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Tool wear processes in low frequency vibration assisted drilling of CFRP/Ti6Al4V stacks with forced air-cooling

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ABSTRACT

Drilling CFRP/Ti6Al4V stacks in one-shot time becomes essential in the modern aerospace manufacturing sectors in order to guarantee the productivity due to the demands of riveting and fastening assembly. In the present study, a novel integrated system of low frequency vibration assisted drilling (LFVAD) coupled with the forced air-cooling was designed to investigate the tool wear issues in drilling of CFRP/Ti6Al4V stacks. The used uncoated solid tungsten carbide tools were specially designed with threaded shanks for fitting the adapter of the LFVAD tool holder. Main geometrical features of the threaded shank drills include a 6.35 mm diameter, a 140° point angle, a 30° helix angle and two cutting edges. Drilling temperatures and forces were *in-situ* measured for the LFVAD subjected to varying conditions, and the results were compared with the conventional drilling under the identical drilling conditions. It is found that the small titanium chip segments produced by the interrupted cut of vibration drilling can be removed efficiently *via* the help of the forced air-cooling. Compared with the conventional drilling, slower flank wear rates and lower cutting temperatures are identified under the LFVAD with the forced air-cooling. The adhesive wear is the main wear mode for both drilling methods; however, the chemical wear becomes more pronounced while the cutting edge chipping predominates in the LFVAD. In sum, the LFVAD with the forced air-cooling is confirmed capable of improving the machinability of the CFRP/Ti6Al4V stacks from the aspects of reducing tool wear.

1. Introduction

The hybrid structure of composites and metal alloys has been widely used in the aerospace industry for the purpose of reducing the weight of airframes and of improving the structural strength [1]. Combination of the single materials with individual advantages generates enhanced properties including high strength-to-weight ratio, excellent design flexibility and high erosion/corrosion resistance which are much better than the use of each individual material [2,3]. Carbon fiber reinforced polymer (CFRP) and Ti6Al4V alloy are two representative materials widely used in the structural stacks which are often assembled by rivets or bolts. Drilling of the bi-material sandwich in one-shot time is the effective method applied in the actual production to produce boreholes with high assembly precision and high productivity. However, drilling of composite/metal stacks with desirable quality is rather challenging due to the disparate machinability of each constituted material [4]. In particular, the highly abrasive carbon fibers and the chemically-reactive titanium alloy during drilling result in harsh cutting environments with coupling effects of heavy mechanical and thermal loads to the drills. Problems of excessive tool wear and short tool life need to be carefully addressed.

Chip removal process in cutting CFRP/Ti6Al4V stacks is of fundamental importance for understanding the wear mechanisms of tools. As claimed by Xu and El Mansori [2], due to the brittle-fracture dominated chip separation mode, "powder" like chips form in machining CFRP phase while continuous chips are generated because of the elasto-plastic deformation of Ti6Al4V in the cutting process. The powdery chips of CFRP can be harmful not only from the view of human health but also from the environmental perspective. Additionally, in a typical process of drilling CFRP/Ti6Al4V stacks under constant feed rates, the continuous spiral chips generated in cutting the metallic phase cannot eject effectively. The residual titanium chips with inability to evacuate can get entangled at the interaction zones between the drill edges and the workpiece causing the excessive tool wear and the dramatic

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increase of cutting forces and temperatures. As experimentally studied by Brinksmeier *et al.* [5], the conventional drilling (CD) brings more thermal loads caused by the higher friction between the drill clearance face and the borehole wall which results in the damage to surface integrity and the adhesive wear of tools. Xu and El Mansori [6] pointed out that the titanium chip evacuation has certain influences on the drilling forces. Thus, in order to achieve the reduction of health hazard and the tool wear, the vibration-assisted machining (VAM) and cutting fluids are proposed from the aspects of reducing mechanical loads and of providing better chip removal ability.

As discussed in the review article published by Brehl and Dow [7], the fundamental difference between conventional machining and VAM is the periodic contact between the tool rake face and the workpiece material, which leads to the interrupted generation of chips. According to the range of the vibrational frequency, the VAM can be divided into ultrasonic machining (USM, usually frequency $\geq$ 20 kHz) [8] and low frequency vibration assisted machining (usually frequency $<$ 1000 Hz) [9]. USM can be utilized as a non-thermal process with relatively small amplitudes of about 10–20 µm to deal with materials with hardness above 40 HRC [10]. However, the material removal rate of USM limited by its small amplitudes becomes the key drawback in the industry for the drilling of CFRP/Ti6Al4V stacks [11]. On the contrary, as revealed by Kuo *et al.* [12], the LFVAD with amplitudes of about 0.05 mm is practical and feasible in both reducing drill flank wear and improving the processing efficiency. The cutting fluids are commonly used to serve as a medium to take away the chips and to provide cooling in the drilling processes [13]. Ishikawa *et al.* [14] pointed out that the decreased drilling forces and tool wear could be attributed to the discharge of cutting chips taken away by the application of working fluids during the LFVAD. However, the cyclic utilization of cutting fluids in the machining of CFRP is uneconomic and environmentally unfriendly due to the heavy pollution of the powdery chips.

The overall tool wear processes in drilling CFRP/Ti6Al4V stacks are a combination of coupling effects of heat and tribology when cutting the bi-material sandwich. Generation and transfer of heat in machining fiber reinforced composites concern not only the thermal defects but also the tool wear which should be carefully measured and studied [15,16]. In order to capture the *in-situ* cutting temperatures, applications of thermocouples embedded into the drills through the coolant holes, dynamic thermocouples between the tool/workpiece and infrared thermography camera are the three most-used measuring methods [15,17].

