the abrasion, adhesion and attrition resulting from the titanium alloy. The vital role of MQL in most metallic alloy machining is to reduce the tool wear and prolong the tool life. To figure out whether the MQL condition is beneficial for the wear reduction of drills during the machining of the composite/titanium stacks, a series of wear tests were conducted under both the dry and MQL conditions subjected to the identical drilling parameters ($V_c$ = 15 m/min and $f$ = 0.025 mm/rev). Each drill bit was used to consecutively machine eight stack holes. After the drilling tests, the wear signatures of drills were examined. Fig.13 shows the SEM morphologies of the chisel edge region of the TiAlN-coated and diamond-coated drills under the dry cutting condition. It is evident that there are quantities of lamellar titanium materials adhering onto the chisel edge region of the TiAlN-coated drill bit. In addition, phenomena of coating peeling occur at the chisel edge region. For the diamond-coated drills, severe edge chipping appears at the end of the chisel edge, which is mainly due to the fact that on the one hand the introduction of the diamond coating increases the radius of the chisel edges, thereby exacerbating the plowing effects of chips at the drill chisel edge zone, and on the other hand, the inherent brittleness of the diamond coating causes a high sensitivity to fracturing when drilling the titanium alloy. Fig.14 shows the SEM morphologies of the identical drill region under the MQL condition. It is noted that a minor degree of edge chipping takes place close to the TiAlN-coated drill chisel edge region due to the adhesive wear. The vegetable oil causes the composite chips to aggregate and stick onto the tool surface. Due to the near-zero cutting velocity at the chisel edge, the composite chips cannot be ejected completely, which increases the friction between the tool and the uncut titanium materials, resulting in highly-localized temperatures and the formation of titanium chip adhesion. The diamond-coated drill experiences a rapid wear progression on the chisel edge. A large area of the diamond coating is found peeling off and the carbide substrate gets blunted due to the loss of the diamond coating.

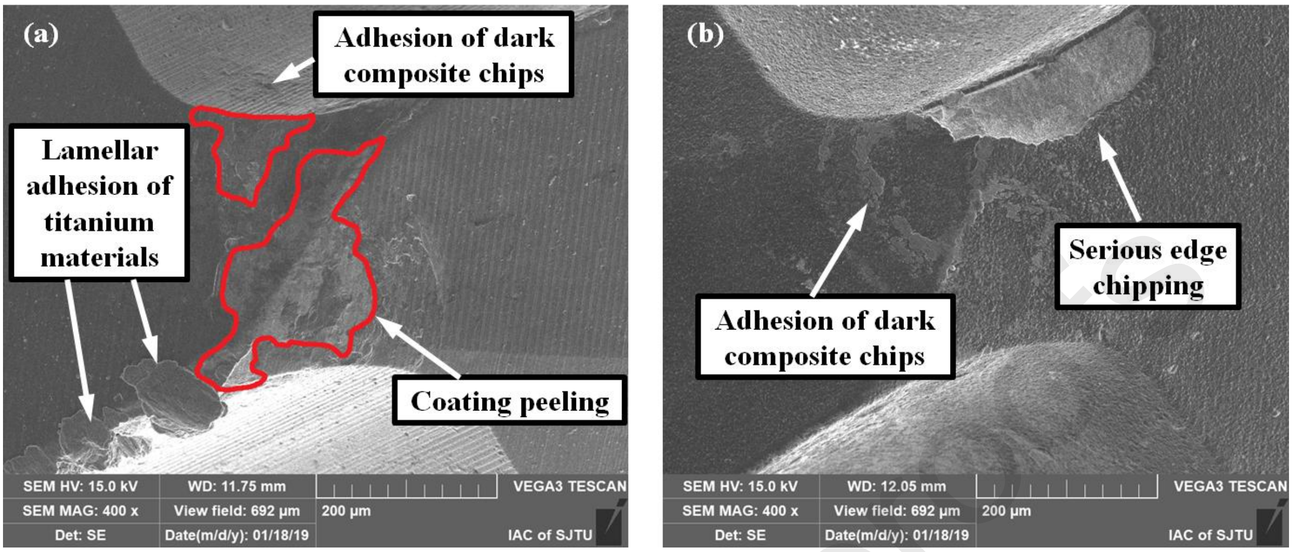

**Fig.13.** SEM morphologies of the chisel edge region under the dry cutting condition: (a) TiAlN-coated drill, and (b) diamond-coated drill.

