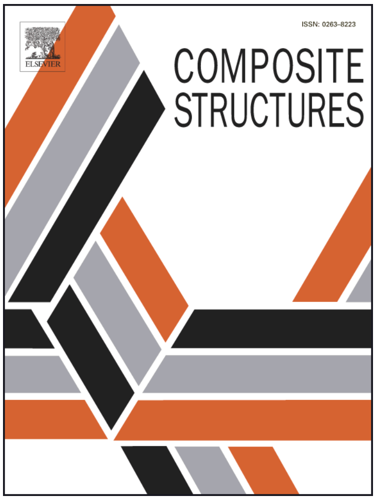

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On the analysis of temperatures, surface morphologies and tool wear in drilling CFRP/Ti6Al4V stacks under different cutting sequence strategies

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Abstract: In drilling CFRP/Ti6Al4V stacks, the cutting sequence strategy, which determines the coupling effects of each phase machining, affects significantly the machinability of the sandwiched material as well as the tool wear characteristics. The present paper contributes to a scientific understanding of the effects of different cutting sequence strategies on the drilling performance of multilayer CFRP/Ti6Al4V stacks when using uncoated tungsten carbide and diamond coated drills. Experimental quantification of the in-situ temperatures during the stack drilling was conducted using the method of infrared thermography camera and the instrumentation of drill bits by embedded thermocouples. Drilling forces, exit burr heights of the titanium holes, surface morphologies of the composite holes and tool wear signatures were analyzed. The results indicate that drilling from titanium to CFRP leads to higher magnitudes of composite cutting temperatures while it benefits the reduction of the stack thrust forces, the improvement of the composite surface morphologies as well as the decrease of the exit titanium burr heights. Additionally, the coupling effects of drilling temperatures and chip adhesion are the influential factors leading to the disparate effects of the cutting sequence strategy on the drill wear progression. Drilling from titanium to CFRP reduces the drill adhesion and flank wear extents owing to the brushing effects of the composite drilling. The diamond-coated drills are confirmed superior to the uncoated ones in terms of lower drilling temperatures, lower drilling forces, minimal hole surface damage, less tool wear while drilling the CFRP/Ti6Al4V stacks.

***Keywords*:** CFRP/Ti6Al4V stacks; mechanical drilling; cutting sequence strategies; drilling temperature; cutting forces; tool wear.

1. Introduction

In recent years, sandwich structures constituted by carbon fiber reinforced polymers (CFRPs) and titanium alloys have become a promising alternative to conventional fibrous composites and metal alloys in various aerospace applications [1, 2]. These bi-material assemblies contribute to the enhancement of mechanical/physical properties and the improvement of structural functionality that facilitate the energy savings and carbon emissions of advanced aircraft components. Sheets or plates of CFRP composites and Ti alloys are often assembled by rivet joints or bolt connections, which require tens of thousands of holes to be drilled. To guarantee the positional accuracy and tight tolerance for the post assembly process, fastener holes are often drilled through the composite-metal stacks instead of drilling each material layer separately [3-7].

Due to the disparate properties of each constituted layer, machining CFRP/Ti6Al4Vsandwiches with high quality poses great challenges to the manufacturing community [8-10]. Drilling these hybrid composite structures is liable to produce critical defects within the cut holes including delamination of composites, exit burrs of both materials as well as the thermal/mechanical damage of the stack interface. Due to the interaction of transfer of thermal/mechanical loads exerted on the workpiece and tool surfaces resulting from the drilling sequence, frictional contacts at the tool-work interface and the associated tool wear progression may change. This leads to the fact that the cutting sequence strategy shall affect not only the quality of cut workpieces but also the wear behavior of drills, which requires a thorough investigation.

Two different cutting sequences *i.e.* drilling from the composite to the metal and vice versa exist in the machining of CFRP/Ti6Al4V stacks. In most cases, the composite → metal sequence is the widely-used strategy since a lower extent of exit delamination can be induced for the sandwich material due to the supporting role of the bottom metal alloy in increasing the stiffness of the exit composite layer while drilling. Most of the investigations reported in the scientific literature are limited to the use of the composite to metal sequence for the machining of CFRP/Ti6Al4V stacks [1, 8, 11-15]. For instance, Alonso et al. [1] studied the effects of different flute numbers and stepped bit geometries on the machining of CFRP/Ti6Al4V stacks under the CFRP → Ti sequence. The results showed that a stepped design with three flutes led to a slower wear progression, lower cutting forces and less hole damage. Hussein et al. [11, 12] identified the advantages of the low-frequency vibration-assisted drilling (LFVAD) in generating discontinuous titanium chips, which alleviates the erosion effects of the titanium chips onto the composite hoes walls during the drilling from the CFRP to Ti6Al4V. Recently, Xu et al. [8] stated that the use of minimum quantity lubrication (MQL) could yield several benefits in improving the surface morphologies of cut composite holes and in alleviating the drill wear severity when drilling the CFRP/Ti6Al4V stacks from the composite to the metallic alloy. However, in such a cutting sequence the extended path of chip removal could impede the efficient ejection of the metallic chips during the machining of the multilayer stacks. Consequently, the hot and sharp-edged spiral titanium chips seriously heat and erode the composite hole wall surfaces introducing both the thermal degradation and mechanical damage onto the composite phase during the chip evacuation process. Brinksmeier and Janssen [16] identified such phenomena of mechanical/thermal damage induced by the metallic chip ejection when drilling Al/CFRP/Ti6Al4V stacks. The authors stated that the other key issues of hole imperfections mostly encountered in the stack drilling include poor consistency of surfaces, bad coaxially and low dimensional accuracy. In a comparative study of twist drilling and orbit drilling of Al/CFRP/Ti6Al4V stacks, Brinksmeier et al. [17] emphasized the pivotal impact of the excessive drilling temperatures gained at conditions of low feed rates and high cutting speeds on the thermal damage of the cut CFRP hole surfaces. Additionally, Park et al. [18] found the progressive tool wear due to the serious titanium adhesion for the tungsten carbide (WC) drills and microchipping occurring for the polycrystalline diamond (PCD) drills when machining CFRP/Ti6Al4V stacks. Severe abrasive wear induced by hard carbon fibers and adhesion wear caused by chemically-active titanium chips were confirmed as the characteristic wear modes following the drilling of these metallic-composite stacks. Further, Wang et al. [19] compared the tool wear behavior in drilling individual CFRPs, individual Ti alloys and their stacks under the CFRP → Ti sequence. The authors pointed out that the edge rounding operates as a primary wear pattern in drilling CFRP only while edge chipping and flank wear predominate when drilling the individual Ti alloys. Serious edge chipping was eliminated by carbon fibers of the composite layer while drilling CFRP/Ti6Al4V stacks due to the removed Ti adhesion and smoothed cutting edge. Additionally, Xu and his co-authors [20-24] have carried out several investigations to clarify the cutting sequence's influences on the machining of CFRP/Ti6Al4V stacks; however, the work was limited to the orthogonal cutting configuration which differs from the actual drilling process most used in the aerospace industry. To date, studies addressing the impact of different drilling sequences on the tool wear in drilling CFRP/Ti6Al4V stacks are rarely reported.

Recently, Xu and El Mansori [25] identified that the metal → composite drilling sequence could be more feasible for the machining of metallic-composite stacks since lower surface roughness and more consistent hole diameters were generated. In this configuration, severe erosions induced by the hot and sharp-edged spiral metal chips onto the composite hole wall surfaces were effectively avoided while a larger extent of delamination was produced at the exit side of the CFRP phase due to the lack of the bottom plate. However, the disparate thermal effects, tool wear mechanisms and chip ejection processes impacted by the interaction of each material layer machining that drive the different performances of the cutting sequence were not clearly revealed by the authors. In fact, the chip ejection process is closely associated with the generation of cutting temperatures which are critical to the tool wear as well as the quality of holes. The excessively high cutting temperatures resulting from the metal drilling may lead to not only the thermal degradation of the composite matrix *i.e.* the glass transition of the resin matrix but also to the rapid tool wear progression in the form of adhesion and oxidation that have to be carefully controlled in the stack drilling. To capture the *in-situ* temperatures of machining, applications of thermocouples embedded into the drill coolant holes, dynamic thermocouples between tool/workpiece interface and infrared thermography camera (IFTC) are three representative methods [26-29]. Recently, Zitoune et al. [30] developed a novel *in-situ* instrumentation of cutting tools by optical fibers with Braggs sensors to quantify the temperatures developed during the drilling of CFRP composites. The results confirmed the feasibility of the temperature measuring method and revealed that the feed rate and the type of coating were the key factors affecting the temperature of composites machining while the spindle speed has a minor slight impact on the temperature of machining. To date, the key research interest of drilling multilayer CFRP/Ti6Al4V stacks was concerned with identifying the parametric effects on various drilling responses mainly the drilling forces and hole quality, evaluating different tool performances and revealing the tool wear modes governing the stack drilling. However, there is no study available in the scientific literature dealing with the issues of drilling temperatures and tool wear behavior under different cutting sequence strategies for CFRP/Ti6Al4V stacks.

The present work is thus aimed at quantifying the *in-situ* temperatures of each material layer and reveal the wear modes of tools subjected to different cutting sequences when drilling composite/metal stacks. For this purpose, a series of drilling tests were conducted on multilayer stacks constituted by high-strength T800/X850 CFRP laminates and Ti6Al4V alloys using uncoated tungsten carbide (WC/Co) and diamond-coated twist drills. Two types of temperature measuring methods including the infrared thermography camera and the embedded thermocouples were utilized to capture the temperature transitions within each sandwiched phase. The mechanical and thermal effects of varying cutting sequence strategies on the drilling characteristics of CFRP/Ti6Al4V stacks were rigorously investigated in terms of drilling temperatures/forces, surface morphologies of cut CFRP phase, burr heights of the metallic phase and the resulting tool wear. The results discussed in this paper could add some knowledge to the interpretation of the impact of drilling sequences on the machinability of CFRP/Ti6Al4V stacks and allow several technical implications for the cutting sequence selection when drilling CFRP/Ti6Al4V.

2. Experimental procedures

2.1. Workpiece specimens and drill bits

In the present work, multilayer stacks constituted by carbon/epoxy composite laminates and metallic alloy plates were selected as the workpiece specimens. The composite material was an aeronautical grade multilayer CFRP laminate fabricated by unidirectional high-strength T800 carbon fibers and X850 thermoset epoxy resin, which was laid up by the $[(45°/90°/-45°/0°)_6]_s$ sequence containing a fiber volume fraction of 65%. The physical properties of the CFRP specimen are summarized in Table 1. The metal constituents are duplex alpha-beta Ti6Al4V alloys that are being extensively used in the modern aerospace industry due to their high specific strength, high-temperature resistance and excellent corrosion resistance. Details of the chemical composition and the physical properties of the Ti6Al4V alloy are given in Tables 2 and 3, respectively. The entire stack workpiece is a rectangular plate possessing the total dimensions of 300 mm (length) × 200 mm (width) × 15.96 mm (thickness). Two different stacking sequences of the CFRP/Ti6Al4Vspecimens were arranged to identify the effects of drilling sequence strategy on the machinability of the multilayer stacks as depicted in Fig.1 (a) and (b). The uncoated solid tungsten carbide (WC/Co) and CVD diamond-coated twist drills having an identical diameter of 6.35 mm were selected in this investigation to finalize the drilling trials based on the industrial applications and tool manufacturer's recommendation. The use of the diamond coating aims to yield comprehensive tool properties between hardness and toughness that can cope with the harsh conditions encountered in the CFRP and Ti machining. The selection of the uncoated tungsten carbide drills is completed based on their industrial availability, economics and practicality. The CVD diamond-coated drills without coolant holes were offered by Shanghai Fengqi Machinery Technology Co., Ltd. and the uncoated drills with coolant holes (tool reference: SD203A-02500-091-0315R1-T) were supplied by the Seco Tools. Both types of drills are featured by a 140° point angle, a 30° helix angle and two cutting lips as depicted in Fig.1(c).

Table 1 Physical properties of the used T800/X850 composite laminate.

Properties	Value	Properties	Value
Density/(kg/m^3)	1600	Tensile modulus/GPa	180
Fiber volume fraction/%	65	Compressive modulus/MPa	160
Lay-up sequence	$[(45°/90°/-45°/0°)_6]_s$	Tensile strain/%	1.68

Table 2 Chemical composition of the used Ti6Al4V alloy.

Element	Ti	Al	V	Fe	C	N	H	O
wt.%	Base	5.5-6.75	3.5-4.5	< 0.25	< 0.08	< 0.05	< 0.01	< 0.2

Table 3 Mechanical/thermal properties of the used Ti6Al4V alloy.

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

Fig.1. (a)-(b) Two stacking sequences of the CFRP/Ti6Al4Vspecimens and (c) the morphologies of the used drills.

2.2. Experimental setup

The drilling tests were carried out on a vertical machining center (HURCO VMX42) with a maximum spindle speed of 12,000 rpm and a positioning accuracy of 0.01 mm under dry cutting conditions. 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 the *in-situ* force signals generated during the stack machining. Due to the absence of coolant holes in the diamond-coated drills, the method of using embedded thermocouples is infeasible for the *in-situ* measurement of the drilling temperature. As such, a FLIR A615 infrared thermography camera (IFTC) featured by a working temperature from -20 °C to 2000 °C and an image acquisition frequency from 50 Hz to 200 Hz was applied to monitor the temperature rise for CFRP/Ti6Al4V stacks under various drilling conditions. The temperature resolution of the equipment is less than 0.05°C which guarantees the accuracy and reliability of the monitored data. To further ensure the measuring accuracy of the IFTC for the diamond-coated drills, boreholes were drilled with a 2 mm distance close to the edge of the composite/metal plate. As indicated by the work done by Yashiro et al. [27], temperatures measured by the IFTC tend to be lower than those captured by embedded thermocouples due to the hidden cutting points within the tool-work interface. To obtain the realistic trend of variations in the drilling temperatures, a novel thermocouple-based temperature measuring system named as the rotary tool temperature (RTT) device was developed for the uncoated twist drills during the drilling of CFRP/Ti6Al4V stacks. In the RTT device, standard OMEGA K-type thermocouples, which have a working temperature ranging from -200 °C to 1370 °C and a length of 15 cm, were inserted into the coolant through-holes of the uncoated twist drill with a 0.50 mm distance close to the drill flank surface and a 1.36 mm distance away from the main drill edge as depicted in Fig.2. Even though the positioning of the thermocouples cannot be placed exactly at the vicinity of the drill tip region, they can still estimate the fundamental evolution trend of the flank surface temperature of a drill while drilling CFRP/Ti6Al4V stacks. The thermocouple equipped drill was then clamped in the self-designed fixture with a microsystem of temperature storage module as shown in Fig.3. During the drilling tests, temperature data were *in-situ* recorded by the micro temperature storage module and then *ex-situ* input to a personal laptop through a micro USB adapter for the further post-process analysis. Note that the maximum drilling temperatures recorded during the CFRP/Ti6Al4Vdrilling were selected as the data of experimental analysis since they determine directly the risk of thermal degradation of the cut multi-material stack particularly the composite phase. An overview of the experimental setup for the drilling of CFRP/Ti6Al4V stacks is shown in Fig.4. In the drilling experiments, two different cutting sequence strategies *i.e.* cutting from CFRP to Ti and cutting from Ti to CFRP were implemented following a full factorial trial design including the cutting speed (V_c) of 20, 35, 50, 65 m/min and the feed rate (f) of 0.015, 0.030, 0.045, 0.060 mm/rev as summarized in Table 4.