Tool wear processes of LFVAD are related to the interrupted chips generated by the periodic separation and contact between the drill rake face and the workpiece material. As reported by Pecat and Meyer [18], the shape and radian of undeformed chip segments depend on the cutting parameters, vibration frequency, vibration amplitude, *etc.* In the LFVAD of CFRP/Ti6Al4V stacks, although the continuous spiral chips are sheared into segments, the hot and sharp metallic chips can still be capable of clogging the drilled holes because of the improper chip shapes induced by inappropriate cutting parameters and the poor chip removal ability. Thus, the thermal damage to the drilled CFRP holes and the abrasive wear to tools may remain severe.

In order to deal with the tool wear issues by efficiently evacuating the residual titanium chips when drilling CFRP/Ti stacks under the low frequency vibration assistance, in this work, a novel integrated system of the LFVAD coupled with forced air-cooling was designed. The forced air-cooling system provides a strip of rectangular area with negative pressure close to the cutting position which can suck away the chip segments during drilling processes ensuring better chip removal ability and cooling effects. Drilling temperatures were *in-situ* measured by embedded thermocouples and infrared thermography camera in the LFVAD subjected to varying conditions, and the results were compared with those gained under the conventional drilling. Special attention was paid to the issues of tool wear in the LFVAD of CFRP/Ti6Al4V stacks using uncoated twist drills with/without forced air-cooling.

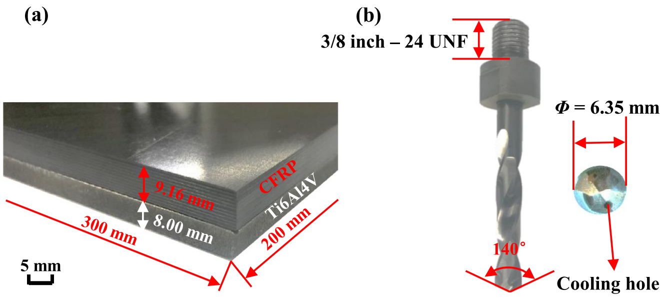

Fig. 1. Photographs showing (a) the utilized multilayer CFRP/Ti6Al4V stack and (b) the uncoated carbide threaded shank drill.

This paper makes efforts to improve the performance of the LFVAD of CFRP/Ti6Al4V stacks which is achieved through a modified cooling equipment and systematic experimental investigations taking drilling forces, cutting temperatures and tool wear into account.

2. Experimental procedures

2.1. Composite/metal stacks and drill bits

The material sandwich investigated in this work consists of the CFRP and Ti6Al4V boards. The specimen has a total size of 300 mm (length) × 200 mm (width) × 17.16 mm (thickness, 9.16 mm for the CFRP and 8 mm for the titanium alloy) as depicted in Fig. 1. In the study, the aeronautical grade CFRP laminate was fabricated by carbon/epoxy prepregs containing T800 reinforced fibers with volume fraction of 65% and the matrix of X850 epoxy resin. The detailed mechanical/physical properties of the stacked Ti6Al4V alloy and T800/X850 composites are summarized in Table 1.

Threaded shank drills were specially designed in this work to fit the adapter of the tool holder used in the LFVAD. As shown in Fig. 1, the uncoated solid tungsten carbide drill bits with coolant holes provided by Fengqi Machinery Technology Co., Ltd. were utilized. The main geometrical features of the used drills include a 6.35 mm diameter, a 140° point angle, a 30° helix angle and two cutting edges.

2.2. Experimental setup of LFVAD with forced air-cooling

As depicted in Fig. 2, all the experiments were carried out on a HURCO VMX42 machining center with a maximum spindle speed of 12,000 rpm and a positioning accuracy of 0.01 mm. With a specially-designed fixture, the CFRP/Ti stacks and the forced air-cooling system were clamped on a dynamometer (Kistler 9272) connected with a multichannel charge amplifier (Kistler 5070A) during the drilling operation. In addition, the cutting forces were recorded at an acquisition frequency of 20 kHz. The forced air-cooling system consists of a chip collection unit equipped with a strip of rectangular suction nozzle connected to a tube and a vacuum pump which can provide the negative pressure to finalize the *in-situ* collection of resected chips.

The axial low frequency oscillations were generated by a mechanical structure (equipment reference: PP3020) consisting of the roller, flat ring and sine ring provided by MITIS Engineering Company. Amplitudes ranging from 0.10 to 0.35 mm and oscillation containing 1.5 and 2.5 osc/rev can be obtained by changing the sine rings. In the present study, a fixed frequency of 1.5 osc/rev (N_v = 1.5 osc/rev) and an amplitude of 0.20 mm (A = 0.20 mm) were applied. The tool holder was modified to reduce the effects of the assembly errors induced by the threaded connection structure, and the radial run-out of the drill bits was maintained within 8 µm.

In order to identify how the LFVAD equipped with the forced air-cooling affects the tool wear in the drilling of CFRP/Ti6Al4V stacks, three groups of experimental tests were performed in this work as summarized in Table 2. Additionally, the drilling temperatures (T) were

Table 1
Material properties of the studied T800/X850 CFRP and Ti6Al4V alloy.