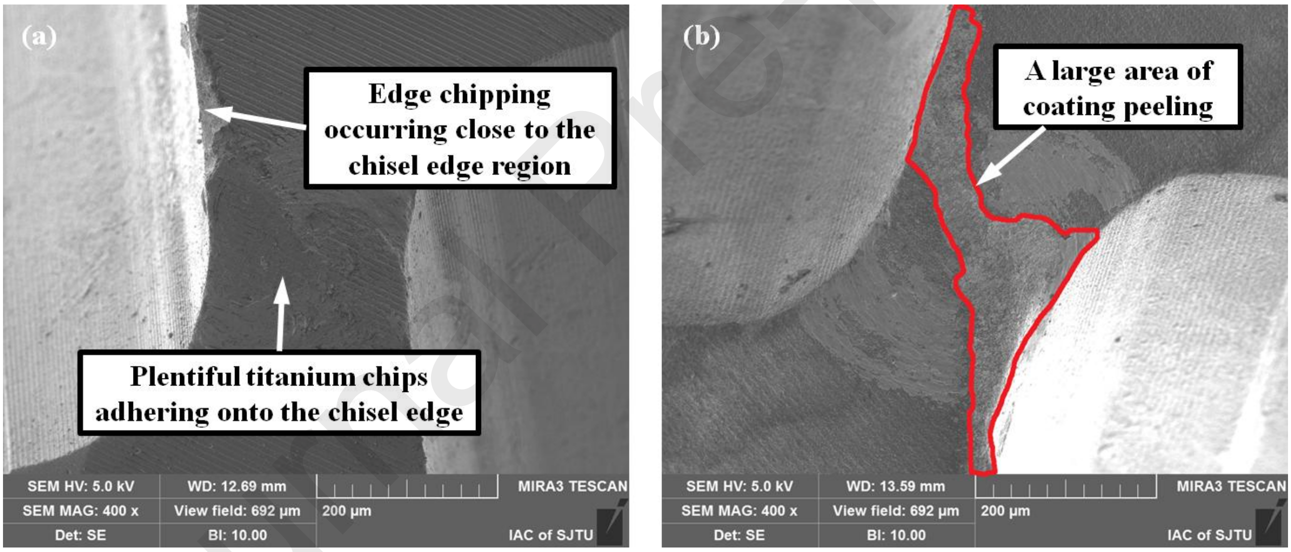

**Fig.14.** SEM morphologies of the chisel edge region under the MQL condition: (a) TiAlN-coated drill, and (b) diamond-coated drill.

The SEM morphologies of the corner edge of the TiAlN-coated and diamond-coated drills under the two cutting environments are shown in Figs.15 and 16. Under the dry condition, the corner edge of the TiAlN-coated drill generally maintains a complete topography whereas the diamond-coated corner edge suffers a severe edge fracture. This is due to the different physical properties of the two coatings. The highest temperature takes place at the drill corner edge due to the existence of the highest cutting velocity. Since the thermal conductivity of the TiAlN-coating is extremely low, a large amount of cutting-induced heat is transferred into the chips, which makes the titanium alloy chips softened and prone to cause adhesive wear. In contrast, the heat-conducting behavior of the diamond coating is superior, so the cutting-induced heat is mainly transferred by the drill body, resulting in high surface temperatures of the drill edges. As stated by the relevant literature [49, 50], the diamond is likely to undergo oxidation and graphitization when exposed to temperatures higher than 600℃ and 700℃, respectively, and brittle graphite tends to crack during the drilling process. In addition, the diamond coating has a larger thickness ($t_c = 10$ μm) than the TiAlN one ($t_c = 3\sim4$ μm), so the edge radius of the diamond drill becomes larger than the TiAlN-coated one which may exacerbate the frictional contact between the drill-workpiece interfaces. When the surface coating fractures, the tool substrate inclines to collapse. Under the MQL condition, both the two drills exhibit different wear behaviors at the corner edges during the drilling of CFRP/Ti6Al4V stacks. As depicted in Fig.15, a large fractured zone takes place along the corner edge for the TiAlN-coated drill. This is mainly due to the hardening of the unprocessed metal phase under the MQL condition, which increases the impulse load acting on the drill corner edge. With respect to the diamond-coated drill, owing to the extremely high hardness of the diamond coating, the cutting edge is mainly preserved with a minor degree of coating peeling under the MQL condition as shown in Fig.16.