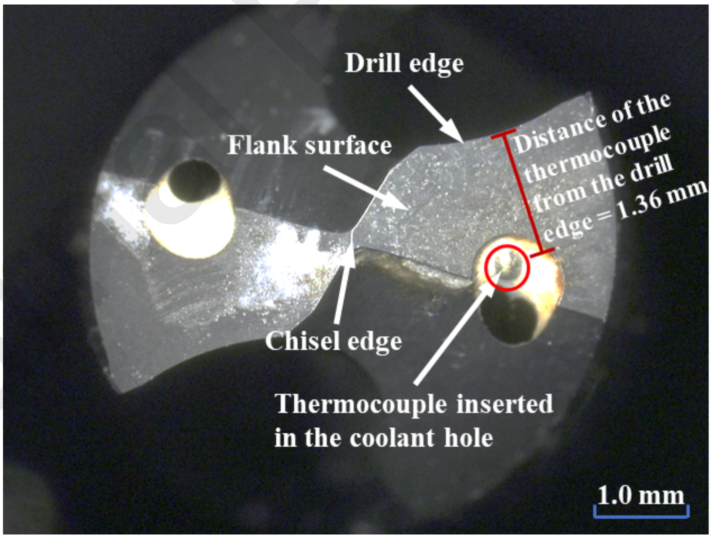

Fig.2. A photograph showing the positioning of the thermocouples into the coolant holes of an uncoated twist drill.

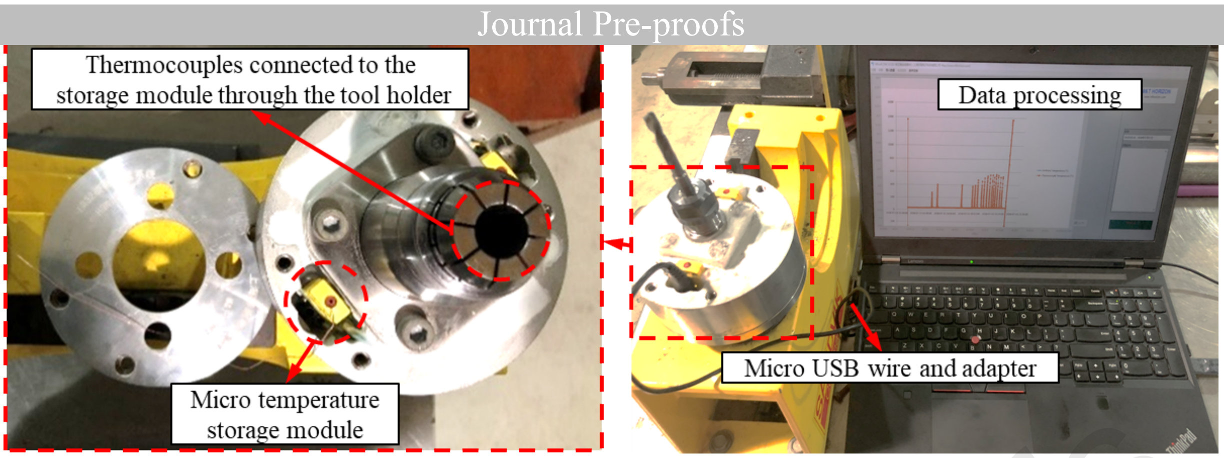

Fig.3. Photographs showing details of the *in-situ* instrumentation of the temperature measuring device.

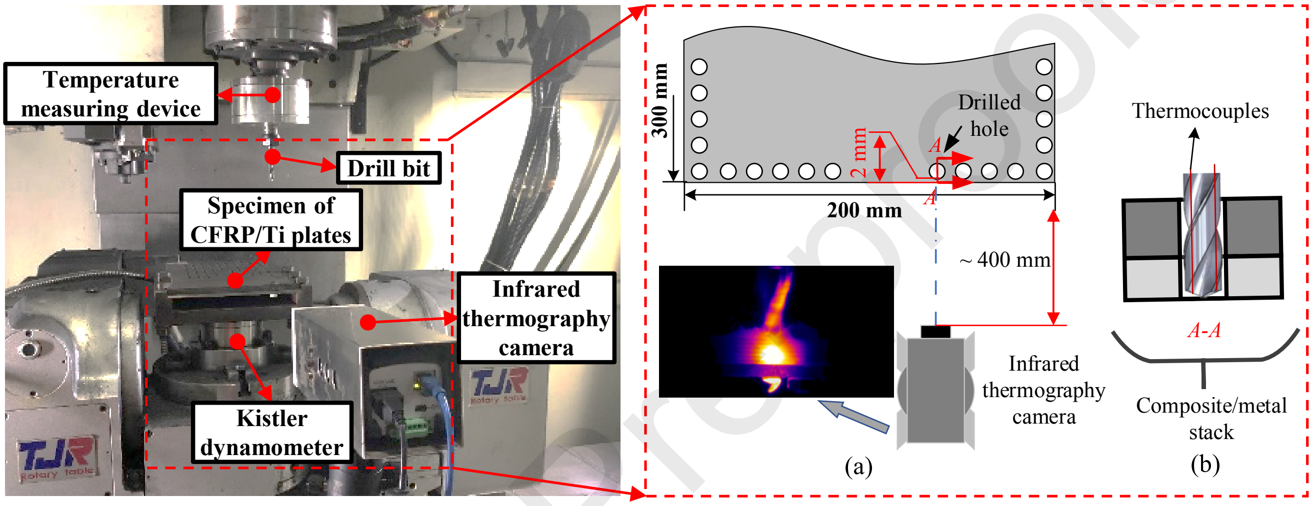

Fig.4. Experimental setup for the drilling of CFRP/Ti6Al4V stacks: schematic setup of (a) the IFTC and (b) the thermocouples for uncoated twist drills.

Table 4 Cutting conditions used for the drilling of CFRP/Ti6Al4V stacks.

Test no.	Cutting speed, V_c [m/min]	Feed rate, f [mm/rev]	Drilling sequence	Drill bit
1 - 4	20	0.015, 0.030, 0.045 and 0.060	CFRP → Ti	Uncoated twist drill
5 - 8	35			
9 - 12	50			Diamond-coated drill
13 - 16	65			
1 - 4	20	0.015, 0.030, 0.045 and 0.060	Ti → CFRP	Uncoated twist drill
5 - 8	35			
9 - 12	50			Diamond-coated drill
13 - 16	65			

2.3. Post-process analysis

After the completion of the drilling trials, the surface morphologies of CFRP holes drilled under different cutting sequences were characterized using an FEI NOVA NanoSEM equipment. Defects of exit burrs produced at the titanium phase under varying process parameters and drilling sequences were quantitatively measured using the criterion of burr height via a high-precision digital microscope (Keyence VHX-500FE). Each measurement was repeated three times in order to get reliable results. Signatures of the worn drills were examined using a TESCAN VEGA3 XMU scanning electron microscope (SEM) to characterize the frictional contacts at the tool-work interface and the wear modes of drills when changing the drilling sequence. Additionally, the local chemical analysis of the worn surfaces of drills was carried out using the energy dispersion spectrometry (EDS) (XFlash 6130, Bruker, Germany) to identify the element content of the examined zone.

3. Results and discussion

3.1. Drilling temperatures and chip evacuation processes

In drilling CFRP/Ti6Al4V stacks, excessive cutting temperatures can be easily accessed due to the presence of the metallic phase involving a large amount of heat generation during the chip removal process. The change of frictional contact at the tool-work interface, which depends on the implemented drilling sequence, becomes a medium of heat transfer and a source of temperature rise onto the composite layer that severely deteriorates the quality and properties of the stacked composite, resulting in the matrix burnout, debonding of fiber/matrix interface or even the glass transition of the heat affected zone. Since there is very little information in the literature reporting the temperature characteristics during the drilling of CFRP/Ti6Al4V stacks, studying the evolutions of the *in-situ* temperatures following the stack drilling becomes necessary in the present work. Fig.5 shows the variations in signals of the drilling temperatures obtained by both the thermocouples and IFTC under the Ti → CFRP sequence. It is clear that the recording frequency of IFTC appears much higher than that of the embedded thermocouples which indicates that the measuring system of IFTC is highly sensitive. Additionally, since the IFTC cannot touch directly the tool-work interaction zone, magnitudes of the recorded temperatures are expected to be lower than those obtained by the embedded thermocouples. To calibrate the drilling temperatures measured by the IFTC, compensations were added to the maximum temperature values of both stacked material layers according to the results gained by the embedded thermocouples. As shown in Fig.5, the differences between the maximum temperatures measured by the thermocouple technique and the IFTC for the Ti phase and CFRP phase are respectively 112°C and 88°C. As the drill starts to attack the titanium alloy, signals of the cutting temperatures evolve sharply with the drill advancement. When the drill edges are fully engaged, the drilling temperatures within the Ti phase rise continuously due to the heat accumulation. The maximum magnitudes of temperature recordings via both the thermocouples and the IFTC method are attained when the drill proceeds to exit the Ti plate. Once the drill tip begins to attack the bottom CFRP layer, the considerably heated drill edges may significantly degrade the polymer matrix of the composite particularly on areas located at the vicinity of the stack interface due to their detrimental high temperatures. Meanwhile, a sudden decrease of the tool flank surface temperature appears, which means on the one hand that the heat generation mechanism varies due to the change in the chip separation mode from elasto-plastic deformation to brittle fracture and on the other hand that the highly accumulated heat originating from the titanium machining is dissipated by the tool-CFRP interaction during drilling. This event could severely degrade the composite properties or even cause burns, pyrolysis and glass transition of the material because of the instantaneous high temperatures transferred across the composite hole surfaces. As the drill is fully engaged in the material removal of the CFRP layer, the drilling temperatures appear to undergo a steady variation as shown in Fig.5. The obtained temperatures in drilling CFRP seem much lower than those gained in drilling Ti due to the brittle-fracture dominated chip removal mode without undergoing any plastic deformation that leads to the minimum quantity of heat generation. Eventually, when the drill edges tend to penetrate out the CFRP plate, both the drilling temperatures recorded by the thermocouples and IFTC are found to decrease rapidly (Ref. Fig.5).

Further, a distinct time delay of thermocouples is clearly visible in Fig.5 which differs from the phenomenon obtained by Zitoune et al. [30] since the thermocouple used in the present work shows a lesser sensitivity to rapid change in temperature than the optical fibers used in Ref. [30]. Additionally, the variation trends of the temperature curves in terms of the cutting time show similarity with those observed by Wang et al. [31] when measuring the drilling temperatures of CFRP/aluminum stacks using the thermocouples. Note that the temperature measured by the IFTC can be affected by the effluent hot metallic chips and this phenomenon becomes more accentuated in drilling titanium alloys than in drilling CFRP. Although there exists a time delay and interferential temperature points due to the ejection of hot metallic chips, the temperatures recorded by the IFTC exhibit a similar varying trend as those obtained by the thermocouple technique, which indicates that the infrared thermography camera is qualified to *in-situ* estimate the evolution of cutting temperatures promoted in the stack drilling operation.

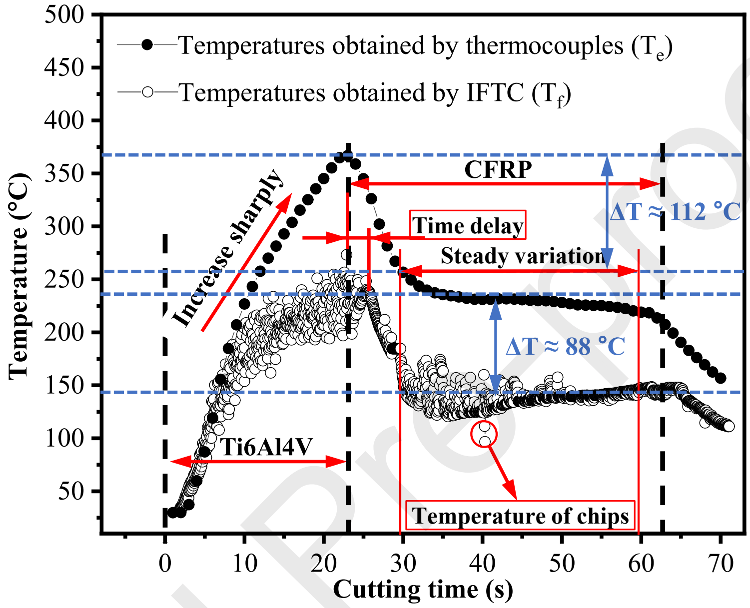

Fig. 5. Evolution of typical signals of *in-situ* temperatures obtained by the embedded thermocouples and IFTC under the Ti → CFRP sequence when using uncoated twist drills (V_c = 20 m/min and f = 0.015 mm/rev).