Properties of T800/X850 CFRP	Density [g/cm^3] 1.60	Fiber volume fraction 65%	Tow 5 μm, 12 K
	Tensile modulus [GPa] 180	Compressive modulus [MPa] 160	Tensile strain [%] 1.68
Properties of Ti6Al4V alloy	Density [g/cm^3] 4.43	Tensile strength [MPa] 90–1160	
	Thermal conductivity [W/(m °C)] 7.0	Specific heat [J/(kg·°C)] 546	

measured by both embedded thermocouples (T_e) and infrared thermography camera (T_f) in test group 1 to identify the functional correlations of these two temperature measuring methods guiding the rest of the two test groups. All the drilling experiments were carried out in dry machining conditions.

2.3. *In-situ* measurement of the drilling temperatures

Due to the structural constraints of the modified tool holder, conventional embedded thermocouples inside the drill bits are not suitable for the *in-situ* measurement of the drilling temperatures in the LFVAD. Thus, an infrared thermography camera was used to realize the *in-situ* measurement of the drilling temperatures under various cutting conditions. As revealed in the relevant research [15], the temperatures measured by the infrared thermography camera tend to be lower than those captured by the embedded thermocouples due to the hidden cutting points. To obtain the realistic development tendency of the drilling temperatures, the measuring method of embedding thermocouples inside the drill bits was applied to serve as the calibration and confirmation in order to improve the measuring accuracy.

The overview of the temperature measurement is given in Fig. 3. All the holes were drilled at a distance of 2 mm close to the edge of the CFRP/Ti stack to make the temperature measurements more reliable. The standard OMEGA K-type thermocouples were embedded into the drill bits through the internal coolant holes. The FLIR A615 infrared thermography camera (IFTC) which has a working temperature ranging from −20 to 2000 °C and an image acquisition frequency ranging from 50 Hz to 200 Hz was applied to *in-situ* measure the drilling temperatures. The temperature resolution of the equipment is less than 0.05 °C which ensures the accuracy and comparability of the monitored data.

Table 2
Details of the utilized parameters in drilling CFRP/Ti6Al4V stacks.

Test group 1 (general cutting parameters)			*Test group 2*	*Test group 3*
Spindle speed, *n* [rpm]	Cutting speed, *V* [m/min]	Feed rate, *f* [mm/rev]	Additional conditions	Additional conditions
1000	20	0.015 0.030 0.045 0.060	Amplitude 0.20 mm Oscillation 1.5 osc/rev	Forced air-cooling

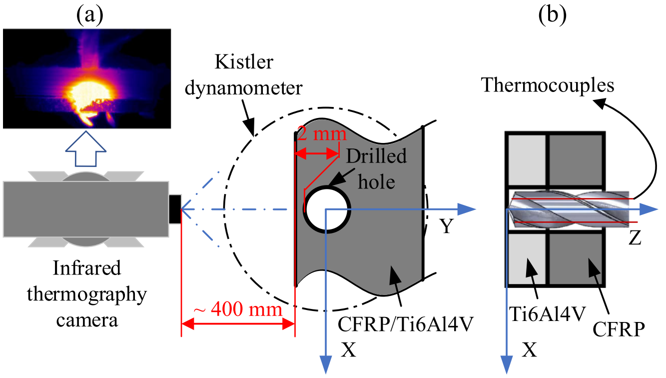

Fig. 3. Schematic view showing the *in-situ* measurement of drilling temperature by (a) the infrared thermography camera and (b) the thermocouples.

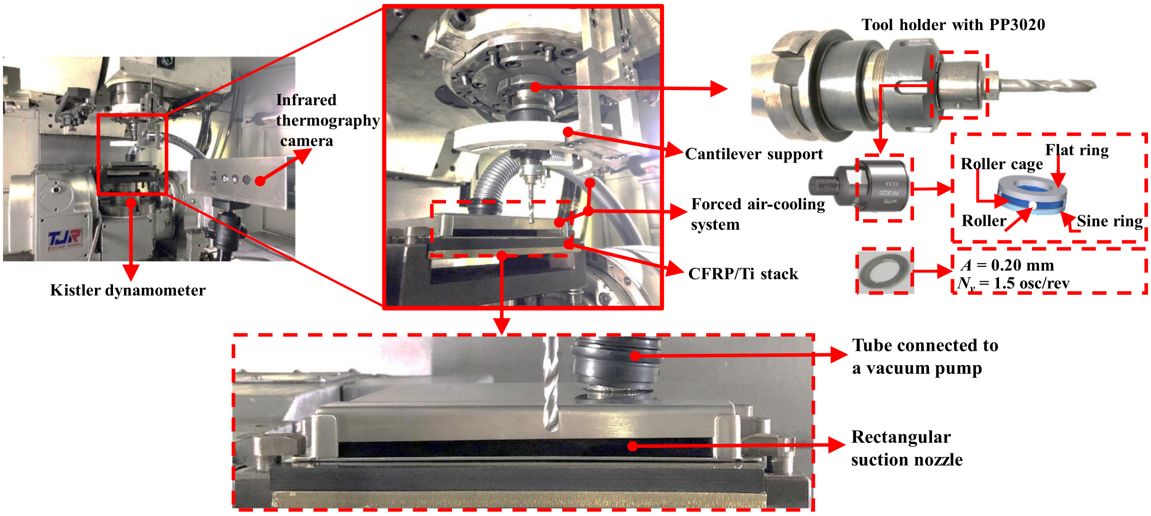

Fig. 2. Photographs showing the experimental setup. Right is the tool holder for the LFVAD and the components of the source of axial oscillations (A = 0.20 mm and N_v = 1.5 osc/rev) and below is the designed forced air-cooling system.