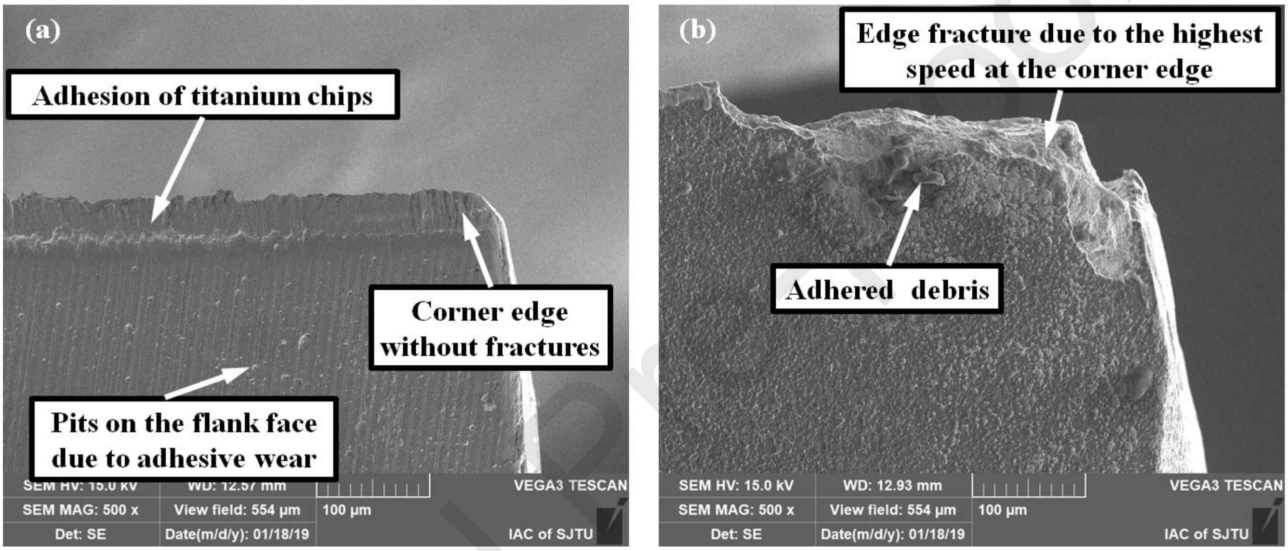

**Fig.15.** SEM morphologies of the corner edge under the dry cutting condition: (a) TiAlN-coated drill, and (b) diamond-coated drill.

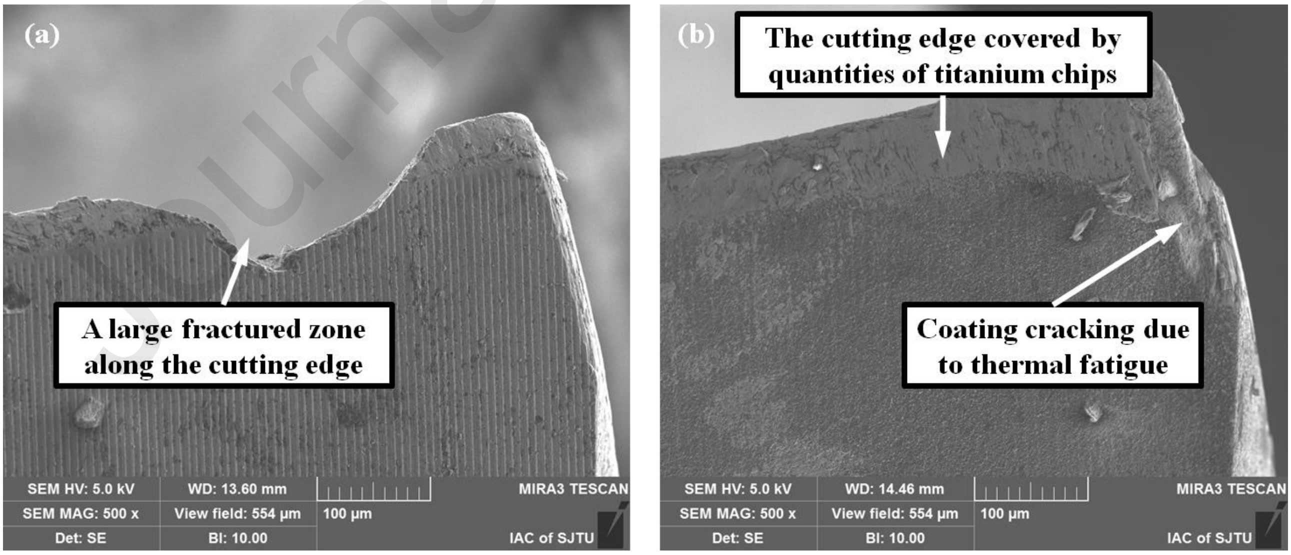

**Fig.16.** SEM morphologies of the corner edge under the MQL condition: (a) TiAlN-coated drill, and (b) diamond-coated drill.