Fig.6 shows the impact of different drilling sequences on the evolution of temperature signals monitored by the IFTC when using the uncoated twist drills under the fixed conditions of V_c = 20 m/min and f = 0.015 mm/rev. The results reveal that in both drilling sequences, the peak temperature values in each phase machining often appear at the exit side of the stacked material due to the heat accumulation. Magnitudes of the CFRP temperatures under the CFRP → Ti sequence are below 125 °C while the temperatures recorded under the Ti → CFRP sequence are found much higher than 125 °C. The results imply that drilling from Ti to CFRP may bring a higher risk of thermal damage to the hole walls of the CFRP phase. The phenomenon is attributed to the fact that drilling titanium alloys involves a larger amount of heat generation than drilling individual CFRP due to the chip removal mode of elasto-plastic deformation, and when operating from Ti to CFRP the tool is considerably pre-heated by the metal drilling process before it starts to cut the composite layer. Hence, the drilling temperatures of the CFRP phase are elevated. Additionally, it is worth noting that the composite temperatures recorded when drilling from Ti to CFRP are found higher than 125°C and the actual temperatures promoted at the drill flank surface should exceed the glass transition temperature limit which is around 180°C if the temperature compensation (ΔT ≈ 88°C) is added. In contrast, the CFRP → Ti sequence involves only the risk of peak temperatures occurring at the exit side of the CFRP layer being superior to the glass transition temperature of the composite.

A sudden rise of the drilling temperature reaching the 268.02°C peak magnitude is noticed at the end of drilling from CFRP to Ti, which is probably 12.32% higher than that obtained in the Ti → CFRP drilling sequence. The phenomenon is associated with the clogging of spiral Ti chips inside the drill flutes as evidenced by the IFTC-captured images shown in Fig.7. From this figure, it is worth noting that the maximum temperatures denoted by the dark red color often exist at the *in-situ* tool-work interface and evolve toward the drilling direction. Distribution of the drilling temperatures is affected partially by the separation of chips from the stack workpiece. Machining the CFRP phase entails low process temperatures and minimum quantity of heat being transferred by the ejection of powdery chips due to the brittle fracture dominated chip removal mode (Ref. t = 13s in Fig.7(a)). In contrast, drilling the titanium phase produces long and spiral chips containing higher temperatures due to the poor conditions of frictional contact at the tool-work interface (Ref. t = 13s in Fig.7(b)). Additionally, the key difference between the two implemented drilling sequences lies in the phenomenon that drilling from CFRP to Ti involves poor evacuation process of titanium chips because of the extended path of the chip ejection channel. As depicted at t = 63s in Fig.7 (a), the spiral Ti chips are observed to get entangled within the drill bit under the CFRP → Ti sequence, which may lead to chip removal problems and flute clogging. Such a phenomenon was also observed by Brinksmeier and Janssen [16], Zitoune et al. [32] and Shyha et al. [33] when drilling multilayer metallic-composite stacks. The problematic metallic chip ejection through the CFRP layer could cause catastrophic erosions as well as thermal damage to the composite and the stack interface, which may further result in extremely poor surface quality and functional problems in the subsequent assembly process of the multilayer sandwich.

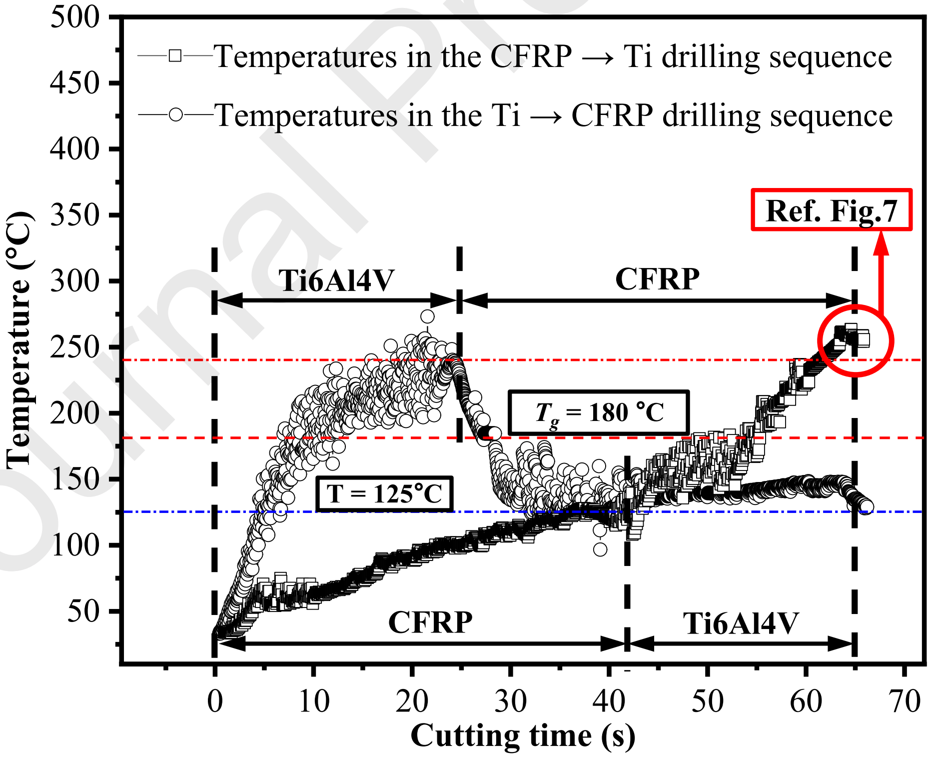

Fig.6. Evolution of representative signals of drilling temperatures recorded by the IFTC under two different drilling sequences when using uncoated twist drills (V_c = 20 m/min and f = 0.015 mm/rev).

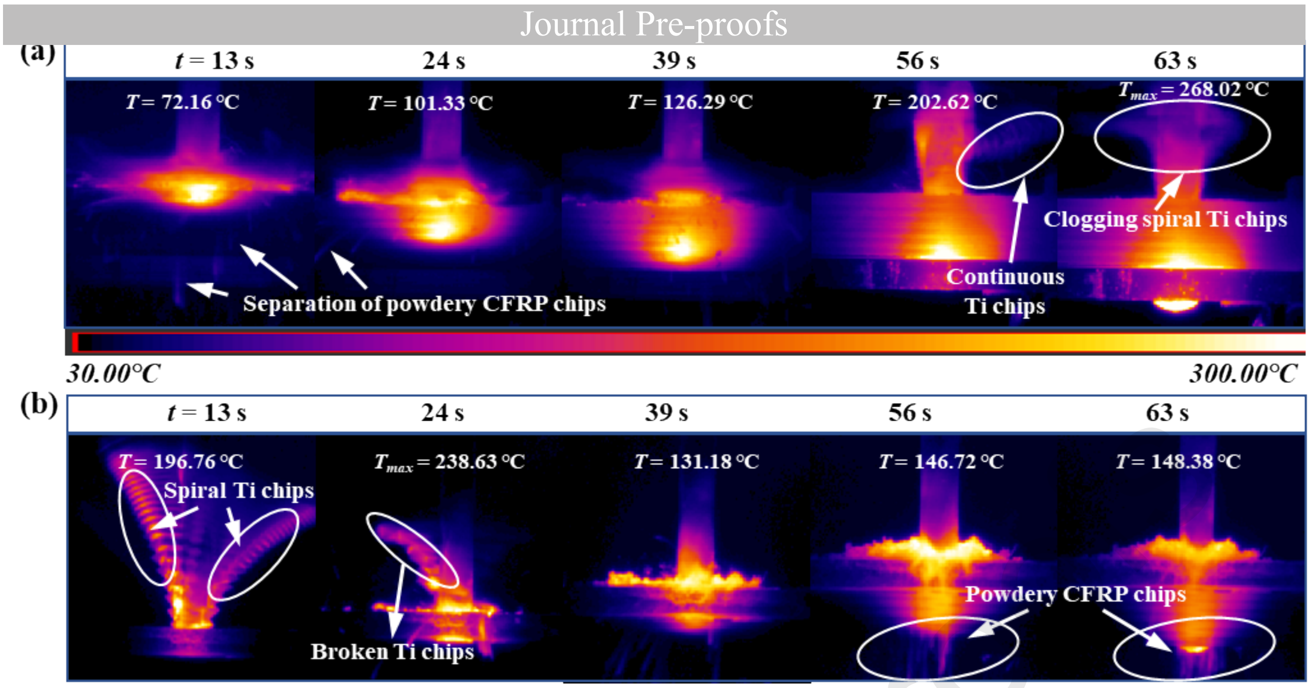

Fig.7. Images of chip formation and evacuation processes captured by the IFTC under two drilling sequences when using uncoated drills: (a) CFRP → Ti and (b) Ti → CFRP (V_c = 20 m/min and f = 0.015 mm/rev).

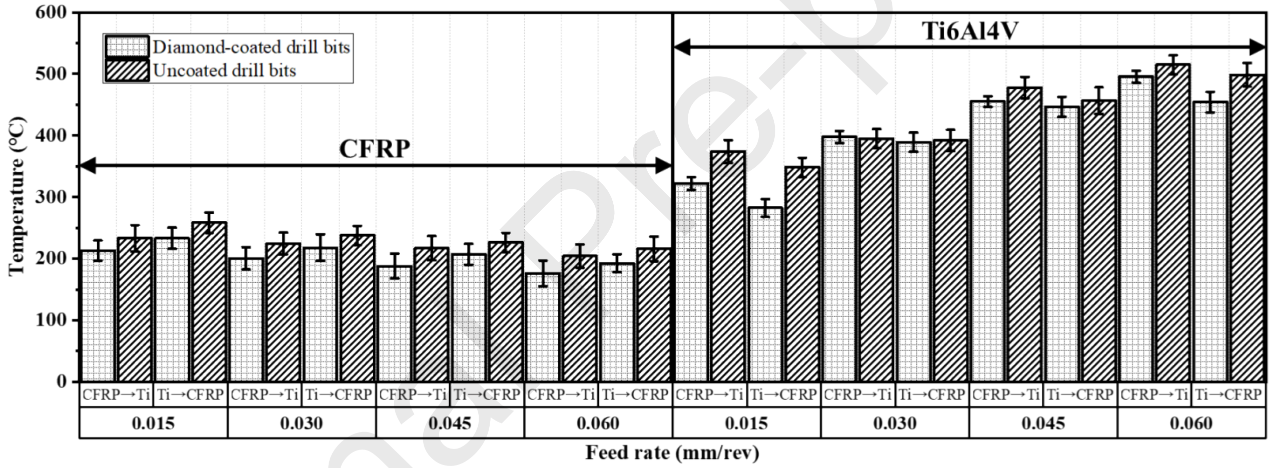

Fig.8. Comparison of the maximum cutting temperatures obtained by the IFTC with the temperature compensations for different drill bits and cutting sequences under varying feed rates (V_c = 20 m/min).

To figure out the thermal effects of the cutting sequence strategy on the heat generation of drilling CFRP/Ti6Al4V stacks, the maximum temperatures occurring at each stacked phase were analyzed according to the data measured by the IFTC. Fig.8 depicts the comparison of the maximum cutting temperatures gained in both the CFRP phase and titanium phase with uncoated and diamond-coated drills under varying feed rates. Note that the compensation of the temperatures measured by the IFTC was added. From this figure, three distinct phenomena are noticeable. Firstly, the titanium phase produces much higher magnitudes of machining temperatures than the CFRP phase for all the drills and process parameters examined. The phenomenon is due to the different chip removal mechanisms and thermal behaviors of the stacked materials. Secondly, the cutting sequence strategy is confirmed to have a great impact on the maximum temperatures developed in each sandwiched phase. For instance, the peak temperatures obtained from the CFRP phase often exhibit relatively higher magnitudes when the stacks are drilled under the Ti → CFRP sequence regardless of the used feed rates and drill bits. The phenomenon is associated with the pre-heating of drills in the initial Ti phase under the Ti → CFRP drilling sequence, which may result in serious thermal damage to the composite hole walls. Additionally, the diamond-coated drills are observed to generate relatively lower cutting temperatures than the uncoated ones under both cutting sequence strategies for all the process parameters investigated, indicating improved heat conduction of interface between the tool and the stack workpiece. This event is attributed to the lower frictional coefficient of the diamond coating that improves the tribological interaction at the tool-chip and tool-work interfaces as well as its higher thermal conductivity (λ = 1600-2000 W/(m•K)) being approximately 54-68 times that of the tungsten carbide (λ = 29.2 W/(m•K)) allowing a rapid heat dissipation at the tool-work interface. Finally, the results given in Fig.8 reveal that the feed rate (f) shows a negative impact on the cutting temperatures for the CFRP phase such that increasing the feed rate tends to decrease the drilling temperatures, while a contrary varying trend of drilling temperatures with the feed rate is observed for the Ti phase. The findings of the variation trend for the composite temperatures agree well with the work done by Chen [34], Brinksmeier et al. [17] and Zitoune et al. [30] when drilling CFRP composites, which are due to the reduced time of the tool-work interaction and the decreased rubbing distance covered by the corner of drill edges with elevated feed rates. With respect to the titanium phase, despite the reduced contact length of the drill edges as the feed rate increases, the uncut chip volume per revolution rises instead and thus higher cutting forces and a larger amount of heat development are induced due to the increased friction between the drill edge and the workpiece material. Such findings are consistent with the those reported by Rahim and Sasahara [35] when drilling Ti6Al4V alloys.

3.2. Drilling forces

To identify the mechanical effects of the cutting sequence strategies on the drilling of CFRP/Ti6Al4Vsandwiches, force signals generated under varying process parameters were recorded. Results of magnitudes of the thrust forces for the CFRP phase under two cutting sequences were plotted relating to the used drill bits as depicted in Fig.9. Note that each measure of the drilling forces was repeated three times under each set of drilling parameters in order to get reliable results. Error bars were added into the plotted figures. It is clear that for both drilling sequences, magnitudes of the CFRP thrust forces exhibit a linear increasing proportion to the feed rate. This phenomenon is firmly associated with the chip thickness such that a higher feed rate results in a larger cross-sectional area of un-deformed chips and consequently greater thrust forces are produced. Such findings agree well with the studies of machining metallic composite stacks reported in the literature [25, 36, 37].

For both drill bits, magnitudes of thrust forces under the Ti → CFRP sequence appear lower than those gained in the opposite sequence. The phenomenon is mainly attributed to the thermal softening of the composite phase due to the significantly heated drill edges resulting from the initial titanium machining, which decreases the cutting resistance of material removal of the carbon/epoxy system. On the other hand, the drill wear arising from the initial titanium cutting may exert a very minor effect on the subsequent drilling of the composite phase and hence the thrust generation. In both drilling sequences, the diamond-coated drill is found to produce lower thrust forces than the uncoated twist one due to its lower frictional coefficient of interaction between the drill edge and the workpiece material as well as its superior wear resistance against the mechanical abrasion. For all cutting conditions tested, the CFRP thrust forces are found to decrease when increasing the cutting speed irrespective of the used drills, which indicates that the thermal softening due to increased speeds becomes a dominant factor in altering the frictional contact between the drill and CFRP.