2.4. Characterization methods

In order to investigate the tool wear issue in the LFVAD of CFRP/Ti6Al4V stacks with the forced air-cooling, several indicators including the drilling forces, cutting temperatures and tool wear were analyzed. Processes of the worn surface morphologies of the used drills in the drilling tests were observed by a high-precision digital microscope (Keyence VHX-500FE) and further inspected using both the scanning electron microscope (SEM) and the energy dispersive spectroscopy (EDS). All the measurements were repeated three times in order to get reliable results.

3. Results and discussion

3.1. Cutting temperatures and chip removal processes

The process temperatures are of great importance to the tool wear in dry drilling CFRP/Ti stacks. However, the temperature measurement in the drilling process especially in the LFVAD is quite difficult because of the hidden cutting points. To realize the *in-situ* measurement of drilling temperatures in the LFVAD with high precision, both the infrared thermography camera and the embedded thermocouples into the drill bits were employed in the conventional drilling (CD) to serve as the references to the individual measuring method of the infrared thermography camera used in the LFVAD. The comparative results of process temperatures obtained by the thermocouples and IFTC in the conventional drilling ($V = 20\,\mathrm{m/min}$ and $f = 0.015\,\mathrm{mm/rev}$) are plotted in Fig. 4.

It is noted that for the same drilling process, temperatures of the cutting zone measured by IFTC are lower than those obtained by the thermocouples at the stable stage which is mainly caused by the poor thermal conductivity of both the CFRP and titanium alloy. Although there exists a time delay and interferential temperature points caused by the evacuation of the hot chips as depicted in Fig. 4(a), the temperatures recorded by the IFTC show the same varying trend as that obtained by the thermocouples, which means that the temperature measurement *via* IFTC is reliable and convincing.

Fig. 5 presents the thermal images of the drilling temperatures when using different drilling methods (CD, LFVAD with and without the forced air-cooling) subjected to the cutting conditions of $V = 20\,\mathrm{m/min}$, $f = 0.015\,\mathrm{mm/rev}$, $A = 0.20\,\mathrm{mm}$ and $N_v = 1.5$ osc/rev. In the conventional drilling, the continuous spiral chips can be clearly observed which lead to the highest temperature of 316.65 °C. By contrast, the use of the LFVAD brings a significant decrease to the drilling temperatures of about 47.9% while the LFVAD with the forced air-cooling leads to a dramatic temperature decrease of about 51.3%. Thanks to the periodical movement of the cutting edge, continuous spiral Ti chips were broken into chip segments and free motion of chip segments can be clearly observed during the vibration assisted drilling in Fig. 5. The proper shapes of chip segments do favor the evacuation of heat generated by drilling. Furthermore, it is shown that the forced air-cooling system can absorb the chip segments timely during the vibration assisted drilling which enhances the ejection process of chips leading to a sharp decrease of the temperatures.

The results of *in-situ* measurement of the drilling temperatures obtained in the conventional drilling, LFVAD with and without the forced air-cooling under the cutting conditions of $V = 20\,\mathrm{m/min}$, f ranging from 0.015 to 0.060 mm/rev, $A = 0.20\,\mathrm{mm}$ and $N_v = 1.5$ osc/rev are given in Fig. 4(b). It can be noted that the vibration assisted drilling can bring reductions of cutting temperatures efficiently under the low feed rates of 0.015 and 0.030 mm/rev while the temperatures rise significantly being higher than those gained in the conventional drilling under the high feed rates of 0.045 and 0.060 mm/rev. This is caused by the large and thick chip segments produced by the high feed rates coupled with the amplitude of cutting edge. Thus, it can be assumed that there exists a critical size of the chip segments beyond which the effectiveness of the chip evacuation would be worse than the conventional drilling. Additionally, the forced air-cooling system can make contributions to the efficient ejection of the chip segments and then lead to the reduction of abrasive wear caused by the Ti adhesion under the high cutting temperatures. It can be concluded that, to take advantages of the vibration assisted drilling, the coupling effects of the vibration frequency, feed rate and amplitude should be carefully considered.

3.2. Cutting forces

Analysis of drilling forces is the fundamental step in understanding the effects of tool kinematics on the wear of drills. Signals of thrust forces in the time domain with respect to different cutting conditions are shown in Fig. 6 for the case corresponding to $V = 20\,\mathrm{m/min}$, $f = 0.015\,\mathrm{mm/rev}$, $A = 0.20\,\mathrm{mm}$ and $N_v = 1.5$ osc/rev. The results show that the local thrust force fluctuations in drilling CFRP are bigger than those gained in drilling Ti6Al4V due to the different machining characteristics of the two materials. For the anisotropic machinability of CFRP, the unstable process of chip formation results from the dynamic changes of the angle between the cutting edge and fibers leading to the random friction on the tools which is externally expressed by the local