To quantify the severity of the drill wear, SEM examinations were performed on the cutting edge zone of both drills, and the flank wear width (*VB*) of each drill was annotated in Figs.17 and 18.

Similar to the previous findings, the TiAlN-coated drill promotes a *VB* value of approximately 31 μm under the dry condition, and the cutting edges are covered by quantities of titanium materials because of the adhesion wear (Ref. Fig.17(a)). In the case of the MQL drilling, the flank wear width decreases to 25 μm, and the cutting edge remains relatively smooth as shown in Fig.18(a). With respect to the diamond-coated drill, very negligible extents of titanium adhesion are identified onto the drill edges owing to its high thermal conductivity and low friction coefficient (Ref. Fig.17 (b) and Fig.18 (b)). Under the dry cutting condition, the *VB* value of the diamond drill is about 23 μm accompanied by severe edge chipping, whereas the MQL condition results in a much larger wear extent of the diamond drill with a maximum flank wear width of 57 μm due to the abrasive effect of the adhered CFRP chips and the congestion of titanium chips. As such, the MQL fails to protect the drills effectively.

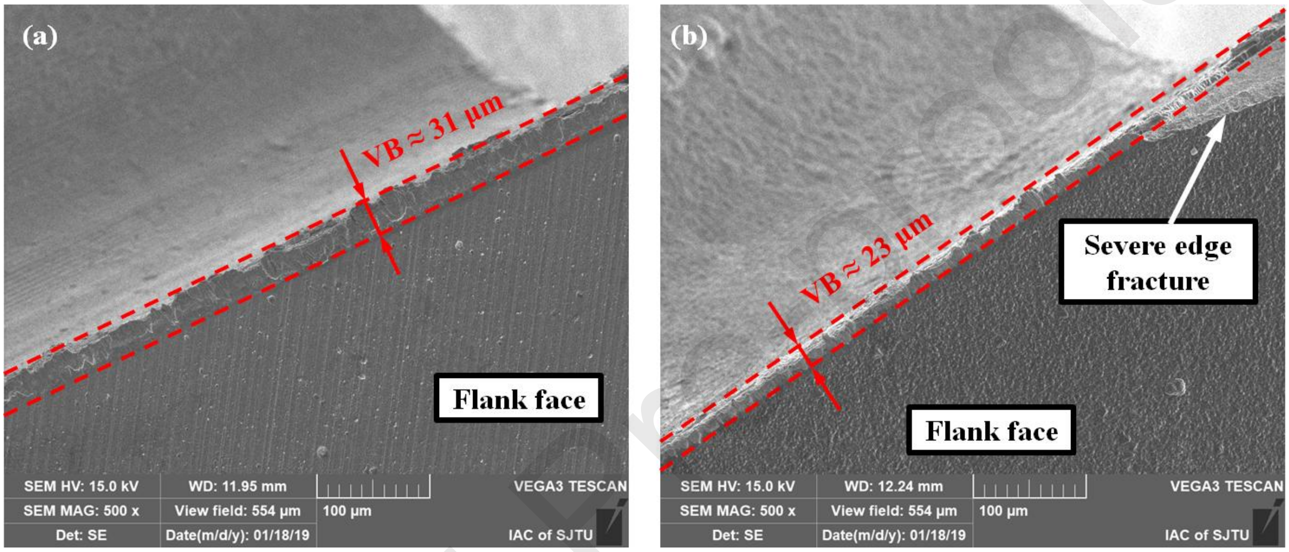

**Fig.17.** SEM morphologies of the cutting edge under the dry cutting condition: (a) TiAlN-coated drill, and (b) diamond-coated drill.