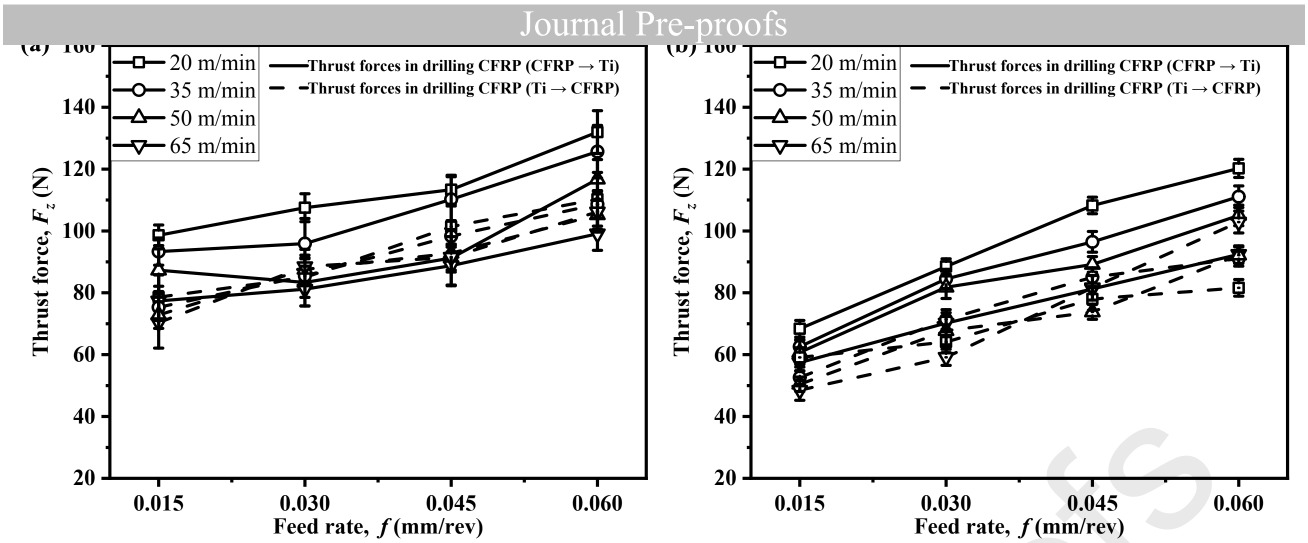

Fig.9. Comparison of the thrust forces for the CFRP phase under two different cutting sequences with (a) uncoated drills and (b) diamond-coated drills.

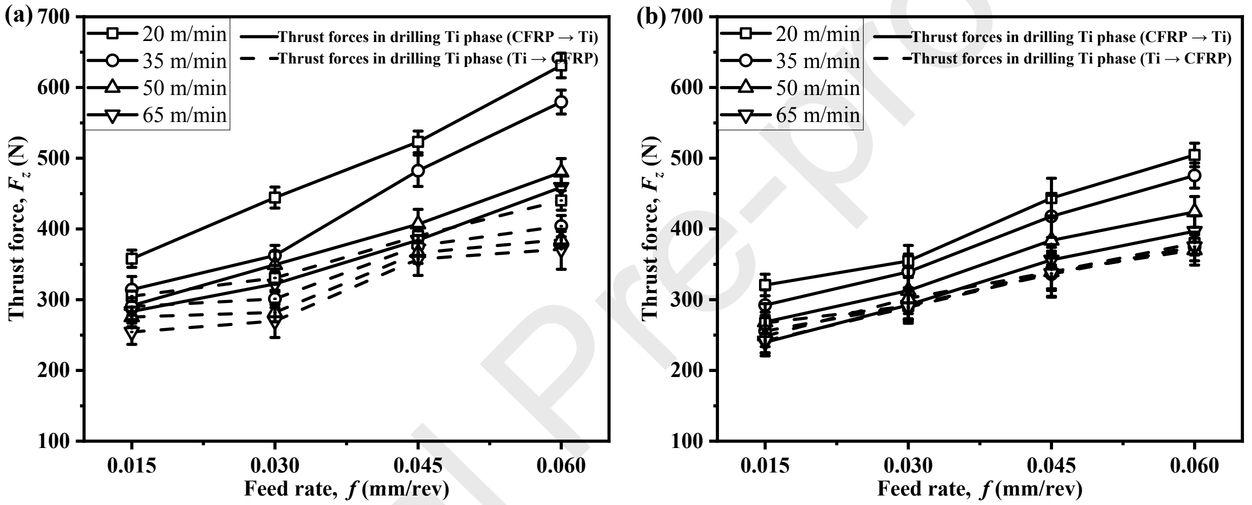

Fig.10. Comparison of the thrust forces for the Ti phase under two different cutting sequences with (a) uncoated drills and (b) diamond-coated drills.

Fig.10 presents the comparison of thrust forces for the Ti phase under two different drilling sequences. Results reveal that the titanium drilling promotes much higher thrust forces than drilling the CFRP layer, which is due to the disparate chip separation modes of the two materials. Additionally, the Ti thrust forces generated in the CFRP → Ti sequence appear relatively higher than those gained in the Ti → CFRP sequence for both drills tested when identical cutting conditions are applied. The phenomenon is due to the edge rounding wear induced by the initial cut of CFRP which enlarges the contact area between the drill edge and the workpiece material. Additionally, a similar variation trend of thrust forces with the feed rate is noted for the Ti phase. The increasing rates of the Ti thrust magnitudes in function of the feed rate appear a little bit larger in the CFRP → Ti sequence than in the opposite sequence, which means that the drill wear plays a more dominant role in the thrust generation for both sequence strategies used. Further, increasing the cutting speed tends to decrease the Ti thrust forces in some extent due to the elevated cutting temperatures occurring at the tool-chip interface that soften the metallic workpiece, making the chip layers much easier to shear off. It is worth noting that the use of diamond-coated drills generally leads to a reduction of Ti thrust forces in contrast with the uncoated drills under identical cutting conditions due to their lower friction characteristics and higher wear resistance. The optimal conditions guaranteeing the lowest titanium thrust forces for the drilling of CFRP/Ti6Al4V stacks consist of highest cutting speed (V = 65 m/min), lowest feed rate (f = 0.015 mm/rev) as well as the Ti → CFRP drilling sequence.

3.3. Surface morphologies of the drilled composite phase

As discussed earlier, machining from CFRP to Ti is likely to induce serious thermal degradation and mechanical abrasion to the cut composite holes due to the poor ejection of the hot and sharp-edged metallic chips, while drilling from Ti to CFRP involves a high risk of glass transition or pyrolysis of the composite matrix owing to the considerably heated drill edges resulting from the initial titanium machining. Inspections on the surface conditions of drilled composite holes thus become very important. Since the impact of the drilling sequence strategy on the geometrical accuracy of multilayer CFRP/Ti6Al4V stacks including hole diameter and cylindricity error has been carefully outlined by Xu and El Mansori [25]. This subsection concerns only the inspections of the effects of the drilling sequence on the surface conditions of cut CFRP holes. Figs.11 and 12 show the SEM images of typical surface morphologies of drilled composite holes obtained under different drilling sequences when using the uncoated twist drills (V_c = 65 m/min and f = 0.06 mm/rev). It is clear that machining from the composite to the titanium creates high levels of mechanical and thermal degradation to the CFRP hole walls due to the poor ejection of the titanium chips. The sharp-edged metallic chips evacuate rapidly across the composite hole walls and thus cause severe abrasions onto the CFRP surface. The observations agree well with those identified by Brinksmeier et al. [16, 17] when drilling multilayer metallic-composite stacks. Surfaces cavities featured by the loss of matrix are mainly the consequences of effects of the mechanical erosion of the metallic chips. Additionally, the hot titanium chips containing excessive temperatures would lead to high heat flux transferred through the superficial surfaces of the CFRP layer as they come in contact with the composite. As a result, the drilling-induced heat delivered by the titanium chips can get congested easily at the composite hole surfaces and result in highly localized temperatures due to its extremely low thermal conductivity. Thermal degradation is expected to occur in such conditions, resulting in the microcracks inside the carbon/epoxy surfaces and the softened matrix protruding out of the cut surfaces as evidenced in Fig.11. Bending-induced fractographs of carbon fibers constitute the rough CFRP surface texture with amounts of loss of matrix. Generally, the entire hole wall surfaces of the CFRP phase are poorly cut being characterized by quantities of fiber pullouts, cavities, smearing of soften matrix, cracking, *etc*. In contrast, the machined composite surfaces appear much smoother under the Ti → CFRP sequence as shown in Fig.12 due to the elimination of effects of the titanium chip ejection. The damaged areas are randomly distributed on the CFRP hole walls mainly due to the overheating by the pre-heated drill edges resulting from the initial titanium drilling. As analyzed in subsection 3.1, after drilling the titanium phase, the drill edges are considerably heated possessing extremely high temperatures being superior to the glass transition temperature of the composite matrix. As the drill edges proceed to cut the composite laminate, the highly-heated drill is able to cause serious thermal deteriorations onto the composite surfaces introducing a variety of damage forms such as burning, pyrolysis, softening, property degradation or the glass transition of the epoxy matrix. In the examined areas of the drilled composite hole, microcracks propagating inside the composite subsurface and pyrolysis due to the over-burning of the matrix are detected being the indications of the thermal degradation. Besides, since the epoxy matrix located in several hole wall regions is thermally degraded or over-burned, its loss causes the formation of fiber pullouts and surface cavities.

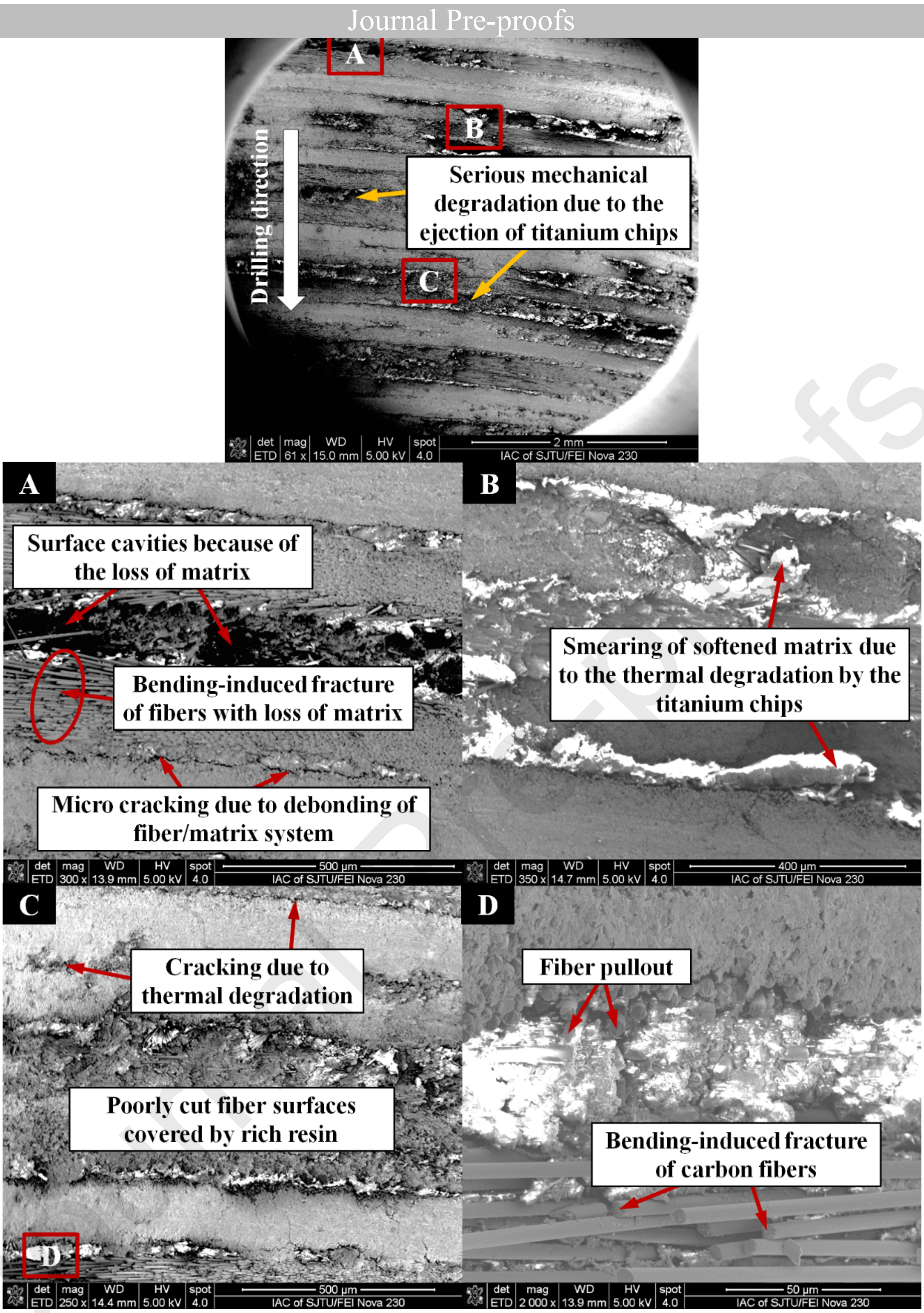

Fig.11. SEM morphologies of the drilled composite hole walls when using the uncoated twist drill under the CFRP → Ti sequence (V_c = 65 m/min and f = 0.06 mm/rev).