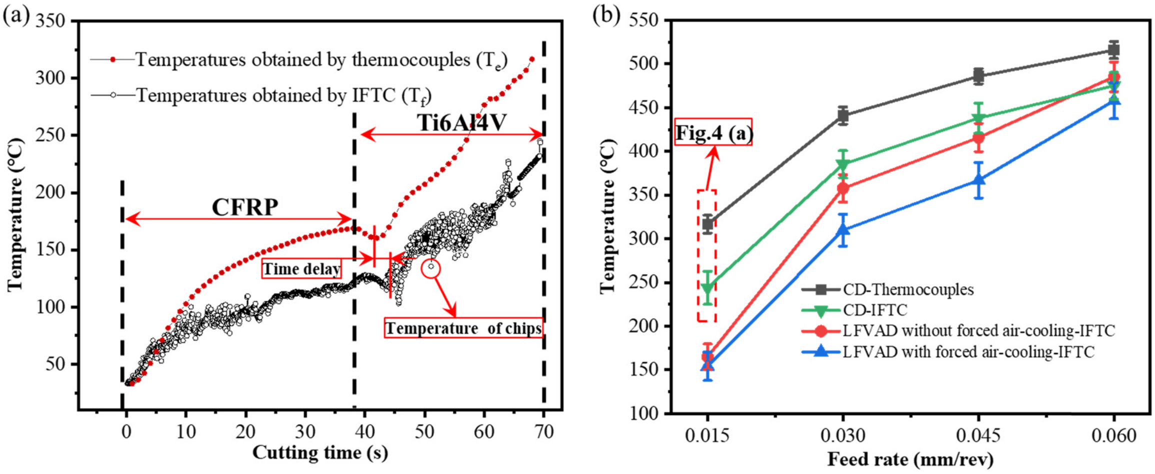

Fig. 4. (a) Evolution of the drilling temperatures in the conventional drilling (CD) with the cutting time ($V = 20$ m/min and $f = 0.015$ mm/rev) and (b) comparison of the drilling temperatures when using different drilling methods (CD, LFVAD with and without the forced air-cooling) ($V = 20$ m/min, $f = 0.015$, 0.030, 0.045, 0.060 mm/rev, $A = 0.20$ mm and $N_v = 1.5$ osc/rev).

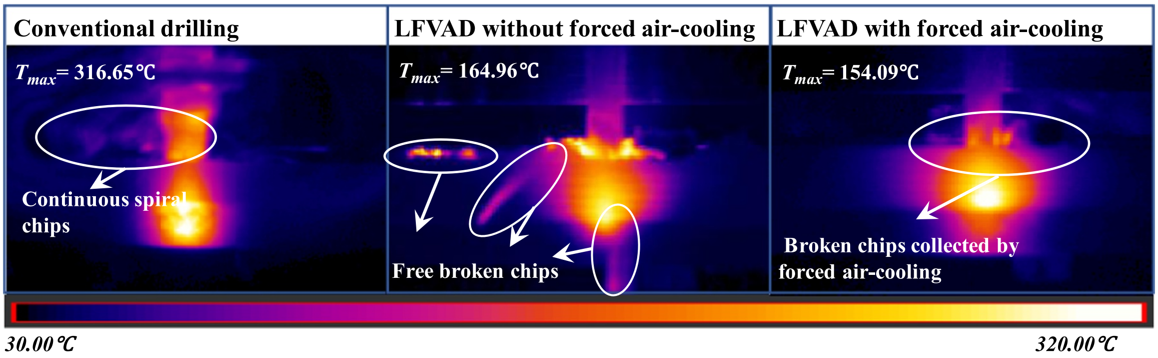

Fig. 5. Thermal infrared images showing the drilling processes when using different drilling methods (V = 20 m/min, f = 0.015 mm/rev, A = 0.20 mm and N_v = 1.5 osc/rev).

force fluctuations. In the stable cutting stage of drilling Ti6Al4V, the thrust forces of the conventional drilling maintain around 150 N except for a sudden fluctuation caused by the clogging spiral Ti chips. In contrast, for the LFVAD with and without the forced air-cooling, no significant alterations of thrust force are observed, which means the efficient ejection of the Ti chips. Furthermore, the drilling process of the LFVAD with the forced air-cooling generates thrust forces of about 25 N lower than the LFVAD without the forced air-cooling. Since the residual chips can lead to higher cutting resistance per revolution, the reduction of thrust forces represents the assistance of the forced air-cooling to remove the residual chips, which makes contributions to the reduction of tool wear caused by the heavy mechanical loads.

The thrust force in the drilling process commonly signifies the formation of chips and the tribological interaction at the tool-work interface. The nearly constant thrust force of the conventional drilling at the stable cutting stage represents the formation of continuous spiral chips with nearly the same chip thickness, while for the LFVAD, the thrust force fluctuates in a certain degree ranging from the minimum (0 N) to the maximum (~280 N). Although the LFVAD produces a much higher mechanical load, the actual cutting time is reduced, and the average cutting forces are lower than those of the conventional drilling. According to the change of the thrust force, the formation processes of chip segments can be analyzed: every two adjacent wave troughs represent the two pieces of separated chips. In fact, the vibration frequency (F_v) of the thrust force can be calculated using the following equation, where n is the spindle speed in rpm and N_v is the oscillation frequency in osc/rev:

$$F_v = \frac{n \cdot N_v}{60} \tag{1}$$

The regularly broken Ti chips produced by the low frequency vibration (25 Hz) assisted drilling cause less contacts between the cutting edge and the workpiece compared with the conventional drilling. As a result, the tool wear caused by the durable contacts with long distance chips can be reduced remarkably. Additionally, it appears that the forced air-cooling leads to much lower thrust forces in drilling Ti6Al4V assisted with the low frequency vibration. However, the effects of reducing thrust forces are insignificant in the drilling of CFRP. This is attributed to the disparate mechanisms of chip formation in the conventional drilling of CFRP and Ti6Al4V. Cutting chips of CFRP exist in the form of dust while continuous spiral chips are the dominant chip type in the conventional drilling of Ti alloys. The forced air-cooling system can effectively promote the evacuation of chip segments and the continuous chips lead to both the significant reduction of the thrust forces and the less local force fluctuation.