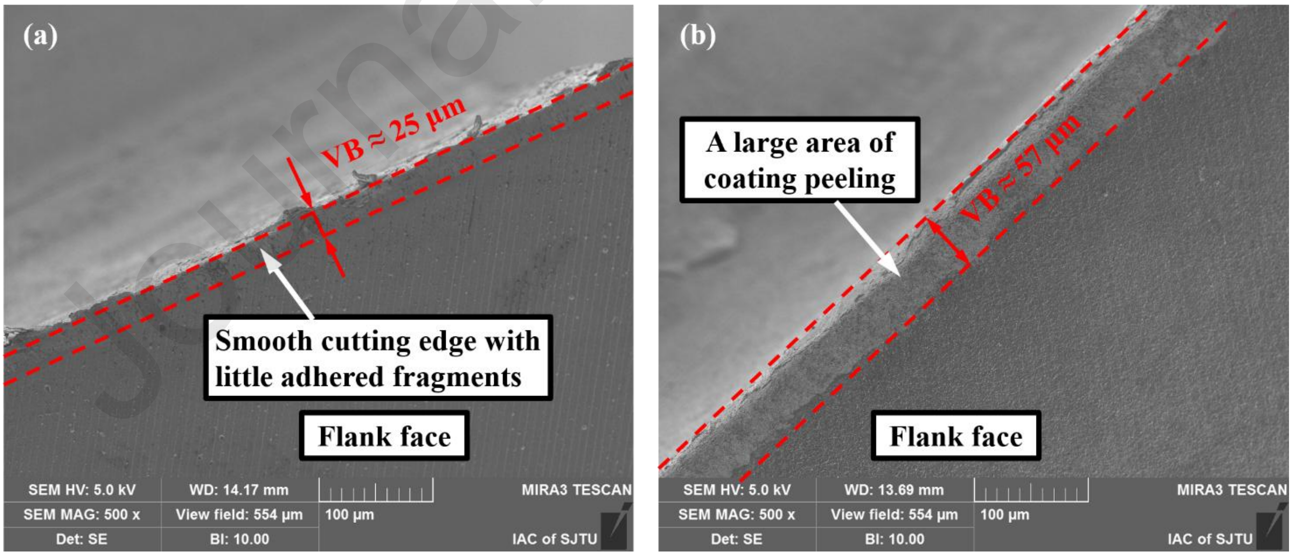

**Fig.18.** SEM morphologies of the cutting edge under the MQL condition: (a) TiAlN-coated drill, and (b) diamond-coated drill.

## 4. Conclusions

In this paper, a comparative study on the effects of the MQL and dry drilling of CFRP/Ti6Al4V stacks was performed. The feasibility and operating mechanisms of the MQL environment for the composite-titanium stack machining was pointed out with respect to the drilling thrust forces, delamination damage and tool wear. Based on the results acquired, the following conclusions can be drawn.

- Both the MQL and dry machining have a remarkable impact on the thrust forces and delamination damage when drilling CFRP/Ti6Al4V stacks due to the changes of the contact conditions at the drill-workpiece interface. Higher magnitudes of thrust forces for both the CFRP and titanium phases are noted under the MQL condition due to the clogging of CFRP chips caused by the minimum quantity fluids. Machining under the dry condition is identified beneficial for the reduction of the thrust forces and the delamination extents.
- The operating mechanisms of the MQL environment in the CFRP phase drilling are totally different from those in the metal cutting process. Due to the brittle-fracture mechanisms of fibers and the hydroscopicity of the carbon/epoxy architectures, the cut composite surface featured by quantities of cavities could absorb the minimum quantity lubricants sprayed instead of forming a protective lubricating film at the drill-composite interface. As a consequence, the MQL environment fails to play an effect in decreasing the drilling forces as well as the delamination damage of the composite phase.
- The eventual wear signatures of drills after machining the composite/titanium stacks are affected by both the cutting environment and the coating material. Adhesion wear due to the welding of titanium chips and abrasion wear leading to the blunt and worn edges are the key wear patterns governing the drilling of CFRP/Ti6Al4V stacks. Both coating peeling and edge fracture are identified as the main failure modes for the TiAlN-coated and diamond-coated drills. The use of the MQL environment benefits the reduction of extents of the titanium adhesion for both drills operating in the drilling of the multilayer composite/titanium stacks, but it fails to show a clear effect on reducing the drill edge wear extent when compared with the conventional dry machining.
- The PVD TiAlN-coated drills are found more suitable for the drilling of CFRP/Ti6Al4V stacks particularly under the dry cutting conditions since no catastrophic failures of coatings are identified. Additionally, the TiAlN-coated drills promote relatively lower magnitudes of thrust forces and lower delamination factors than the diamond-coated ones. Moreover, the TiAlN-coated drills show a higher wear resistance to catastrophic failures in comparison with the diamond-coated drills when identical cutting conditions are applied.

## Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship and/or publication of this article.

## Author Statement

All the authors contribute equally to the work of the submitted manuscript.

## Acknowledgments

The authors gratefully acknowledge the financial support of the National Natural Science Foundation of China (Grant No.51705319) and the Shanghai Pujiang Program (Grant No.17PJ1403800).

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