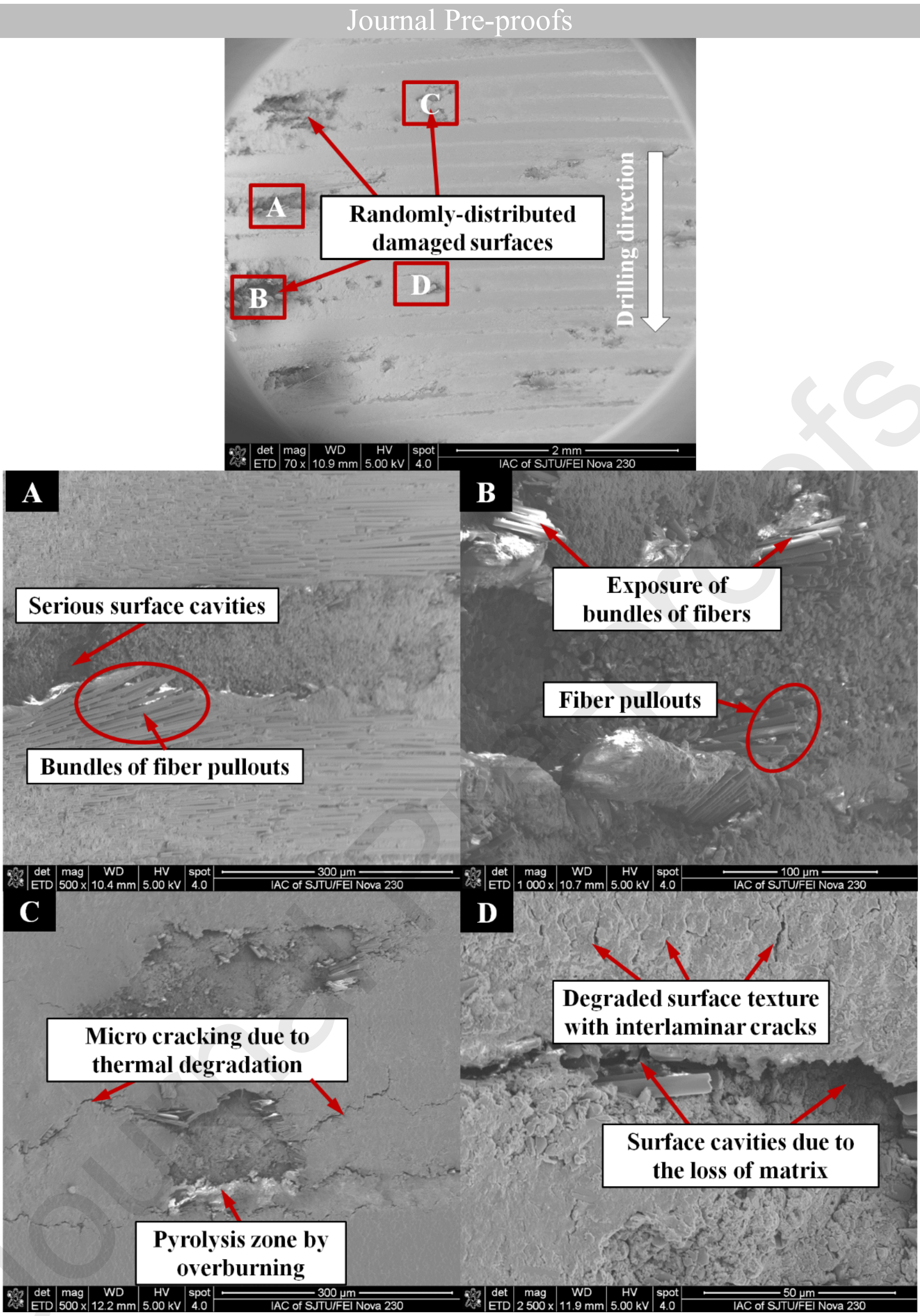

Fig.12. SEM morphologies of the drilled composite hole walls when using the uncoated twist drill under the Ti → CFRP sequence (V_c = 65 m/min and f = 0.06 mm/rev).

In the case of using diamond-coated drills, the cutting sequence seems to have a similar impact on the damage signatures and surface morphologies of drilled composite hole walls as shown in Figs.13 and 14. The key difference lies in the fact that the diamond-coated drills produce much better hole surface morphologies with minimal drilling-induced damage compared with the uncoated ones due to the lower drilling forces and temperatures promoted which reduce the mechanical/thermal effects of the cutting sequence strategy on the stack drilling. In the CFRP → Ti sequence depicted in Fig.13, minor levels of erosion damage are identified onto the CFRP hole surfaces thanks to the superior behavior of the diamond coating that alleviates the impact of the titanium chip ejection. A zoom-in view with magnification at zone A in Fig.13 confirms that the poorly cut CFRP surfaces with quantities of cavities are primarily concentrated at the -45° plies. The phenomenon can be explained by the fact that during drilling fibers in the -45º direction are typically subjected to intense elastic bending instead of shearing by pressure from the drill cutting edge as stated by Li et al. [38]. When the load exceeds the fiber yield strength, failure occurs below the cutting plane with the debris removed as the tool passes, thus creating cavities or grooves onto the surfaces. Moreover, when drilling in the opposite sequence, only minor extents of thermally-induced damage are observed on the composite hole surfaces with the diamond-coated drill as depicted in Fig.14. The event is attributed to the inherent high hardness, low friction coefficient and high thermal conductivity of the diamond coating which reduce the mechanical/thermal effects of the chip removal process as well as the drill wear extent. The thermal defects residing within the drilled composite holes are featured by the signatures of fuzzing, pyrolysis, matrix softening and degradation due to the highly heated drill edges that come in touch with the composite during the drilling.

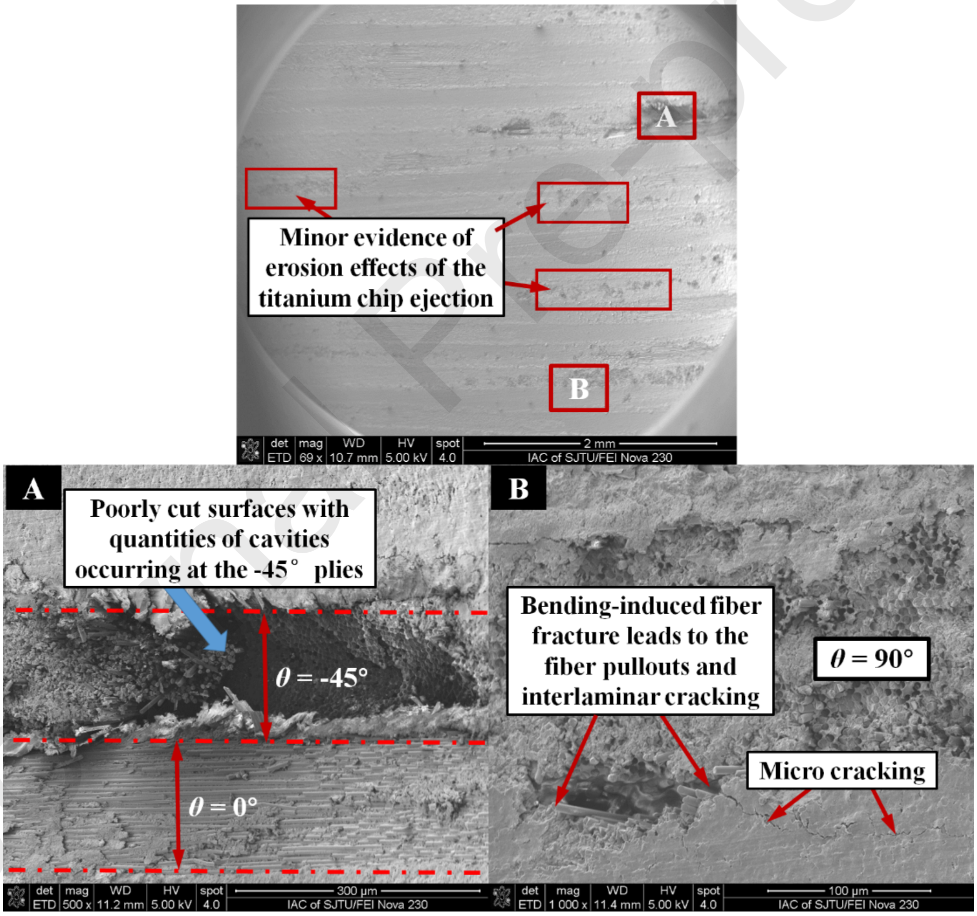

Fig.13. SEM morphologies of the drilled composite hole walls when using the diamond-coated drill under the CFRP → Ti sequence (V_c = 65 m/min and f = 0.06 mm/rev).

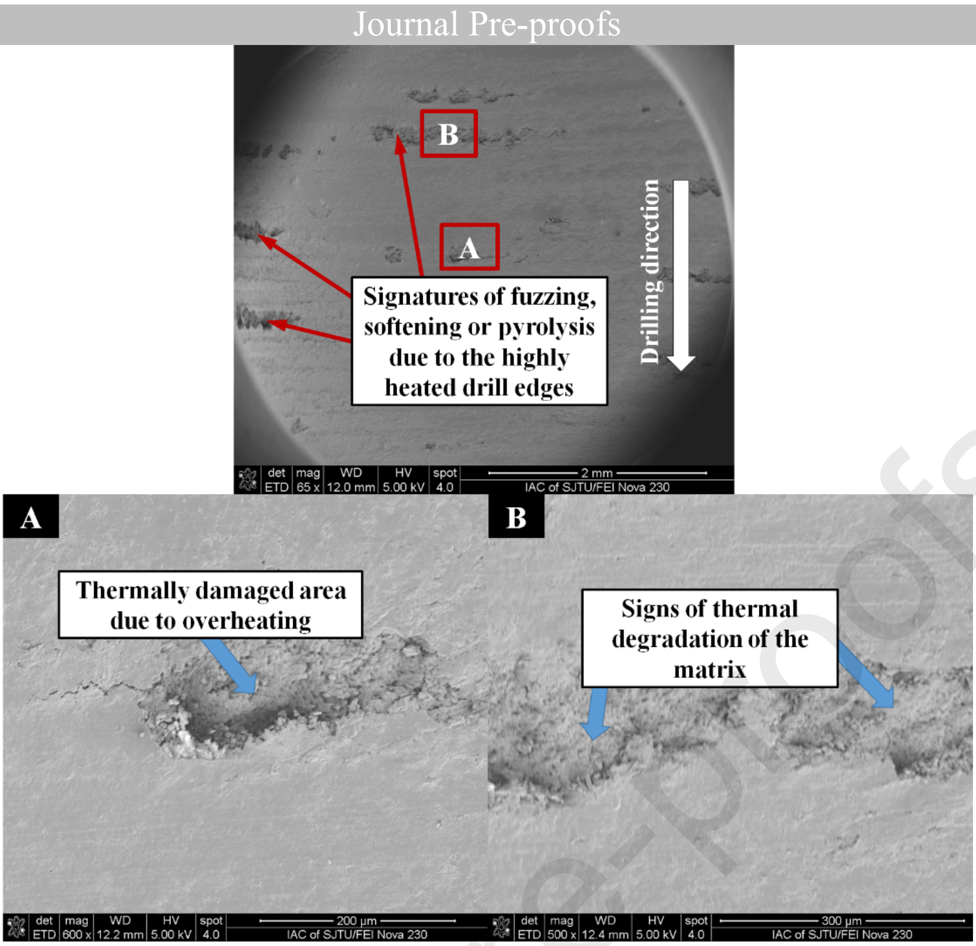

Fig.14. SEM morphologies of the drilled composite hole walls when using the diamond-coated drill under the Ti → CFRP sequence (V_c = 65 m/min and f = 0.06 mm/rev).

3.4. Exit burr heights

Burr formation is a characteristic phenomenon when cutting ductile metallic alloys. In machining operations, burrs are undesirable or unwanted projections of a work material formed as the result of the plastic flow from the chip removal process as stated by Aurich et al. [39], being detrimental to the functionality and integrity of desired surfaces. The formation of burrs is closely associated with the cutting temperature promoted at the tool-work interface that significantly degrades the stiffness of uncut chip layers and makes them rather difficult to shear off completely. As discussed in subsection 3.1, the maximum temperatures often exist at the exit side of the titanium phase, so the severity of drilling-induced burrs should be much higher at the exit side rather than at the entry side during the drilling of CFRP/Ti6Al4V stacks. The present work thus focuses on the quantification of the exit Ti burrs subjected to two cutting sequence strategies when drilling CFRP/Ti6Al4V stacks. Evolutions of the exit burr height (h_d) with the feed rate (f) when using uncoated and diamond-coated drills are shown in Fig.15. It is clear that the cutting sequence strategy affects significantly the extents of the exit Ti burrs. Drilling from Ti to CFRP generally leads to much lower burr heights than the CFRP → Ti sequence. The phenomenon is attributed to the fact that on the one hand the supporting effect offered by the bottom CFRP board under the Ti → CFRP sequence improves the stiffness of the last layers of the titanium plate, thus facilitating the shearing of the bottom surface layers; on the other hand, drilling from Ti to CFRP induces relatively lower temperatures localized at the exit side of the Ti alloy (Ref. Fig.8), which alleviates the extent of thermal softening of the exit titanium layer and thus increases slightly the ductility of the Ti layers. It is worth to mention that increasing the feed rate tends to give rise to an elevated extent of exit burrs. The observation contradicts with the findings of Ramulu et al. [3] when drilling Gr-Bi/metal stacks. Such a phenomenon is mainly due to the increase of the maximum drilling temperatures at the exit titanium layer with elevated feed rates that significantly degrades the stiffness of the titanium layer thus promoting higher extents of exit burrs. Further, in the case of the uncoated carbide drill, the higher cutting temperatures promoted due to the poor frictional contact between the tungsten carbide and the titanium surfaces as well as the tool's inherent low thermal conductivity often considerably degrade the stiffness of the exit titanium layers, making the drill generate a larger extent of burrs as shown in Fig.15. In contrast, since the diamond-coated drill induces relatively lower heat generation/mechanical loads acting at the tool-work interface and possesses high wear resistance due to its superior properties, the burr heights produced at the exit Ti layers seem much lower than those gained by the uncoated ones irrespective of the examined process parameters. Even when the feed rate increases from the lowest value of 0.015 mm/rev to the maximum value of 0.060 mm/rev, the burr height undergoes a quite small degree of increment. The above analysis confirms the feasibility of using the Ti → CFRP drilling sequence and the diamond-coated drills in minimizing the burr formation when drilling CFRP/Ti6Al4V stacks.