3.3. Tool wear

Tool wear occurring in drilling is induced by the coupling effects of thermal and mechanical loads which is further enhanced by the combination of abrasive fibers and the difficult-to-machine titanium alloy in the CFRP/Ti stacks. Localized dynamic loads in the cutting zone are modified during the drilling assisted by low frequency vibration and forced air-cooling, which leads to the changes of the cutting and wear mechanisms. In order to understand the tool wear process in the LFVAD with the forced air-cooling, SEM inspections and EDS analyses were conducted, and the results are shown in Figs. 7 and 8 respectively. All of the three test groups of drilling methods were investigated after drilling an identical number of 45 holes under the fixed cutting conditions of V = 20 m/min, f = 0.015 mm/rev, A = 0.20 mm and N_v = 1.5 osc/rev.

It is noted that the adhesive wear is the main wear pattern and the edge fracture operates as the key drill failure mode in the conventional

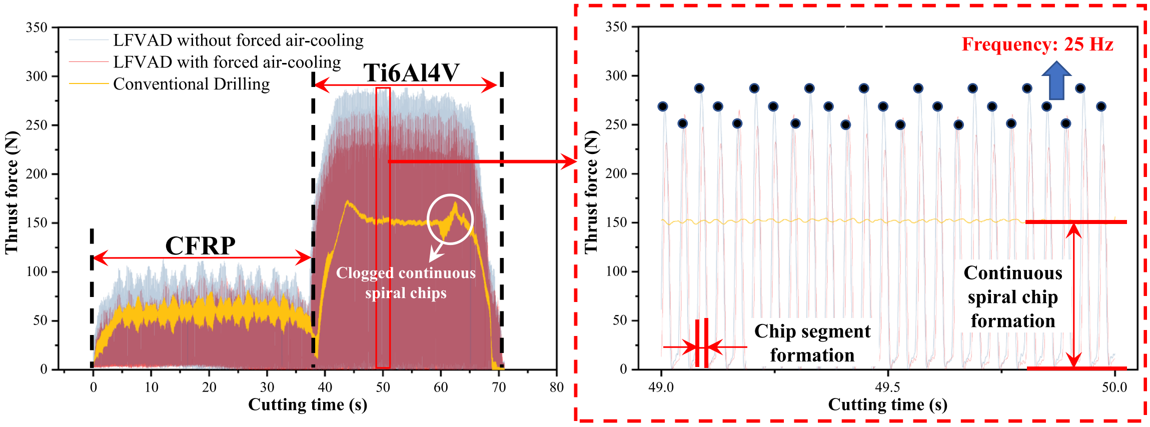

Fig. 6. Comparison of signals of the thrust forces gained when using different drilling methods (V = 20 m/min, f = 0.015 mm/rev, A = 0.20 mm and N_v = 1.5 osc/rev).

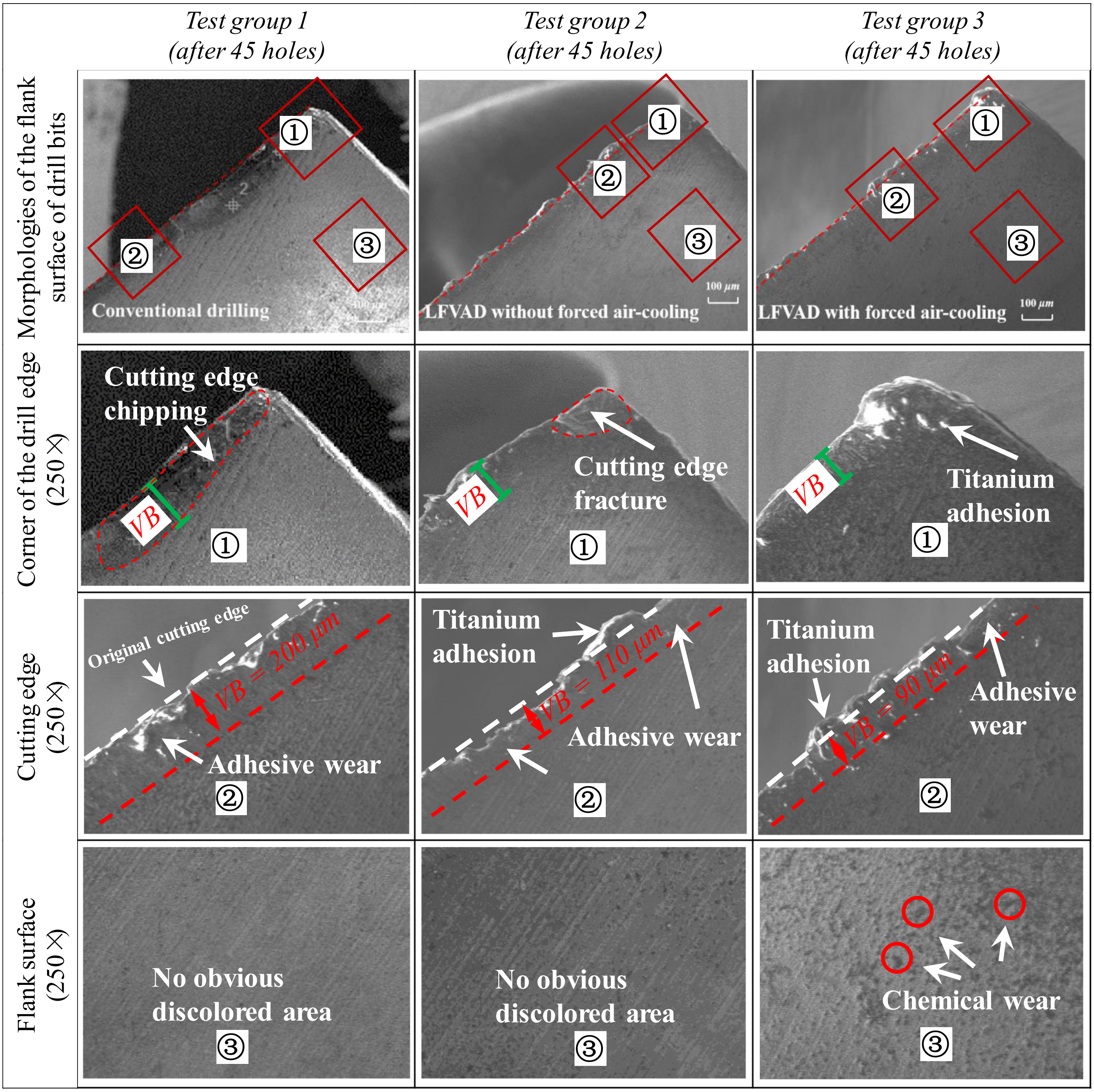

Fig. 7. SEM morphologies of the worn drill surfaces obtained under different test groups.

drilling. Large titanium adhesions can be observed along the cutting edge with a large width. This can be attributed to the generation of the clogging Ti chips derived from the continuous process of chip formation in the conventional drilling corresponding to the sudden alteration of thrust force signals shown in Fig. 6. The constant contact between the drill flank face and the workpiece leads to the heavy thermal loads and high temperatures due to the low thermal conductivity of the titanium alloy. In contrast, the edge chipping which leads to the most severe reduction of tool life is reduced by the use of the LFVAD with the suitable cutting parameters.

One of the advantages of the vibration assisted drilling is the intermittent cutting process in which the discontinuous titanium chips are periodically produced. The absence of continuous chips provides a better environment for the chip evacuation and a possible reduction in coefficient of the sliding friction which signifies the elimination of unstable cutting stages. Thus, less abrasive wear and edge fracture constitute the combined wear mode in the vibration assisted drilling of CFRP/Ti stacks compared with the conventional drilling.

Furthermore, a large extent of discolored area can be identified on the drill flank surface which signifies the enhancement of the chemical wear in the LFVAD with the forced air-cooling instead of the edge fracture. Meanwhile, a significant reduction of titanium adhesions can be observed. This can be evidenced by the presence of various oxidizing particles which are detected *via* the EDS analysis shown in Fig. 8. Compared with the conventional drilling, the LFVAD provides not only small titanium chip segments but also the cooling effects to the cutting zone by enhancing the local air motion *via* the help of the forced air-cooling system. On the one hand, slower flank wear rates can be