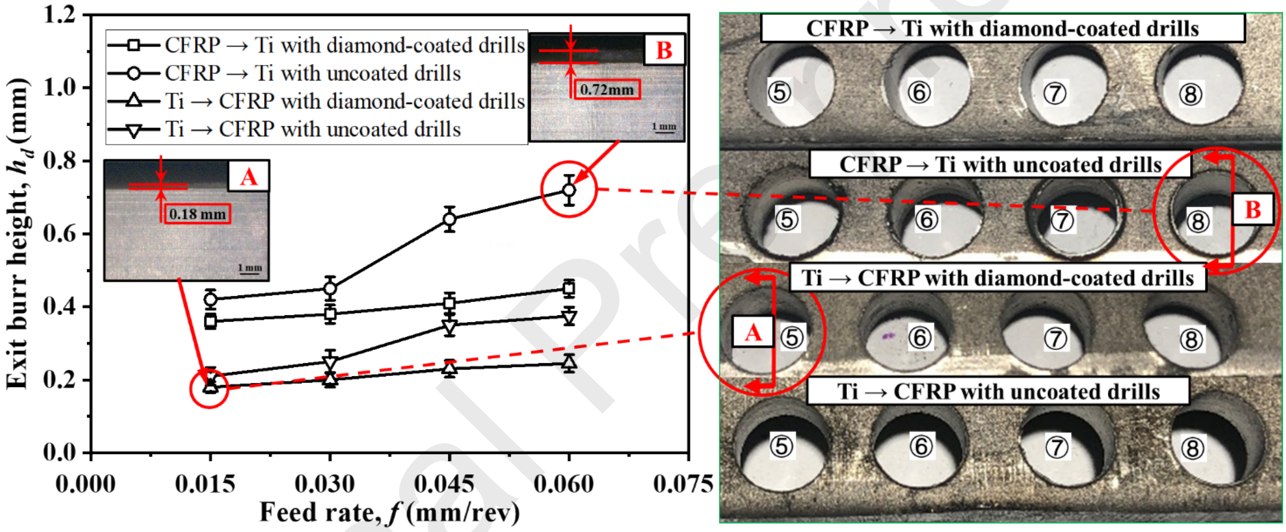

Fig.15. (a) Effect of different drilling sequence strategies on the burr heights with uncoated and diamond-coated drills at the constant cutting speed of 35 m/min and (b) exit morphologies of Ti holes (Note that the holes designated by Nos.5-8 correspond to the drilling conditions summarized in Table 4).

3.5. Tool wear modes

Drilling multilayer stacks involves the physical changes of the frictional contact between the drill and workpiece surfaces when the tool cuts from one phase to another phase, which affects the wear modes acting on the drill active zones. Tool wear is regarded as one of the most important criteria in assessing the machinability of work materials subjected to a machining process, which influences directly the tool life, surface quality and production cost. Signatures of the worn drill surface morphologies were inspected via the SEM in order to figure out the impact of the drilling sequence strategy on the tool wear mechanisms during drilling CFRP/Ti6Al4V stacks. The SEM examinations were conducted with a particular focus on the zones of the chisel edge, the main/minor drill edges, and the zone of drill edge corner. Before analyzing the wear modes of drilling CFRP/Ti6Al4V stacks, it is necessary to know the fundamental wear mechanisms operating in cutting each stacked material layer. When machining individual CFRP composites, mechanical abrasion operates as the dominant wear mode for tool edges due to the highly abrasive character of reinforcing carbon fibers leading to the edge dulling or blunting which is termed as the cutting edge rounding. In contrast, machining titanium alloys entails a rapid tool wear progression involving serious adhesion, diffusion and crater wear as well as catastrophic failures such as edge chipping or fracture due to their inherent high strength maintained at elevated temperatures and low thermal conductivity leading to high cutting temperatures. When drilling CFRP/Ti6Al4V stacks in one-shot time, the cutting sequence strategy may change the coupling effects of wear modes operating in each stacked phase, thus influencing the eventual tool wear signatures and tool lifetime.

Figs.16-19 show the recorded wear morphologies of the worn uncoated tungsten carbide drills under two different sequence strategies after drilling 16 holes of CFRP/Ti6Al4V stacks at the cutting speed of 65 m/min and feed rate of 0.06 mm/rev. The SEM observations reveal a clear impact of the drilling sequence strategy on the wear signatures and failure modes of drills when machining CFRP/Ti6Al4V stacks. In the case of drilling from CFRP to Ti, evidence of lamellar titanium materials sticking onto the drill rake face and phenomena of quantities of dark composite chips firmly welding along the chisel edge region are observed for the uncoated WC/Co drill. Such phenomena agree well with those observed by Park et al. [40] when drilling composite/titanium stacks using tungsten carbide drills. This event signifies the extremely poor frictional contact between the drill chisel edge and the stack workpiece. Formation of serious adhesion within the drill chisel edge zone relates to the highly localized temperatures and high pressures promoted at the chisel edge-workpiece interface because of the extruding action of the chisel edge instead of shearing materials. Additionally, the worn drill rake face shows evidence of partial titanium adhesion due to the high chemical affinity between titanium from the metal phase and carbon from the drill material. Attrition wear is likely to occur in these areas by means of workpiece adhesions since they would be torn away dislodging grains of carbide and cobalt binders from the tool substrate, leading to the flaking of tools as depicted in Fig.16 (a).

The broken WC particles detached away by the cyclic stick-slip process of titanium chips subjected to the plucking action will eventually accelerate the tool wear and induce catastrophic failures like microchipping or edge fracture. In contrast, phenomena of chip adhesion appear insignificant at the vicinity of drill chisel edge zone subjected to the Ti → CFRP sequence. This is attributed to the brushing effects of carbon fibers being drilled at the bottom CFRP phase. Since the carbon fibers are featured by high hardness and high abrasiveness, adhesion of titanium chips onto the drill chisel edges and rake faces would be eroded and smoothed cleanly when the drill completes the cutting of the bottom CFRP phase. Such effects were also identified by Wang et al. [19] when drilling CFRP/Ti6Al4V stacks and their individual layers.

In view of the drill cutting edges subjected to the CFRP → Ti sequence, the initial cut of the composite phase causes serious abrasions and erosions within the drill edge zones, leading to the edge dulling and blunting. Additionally, the resected powdery composite chips could embed into the tool-chip interface and accelerate the scratching of the drill edges, thus resulting in the micro-pits or internal cracks of drill cutting zones. When the drill starts to cut the bottom metallic phase, the sudden rise of mechanical loads and heat generation creates uneven stress/temperature distributions along the drill cutting edges, which leads to the catastrophic failure of tools in the form of microchipping as evidenced in Fig.17 (a). Inspections of signatures of the main drill edge show that the original cutting edge is significantly modified by the adhesion wear resulting from the eventual titanium drilling. Effects of the initial cut of the composite phase do not induce a clear wear signature onto the drill edges, the surface of which is basically characterized by quite rough surface morphologies with an average flank wear width of approximately 80 μm being covered by a series of unevenly-distributed chip adhesion. Surfaces close to the minor drill edges are adhered by quantities of titanium materials due to the high welding tendency of the metal alloy. Moreover, a certain degree of edge fracture is detected at the outer corner of the drill when drilling from CFRP to Ti due to the highest cutting speed involved. The above observations reveal that adhesion wear, flank wear, microchipping and edge fracture dominate the wear progression of the uncoated drills under the CFRP → Ti drilling sequence. In the opposite drilling sequence, the severity of wearing of the drill edges is considerably alleviated as depicted in Fig.17 (b) and Fig.18 (b). The geometrical shapes of the main cutting edge maintain intact without suffering serious modification or chipping failure. Abrasive wear appears to guide the eventual drill edge signatures by evidence of the uniformly-distributed smooth flank wear land without significant amounts of local chip adhesion. The phenomenon confirms the clear brushing and smoothing effects of carbon fibers within the bottom composite material. The resulting flank wear land of drills exhibits a lower width of nearly 42 µm which is approximately half that of drills subjected to the CFRP → Ti sequence. From a tribological point of view, drilling from the titanium alloy to the composite phase benefits the reduction of drill wear extents and hence the tool lifetime.

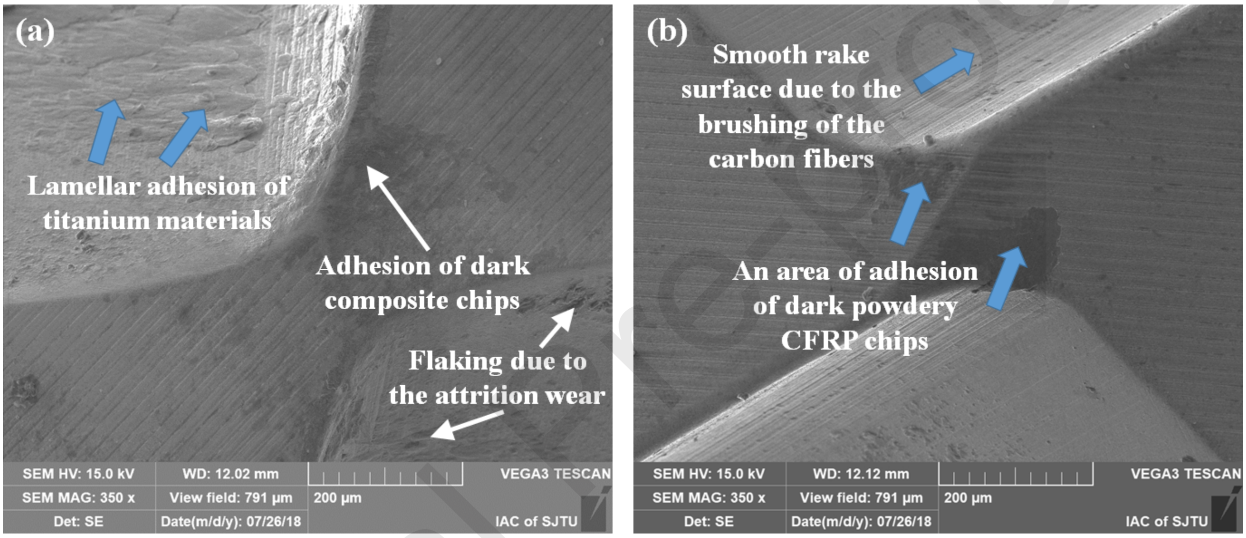

Fig.16. SEM morphologies of the chisel edge region of uncoated drills after drilling 16 holes of CFRP/Ti6Al4V stacks under different drilling sequences (V_c = 65 m/min and f = 0.06 mm/rev): (a) CFRP → Ti and (b) Ti → CFRP.

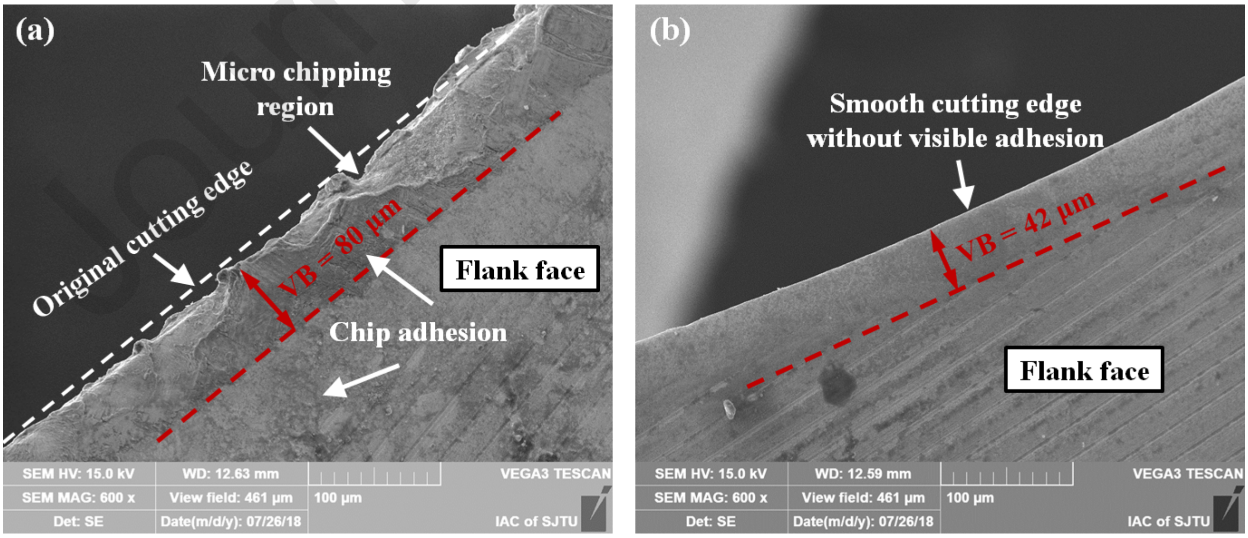

Fig.17. SEM morphologies of the main cutting edges of uncoated drills after drilling 16 holes of CFRP/Ti6Al4V stacks under different drilling sequences (V_c = 65 m/min and f = 0.06 mm/rev): (a) CFRP → Ti and (b) Ti → CFRP.

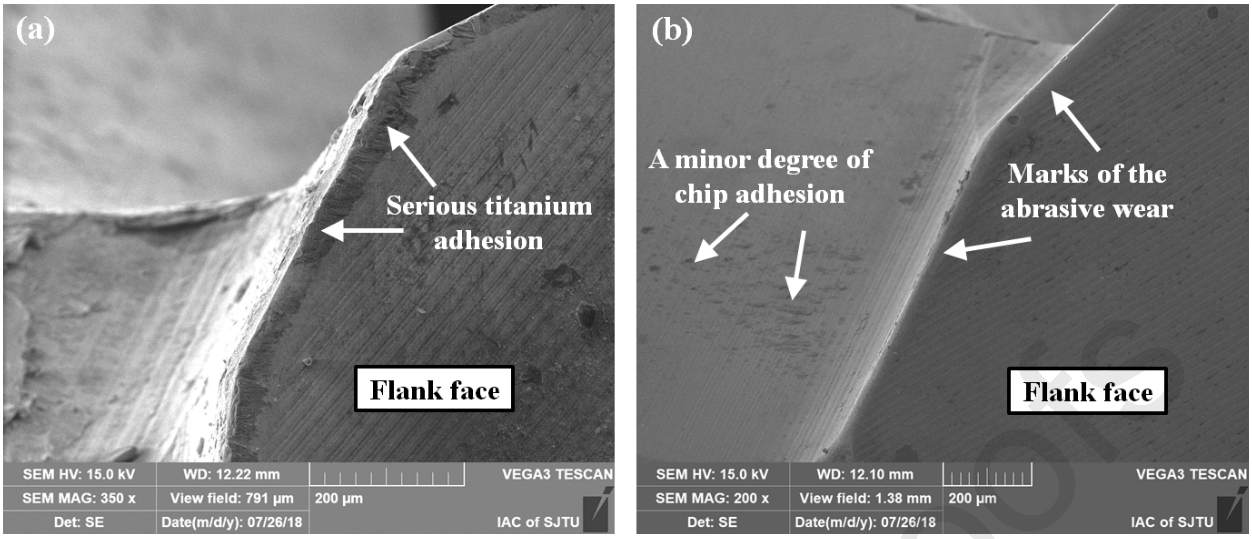

Fig.18. SEM morphologies of the minor cutting edges of uncoated drills after drilling 16 holes of CFRP/Ti6Al4V stacks under different drilling sequences (V_c = 65 m/min and f = 0.06 mm/rev): (a) CFRP → Ti and (b) Ti → CFRP.

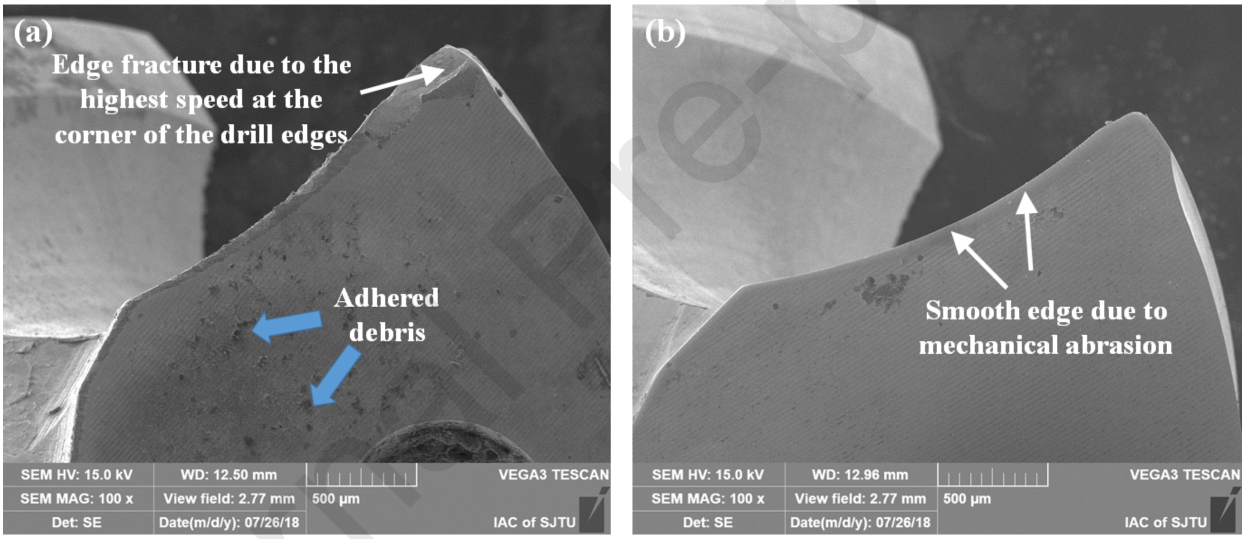

Fig.19. SEM morphologies of the edge corner of uncoated drills after drilling 16 holes of CFRP/Ti6Al4V stacks under different drilling sequences (V_c = 65 m/min and f = 0.06 mm/rev): (a) CFRP → Ti and (b) Ti → CFRP.

With respect to the diamond-coated drills, the tools are found to show a higher wear resistance against both adhesion and abrasion when operating in either the CFRP → Ti sequence or the Ti → CFRP sequence as evidenced in Figs.20-23. Table 5 shows the EDS analysis of point A of adhered materials in Fig.20 (a) in order to identify the element content of the examined zone. A similar impact of the drilling sequence strategy on the wear signatures and modes of diamond-coated drills is identified as well. The EDS analysis of point A in Fig.20 (a) reveals the presence of titanium chips welding onto the drill chisel edge zone. Titanium adhesion becomes more severe particularly under the CFRP → Ti drilling sequence. However, extents of chip adhesion are significantly decreased if the fibrous composite phase is drilled eventually due to the brushing effects of the reinforcing carbon fibers as shown in Fig.20 (b). The SEM images conducted on the main drill edges also show the enlarged radius of the cutting edge and the marks of the abrasive wear (Ref. Fig.21). In the case of the CFRP → Ti sequence, the worn flank surface close to the main drill edges appears much rougher being covered with quantities of titanium chip adhesion. In the opposite drilling sequence, abrasive wear dominates the formation of the final wear morphologies of drill edges and evidence of edge rounding becomes rather apparent. The observations are consistent with the findings reported in the case of the uncoated twist drills. In both drilling sequences, diamond-coated drills are found to outperform the uncoated ones in terms of lower extents of flank wear width, which is attributed to the improved frictional contact between the diamond coating and the workpiece as well as the lower thrust forces and temperatures promoted. By inspecting the morphologies of the minor cutting edge and the drill corner given in Figs. 22 and 23, coating peeling is identified as the dominant failure mode of the diamond-coated tools governing the stack drilling. The key difference of edge conditions between the two drilling strategies lies in the extent of coating peeling such that the CFRP → Ti sequence promotes a higher level of peeling failure of coatings. This can be explained by the fact that when drilling initially the CFRP composite, abrasive wear being operating as the key wear mode would enlarge the cutting edge radius and cause mechanical cracks inside the diamond coating that degrade the bonding strength of the coating to the drill substrate. Consequently, when the worn drill edge cuts across the interface and the metallic phase, concentrations of thermal heat and mechanical stresses take place, which accelerates the peeling of the diamond material. As evidenced in Fig.23 (a), a large area of the diamond coating is detached away from the edge corner exposing the tool substrate under the CFRP → Ti sequence, while drilling from Ti to CFRP creates a relatively lower extent of coating failure along the edge corner.

In general, the results of the wear analysis show that the drilling sequence strategy indeed exhibits a pronounced effect on the wear mechanisms and signatures of tools during the drilling of CFRP/Ti6Al4V stacks. Drilling from Ti to CFRP facilitates the reduction of extents of adhesion wear and flank wear due to the brushing and smoothing effects arising from the eventual composite phase drilling. The diamond-coated drill shows a higher wear resistance and a better tool performance related to its higher hardness and lower friction characteristics that improve the conditions of the tool-work interaction during drilling.

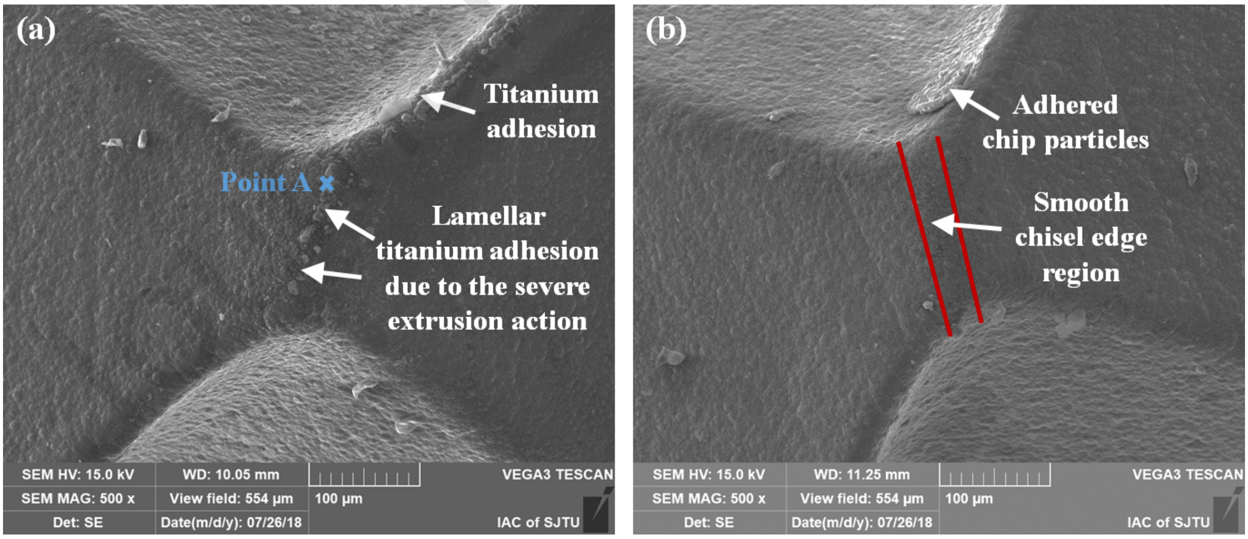

Fig.20. SEM morphologies of the chisel edge region of diamond-coated drills after drilling 16 holes of CFRP/Ti6Al4V stacks under different drilling sequences (V_c = 65 m/min and f = 0.06 mm/rev): (a) CFRP → Ti and (b) Ti → CFRP.

Table 5 The EDS analysis of point A in Fig.20 (a).

	Element	Normalized mass [%]	Atom [%]	Abs. error [%] (1 sigma)	Rel. error [%] (1 sigma)
EDS results	Ti	78.29	49.76	1.71	2.81
	C	17.09	43.31	1.85	14.00

O	3.50	6.65	0.68	24.99
W	0.99	0.16	0.07	8.64
Si	0.08	0.08	0.03	49.69
Cr	0.04	0.02	0.00	11.78
Fe	0.02	0.01	0.00	20.12

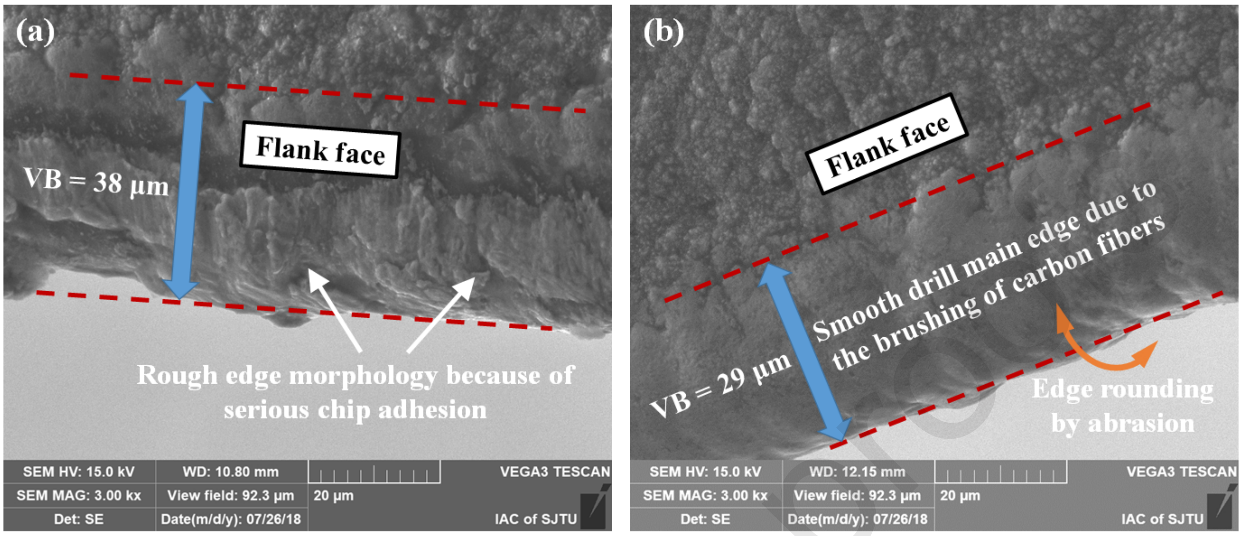

Fig.21. SEM morphologies of the main cutting edges of diamond-coated drills after drilling 16 holes of CFRP/Ti6Al4V stacks under different drilling sequences (V_c = 65 m/min and f = 0.06 mm/rev): (a) CFRP → Ti and (b) Ti → CFRP.

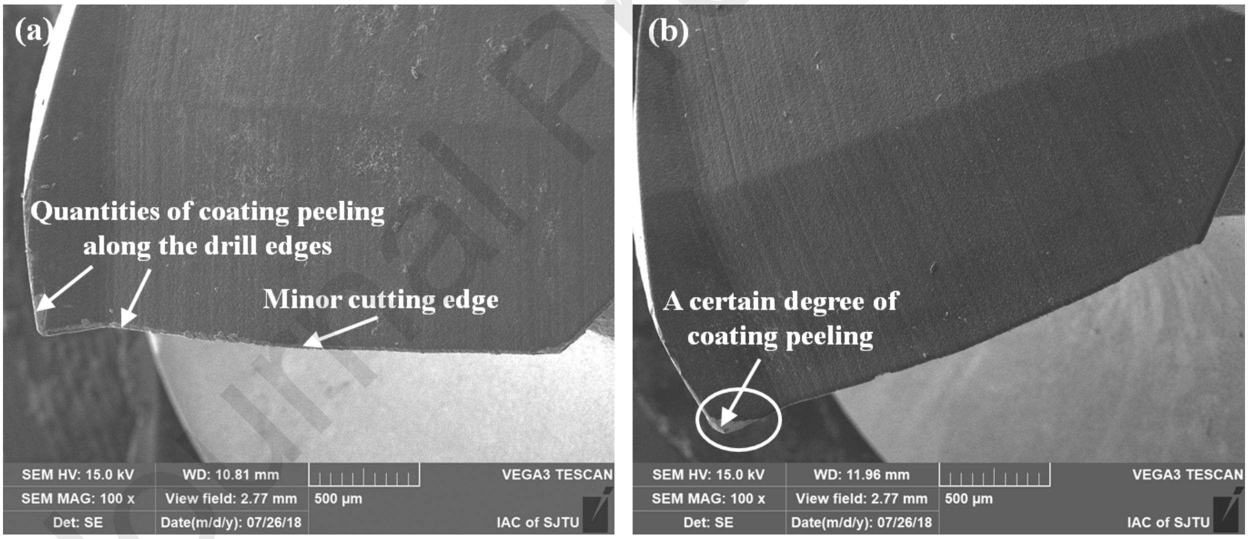

Fig.22. SEM morphologies of the minor cutting edges of diamond-coated drills after drilling 16 holes of CFRP/Ti6Al4V stacks under different drilling sequences (V_c = 65 m/min and f = 0.06 mm/rev): (a) CFRP → Ti and (b) Ti → CFRP.