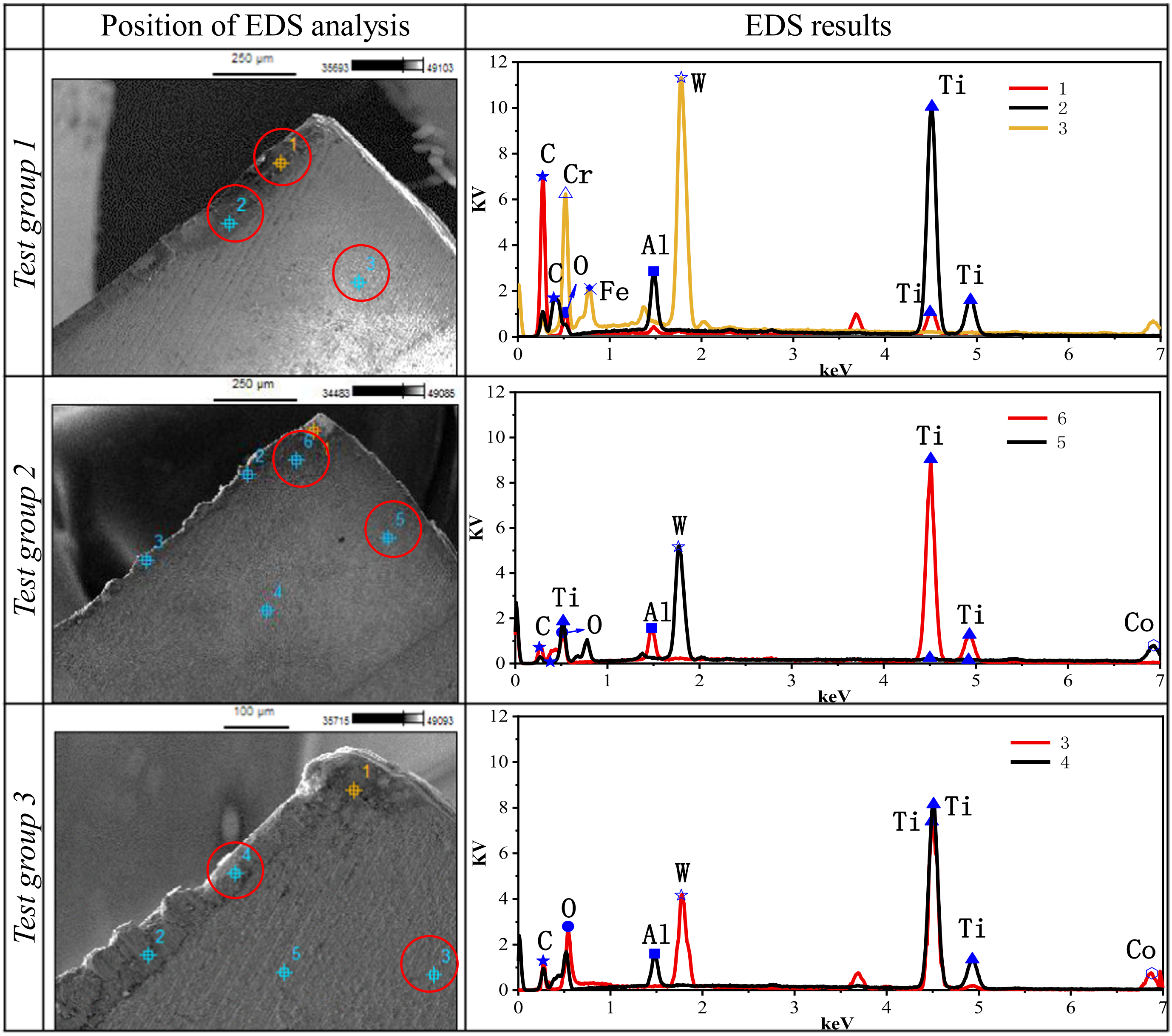

Fig. 8. Results of comparison of the EDS analysis on the drill flank surfaces after the completion of three groups of drilling tests.

achieved by the reduction of the cutting temperatures while on the other hand, heavier oxidation wear becomes pronounced. This phenomenon can be attributed to the air exchange occurring at the cutting zone during drilling *via* the help of the forced air-cooling system. The flowing air provides the cooling effects to the drilling process resulting in a lower tool wear rate while the air with oxygen will degrade the contact surface under high drilling temperatures. Thus, the discolored area signifying the chemical wear can be observed from the results of SEM depicted in Fig. 7.

In this work, tool wear was measured as the average flank wear land width (VB), as a function of number of drilled holes. The results are shown in Fig. 9. From this figure, it is clear that the tool wear processes undergo the initial, normal and rapid wear stages for all the test groups. In the initial wear stage, the interrupted contact between the cutting edge and the workpiece provides the drill bit with higher wear resistance under the vibration assisted drilling. Furthermore, the forced air-cooling provides not only the enhancement of the chip evacuation ability but also the cooling effects to the drilling processes which leads to a longer stable normal wear stage. As expected, the results confirm the feasibility of the vibration assisted drilling especially combined with the use of the forced air-cooling in reducing the extents of drill flank wear. The rising tendency of the flank wear indicates that the use of the vibration assisted drilling with forced air-cooling could effectively slow down the growth rate of the flank wear when proper cutting parameters are adopted.

4. Conclusions

In this paper, an integrated system of the LFVAD coupled with forced air-cooling was designed and applied to investigate the tool wear issue in drilling of CFRP/Ti6Al4V stacks using uncoated twist drills. The work concerns the effects of the LFVAD with the forced air-cooling on the tool wear process through the analysis of the drilling-induced temperatures and forces at the cutting zone. The flank wear was quantified to estimate the tool life with respect to different drilling methods. The results gained in the present work reveal some implicit mechanisms of the temperature and tool wear issues in the vibration assisted drilling. Based on this study, the following conclusions are

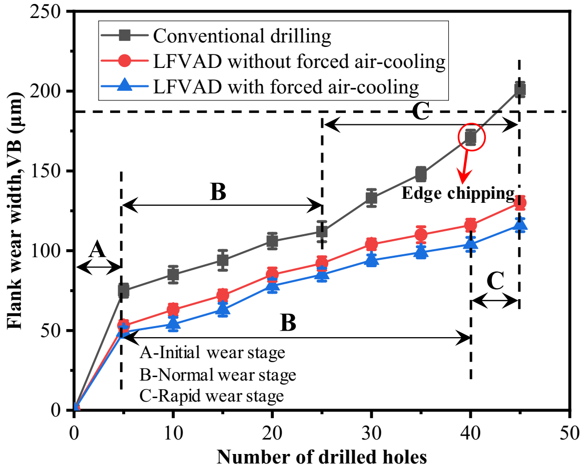

Fig. 9. Progression of the drill flank wear with the number of drilled holes under different test groups ($V = 20$ m/min, $f = 0.015$ mm/rev, $A = 0.20$ mm and $N_v = 1.5$ osc/rev).

drawn.

- Compared with the embedded thermocouples, there exists a time delay and overall reductions of temperatures measured by the infrared thermography camera. The use of the vibration assisted drilling brings a significant decrease to the drilling temperatures of about 47.9% while the dramatic temperature decrease of about 51.3% can be achieved *via* the help of the forced air-cooling at the feed rate of 0.015 mm/rev.
- The small chip segments produced by the periodical cutting of the LFVAD can be efficiently evacuated *via* the help of the forced air-cooling and better cooling effects can be achieved at the meanwhile. The forced air-cooling can lead to much lower thrust forces in drilling Ti6Al4V by the LFVAD while its effects on reducing the thrust forces of the CFRP phase are insignificant due to the dissimilar chip formation mechanisms of the two materials. The separated chips of the carbon/epoxy composite exist mainly in the form of dust while continuous spiral chips are the dominant chip type in the conventional drilling of Ti alloys.
- In contrast with the conventional drilling, the LFVAD with the forced air-cooling facilitates the decrease of the titanium adhesion and the flank wear on the drills and then prolongs the tool life. Furthermore, the oxidation wear becomes more pronounced due to the activated local air movement which indicates that the dominating wear mechanisms are changed.
- In sum, the LFVAD coupled with the forced air-cooling is confirmed capable of improving the machinability of CFRP/Ti6Al4V stacks from the aspect of reducing tool wear. However, to improve the chemical wear resistance, coated drills can be adopted to reduce the diffusion of chemical elements between the tool and the chips. Moreover, the coupling effects of the vibration frequency, feed rate and amplitude should be carefully considered.

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