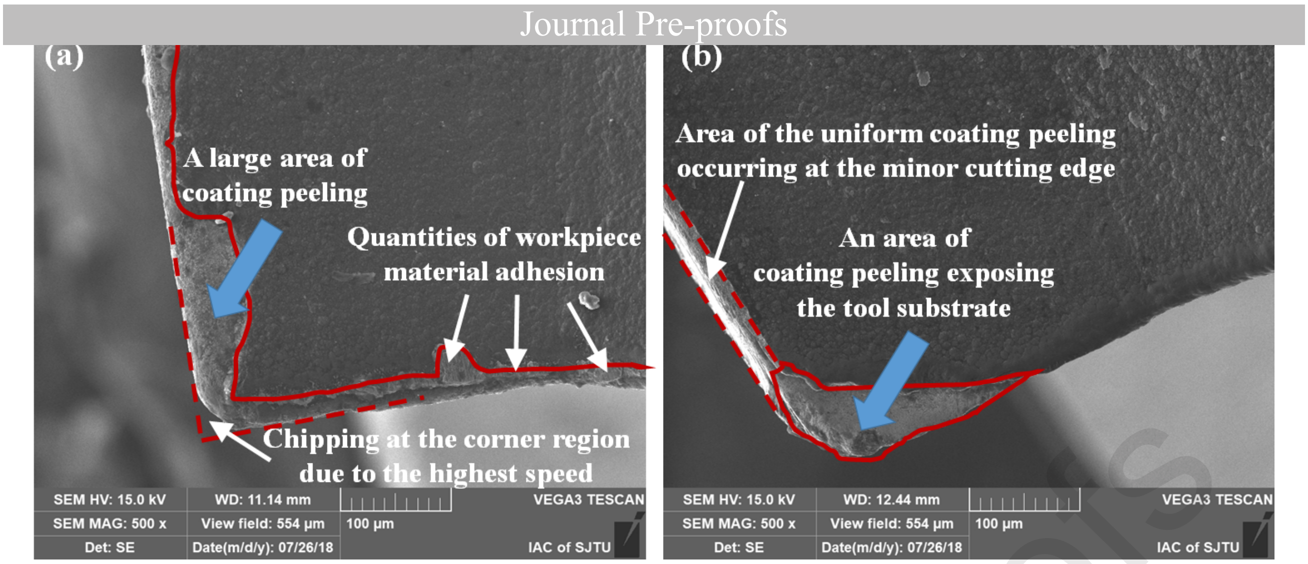

Fig.23. SEM morphologies of the edge corner of diamond-coated drills after drilling 16 holes of CFRP/Ti6Al4V stacks under different drilling sequences (V_c = 65 m/min and f = 0.06 mm/rev): (a) CFRP → Ti and (b) Ti → CFRP.

4. Conclusions

In this paper, drilling studies were conducted on multilayer CFRP/Ti6Al4V stacks using uncoated carbide and diamond-coated twist drills under different drilling sequence strategies. The frictional contacts between the drill surface and the stack workpiece were characterized via the inspections of the drilling forces/temperatures and wear signatures of tools in order to identify the impact of different cutting sequence strategies on the machinability of CFRP/Ti6Al4V stacks. A particular focus was put on the evaluation of cutting performances of uncoated and diamond coated drills by investigating the drilling temperatures/forces, exit burr heights of the Ti holes, surface morphologies of the composite holes and the resulting tool wear while drilling multilayer CFRP/Ti6Al4V stacks. Based on the results acquired, the following conclusions can be drawn.

- The cutting sequence strategy has a remarkable impact on the maximum temperatures developed in the drilling of CFRP/Ti6Al4V stacks due to the changes of conditions in the frictional contact at the tool-workpiece interface. Higher magnitudes of CFRP cutting temperatures are noted in drilling from Ti to CFRP due to the pre-heating of drills in the initial cut of the Ti alloy. The diamond-coated drill exhibits a better thermal capability of reducing heat generation and ensuring rapid heat dissipation due to its lower friction coefficient and higher thermal conductivity, which produces lower cutting temperatures than the uncoated tool for both drilling sequences.
- The cutting sequence strategy shows a clear impact on the thrust force generation of each sandwiched constituent when drilling CFRP/Ti6Al4V stacks. Machining from Ti to CFRP is identified benefitting the reduction of thrust forces for both the CFRP and Ti phases in comparison with the opposite drilling sequence. However, the operating mechanisms are different, depending on which factor (thermal softening or drill wear) dominates the material removal process in drilling.
- In the CFRP → Ti drilling sequence, both mechanical and thermal effects of metallic chip ejection are found to dominate the final composite surface morphologies, while under the sequence of drilling from Ti to CFRP the thermal effects due to the pre-heated drill may

play a decisive role in the formation of the composite hole wall surfaces. Mechanical abrasions/erosions, surface cavities, fuzzing, burning and pyrolysis of the matrix are the characteristic damage patterns of the composite surfaces when drilling CFRP/Ti6Al4V stacks. The diamond-coated drills are confirmed capable of producing much better surface morphologies of the composite holes than the uncoated ones in terms of minimal hole damage extents.

- The cutting sequence affects the extents of the titanium burr formation when drilling CFRP/Ti6Al4V stacks irrespective of the examined drill bits. Strategies of cutting from Ti to CFRP with the diamond-coated drills are found to favor the reduction of the exit titanium burr height.
- The cutting sequence strategy affects the eventual wear signatures of drills when machining CFRP/Ti6Al4V sandwiches as it changes the coupling effects of wear modes operating in each stacked phase machining. Adhesion, abrasion, attrition and flank wear are the key wear patterns governing the drilling of CFRP/Ti6Al4V stacks while microchipping and coating peeling dominate respectively the failure of the uncoated and diamond-coated drills. Drilling from Ti to CFRP benefits the reduction of drill adhesion and flank wear extents due to the brushing effects of the final composite drilling. Moreover, the diamond-coated drills are found to yield a higher wear resistance than the uncoated ones for all the drilling sequences tested due to their higher hardness, higher thermal conductivity and lower friction characteristics.
- In the present investigation, the selection of the drilling sequence strategy depends on which machining outputs are critical concerns when drilling CFRP/Ti6Al4V stacks. In most cases, the titanium → CFRP sequence, the diamond-coated drills combined with the low feed rates are the optimal conditions for the machining of these compound materials as they produce lower thrust forces, better quality of composite hole walls and less drill wear severity.

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References

[1] Alonso U, Calamaz M, Girot F, Iriondo E. Influence of flute number and stepped bit geometry when drilling CFRP/Ti6Al4V stacks. J Manuf Process 2019; 39: 356-70.
[2] Xu J, El Mansori M. Experimental studies on the cutting characteristics of hybrid CFRP/Ti stacks. Procedia Manuf 2016; 5: 270-81.
[3] Ramulu M, Branson T, Kim D. A study on the drilling of composite and titanium stacks. Compos Struct 2001; 54 (1): 67-77.
[4] Kim D, Beal A, Kwon P. Effect of tool wear on hole quality in drilling of carbon fiber reinforced plastic–titanium alloy stacks using tungsten carbide and polycrystalline diamond tools. J Manuf Sci Eng-Trans ASME 2016; 138 (3): 031006.
[5] Xu J, Mkaddem A, El Mansori M. Recent advances in drilling hybrid FRP/Ti composite: a state-of-the-art review. Compos Struct 2016; 135: 316-38.

[6] Park KH, Beal A, Kim D, Kwon P, Lantrip J. A comparative study of carbide tools in drilling of CFRP and CFRP-Ti stacks. J Manuf Sci Eng-Trans ASME 2014; 136 (1): 014501.

[7] Pramanik A, Littlefair G. Developments in machining of stacked materials made of CFRP and titanium/aluminum alloys. Mach Sci Technol 2014; 18 (4): 485-508.

[8] Xu J, Ji M, Chen M, Ren F. Investigation of minimum quantity lubrication effects in drilling CFRP/Ti6Al4V stacks. Mater Manuf Process 2019; 34 (12): 1401-10.

[9] Xu J, Li C, Chen M, Ren F. A comparison between vibration assisted and conventional drilling of CFRP/Ti6Al4V stacks. Mater Manuf Process 2019; 34 (10): 1182-93.

[10] Xu J, Zhou L, Chen M, Ren F. Experimental study on mechanical drilling of carbon/epoxy composite-Ti6Al4V stacks. Mater Manuf Process 2019; 34 (7): 715-25.

[11] Hussein R, Sadek A, Elbestawi MA, Attia MH. Low-frequency vibration-assisted drilling of hybrid CFRP/Ti6Al4V stacked material. Int J Adv Manuf Technol 2018; 98 (9-12): 2801-17.

[12] Hussein R, Sadek A, Elbestawi MA, Attia MH. An investigation into tool wear and hole quality during low-frequency vibration-assisted drilling of CFRP/Ti6Al4V stack. Journal of Manufacturing and Materials Processing 2019; 3 (3): 63.

[13] Senthilkumar M, Prabukarthi A, Krishnaraj V. Machining of CFRP/Ti6Al4V stacks under minimal quantity lubricating condition. Journal of Mechanical Science and Technology 2018; 32 (8): 3787-96.

[14] Impero F, Dix M, Squillace A, Prisco U, Palumbo B, Tagliaferri F. A comparison between wet and cryogenic drilling of CFRP/Ti stacks. Mater Manuf Process 2018; 33 (12): 1354-60.

[15] Alonso Pinillos U, Fernández Vidal SR, Calamaz M, Girot Mata FA. Wear mechanisms and wear model of carbide tools during dry drilling of CFRP/TiAl6V4 stacks. Materials 2019; 12 (18): 2843.

[16] Brinksmeier E, Janssen R. Drilling of multi-layer composite materials consisting of carbon fiber reinforced plastics (CFRP), titanium and aluminum alloys. CIRP Ann - Manuf Technol 2002; 51 (1): 87-90.

[17] Brinksmeier E, Fangmann S, Rentsch R. Drilling of composites and resulting surface integrity. CIRP Ann - Manuf Technol 2011; 60 (1): 57-60.

[18] Park K-H, Beal A, Kim D, Kwon P, Lantrip J. Tool wear in drilling of composite/titanium stacks using carbide and polycrystalline diamond tools. Wear 2011; 271 (11-12): 2826-35.

[19] Wang X, Kwon PY, Sturtevant C, Kim D, Lantrip J. Comparative tool wear study based on drilling experiments on CFRP/Ti stack and its individual layers. Wear 2014; 317 (1-2): 265-76.

[20] Xu J, El Mansori M. Numerical modeling of stacked composite CFRP/Ti machining under different cutting sequence strategies. Int J Precis Eng Manuf 2016; 17 (1): 99-107.

[21] Xu J, El Mansori M. Numerical studies of frictional responses when cutting hybrid CFRP/Ti composite. Int J Adv Manuf Technol 2016; 87 (1): 657-75.

[22] Xu J, El Mansori M. Wear characteristics of polycrystalline diamond tools in orthogonal cutting of CFRP/Ti stacks. Wear 2017; 376-377: 91-106.

[23] Xu J, El Mansori M, Chen M, Ren F. Orthogonal cutting mechanisms of CFRP/Ti6Al4V stacks. Int J Adv Manuf Technol 2019; 103 (9): 3831-51.

[24] Xu J, El Mansori M, Voisin J, Chen M, Ren F. On the interpretation of drilling CFRP/Ti6Al4V stacks using the orthogonal cutting method: Chip removal mode and subsurface damage formation. J Manuf Process 2019; 44: 435-47.

[25] Xu J, El Mansori M. Experimental study on drilling mechanisms and strategies of hybrid CFRP/Ti stacks. Compos Struct 2016; 157: 461-82.

[26] Davies MA, Ueda T, M'Saoubi R, Mullany B, Cooke AL. On the measurement of temperature in material removal processes. CIRP Ann - Manuf Technol 2007; 56 (2): 581-604.
[27] Yashiro T, Ogawa T, Sasahara H. Temperature measurement of cutting tool and machined surface layer in milling of CFRP. Int J Mach Tools Manuf 2013; 70: 63-9.
[28] Merino-Pérez JL, Royer R, Ayvar-Soberanis S, Merson E, Hodzic A. On the temperatures developed in CFRP drilling using uncoated WC-Co tools Part I: Workpiece constituents, cutting speed and heat dissipation. Compos Struct 2015; 123 (Supplement C): 161-8.
[29] Merino-Pérez JL, Hodzic A, Merson E, Ayvar-Soberanis S. On the temperatures developed in CFRP drilling using uncoated WC-Co tools Part II: Nanomechanical study of thermally aged CFRP composites. Compos Struct 2015; 123 (Supplement C): 30-4.
[30] Zitoune R, Cadorin N, Collombet F, Šíma M. Temperature and wear analysis in function of the cutting tool coating when drilling of composite structure: In situ measurement by optical fiber. Wear 2017; 376: 1849-58.
[31] Wang C, Chen Y, An Q, Cai X, Ming W, Chen M. Drilling temperature and hole quality in drilling of CFRP/aluminum stacks using diamond coated drill. Int J Precis Eng Manuf 2015; 16 (8): 1689-97.
[32] Zitoune R, Krishnaraj V, Collombet F. Study of drilling of composite material and aluminium stack. Compos Struct 2010; 92 (5): 1246-55.
[33] Shyha IS, Soo SL, Aspinwall DK, Bradley S, Perry R, Harden P, et al. Hole quality assessment following drilling of metallic-composite stacks. Int J Mach Tools Manuf 2011; 51 (7-8): 569-78.
[34] Chen WC. Some experimental investigations in the drilling of carbon fiber-reinforced plastic (CFRP) composite laminates. Int J Mach Tools Manuf 1997; 37 (8): 1097-108.
[35] Rahim EA, Sasahara H. A study of the effect of palm oil as MQL lubricant on high speed drilling of titanium alloys. Tribol Int 2011; 44 (3): 309-17.
[36] Isbilir O, Ghassemieh E. Comparative study of tool life and hole quality in drilling of CFRP/titanium stack using coated carbide drill. Mach Sci Technol 2013; 17 (3): 380-409.
[37] Ghassemieh E. Performance and wear of coated carbide drill in machining of carbon fibre reinforced composite/titanium stack. Int J Mater Prod Technol 2012; 43 (1-4): 165-83.
[38] Li MJ, Soo SL, Aspinwall DK, Pearson D, Leahy W. Influence of lay-up configuration and feed rate on surface integrity when drilling carbon fibre reinforced plastic (CFRP) composites. Procedia CIRP 2014; 13: 399-404.
[39] Aurich JC, Dornfeld D, Arrazola P, Franke V, Leitz L, Min S. Burrs—Analysis, control and removal. CIRP Ann - Manuf Technol 2009; 58 (2): 519-42.
[40] Park KH, Beal A, Kim D, Kwon P, Lantrip J. Tool wear in drilling of composite/titanium stacks using carbide and polycrystalline diamond tools. Wear 2011; 271 (11-12): 2826-35.

Declaration of conflicting interests

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