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Wear behavior of special tools in the drilling of CFRP composite laminates

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Abstract: Mechanical drilling of carbon fiber reinforced polymers (CFRPs) has been notoriously difficult due to the high abrasiveness of reinforcing fibers and the anisotropic behavior of the constituents leading to poor hole quality and rapid tool wear. Special drill bits featured by novel geometrical designs have been proved as a promising alternative to conventional twist drills for the machining improvement of fibrous composites due to their capability to suppress delamination formation and ensure superior surface quality. The present work aims to address the wear characteristics of two types of special tools including a candlestick drill and a step drill when machining CFRPs. The novelty of the current work lies in identifying the underlying mechanisms controlling the wear development of the special tools and in quantifying their wear effects on the composite machining responses such as delamination extents, hole wall morphologies, and dimensional accuracy. Progressive abrasion wear is confirmed as the dominant wear pattern for both drills, while premature microchipping occurs for the step drill even after the tool makes only few composite holes. For both tools, the drill edge segments residing close to the tool periphery basically undergo the most severe abrasion wear due to the highest instantaneous cutting speed involved. The results discussed in this paper highlight the effectiveness of the functionally-designed tool geometries in improving the wear resistance of drill bits and emphasize the vital role of the tool wear in affecting the composite machinability.

***Keywords*:** CFRP composites; special drills; wear development; wear mechanisms; hole quality.

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1. Introduction

Carbon fiber reinforced polymers (CFRPs) are featured by excellent structural designability and superior mechanical/physical properties such as high specific strength, high specific modulus, excellent corrosion and fatigue resistance. Consequently, they have become rather attractive in diverse industrial fields, including aerospace, automobile, and robotics [1-4]. CFRP composites are a class of extremely strong and light-weight fiber-reinforced polymers based on carbon/graphite fibers consisting of two different phases, including the reinforcing fibers and the matrix base [5]. The roles of the reinforcing fibers are to offer the main properties of the composite material and to withstand the applied loads, while the matrix base aims to bind the reinforcements, transfer the loads and protect the fibers from damage [6, 7]. Due to the different mechanical/physical properties of the two main constituents, the CFRP composites exhibit anisotropic behavior and heterogeneous architecture. In particular, a fiber-orientation dependent behavior is noted for the machinability of the fibrous composites.

To meet the stringent requirements of successful industrial applications, CFRP composites have to be machined with desired dimensional accuracy and surface quality despite the near-net shapes gained by the preceding molding operations. Mechanical drilling is an essential machining process when assembling CFRP components [7-9]. Contrary to metallic materials in which elastoplastic deformation dominates the chip separation process, more complicated and interrelated mechanisms are involved in the machining of fibrous composites [1, 10]. The phenomena are due to the anisotropic machinability and inhomogeneous behavior of the fiber/matrix system resulting in the fiber-orientation-dependent cutting modes and defect formation mechanisms. Particularly in a drilling operation, the tool edge segments rotate periodically to attack the fibers and matrix alternately, leading to the uneven distribution of cutting loads and heat generation acting onto the tool edges during the material removal process. The highly abrasive reinforcing fibers then mechanically abrade and erode the sharpness of drill edges while the soft matrix rubs against the tool surfaces, resulting in the blunting and dulling of drill bits. Some authors have stated that the abrasion wear of tools encountered in the composites machining can be reflected in the form of edge rounding [11, 12]. Sakuma et al. [13] pointed out that the tool wear mechanisms in CFRP machining are the dislodging of hard tool particles from the tool surface, while Rawat and Attia [14] attributed the abrasive wear of WC drills to the results of both hard and soft abrasion modes when drilling woven CFRPs. In addition to the abrasion-related wear issues, the inherent heterogeneity and anisotropy of the CFRP composites are the key cause of critical quality problems associated with the drilling processes, such as interlaminar delamination, surface cavities, fiber pullouts, and splintering. According to previous investigations, interlaminar delamination is regarded as the most critical damage among defects induced by drilling as it is irreparable in nature and directly determines the final acceptance of the composite parts [1, 15, 16]. Therefore, the manufacturing community is facing enormous challenges when dealing with the drilling of CFRPs.

To overcome the technical difficulties associated with the composites drilling, an effective way is to develop special drill bits or select optimized cutting parameters capable of alleviating the wear progression and suppressing the hole damage formation. Drill geometries have been confirmed as a vital factor that significantly influences the tool performance and the final composite quality [9]. Through the literature survey, it is clear that there is an ongoing demand of special drills for the hole making of CFRP structures, which is attributed to the functionally-designed tool geometries or modified structures that favor the force reduction and delamination suppression. In such circumstances, various types of specially-designed tools such as dagger drills, step drills, saw drills, *etc*., have been developed and applied in the drilling of fibrous composites, and their cutting

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performances were thus thoroughly investigated. For instance, Sugita et al. [9] proposed a dedicated drill design for the suppression of burr and delamination formation when drilling CFRPs. The results indicated that the drill bits containing the novel geometries greatly shortened the process time and improved the composite hole accuracy. Grilo et al. [17] studied the influence of three special drills including the spur drills, twist drills, and four-flute drills when machining CFRPs and found that the spur drills produced the best results in terms of the delamination extent. Qiu et al. [18] addressed the impact of the chisel edge of step drills on the drilling-induced delamination for CFRPs. The authors highlighted the key role of the chisel edge in the delamination formation, particularly when the ratio of the drill primary diameter to the secondary diameter was higher than 0.75. Xu et al. [19] performed a detailed analysis of the effects of special drills on the cutting defects of multidirectional CFRP laminates. The results indicated that the brad spur drill yielded the best cutting performance to suppress the delamination formation due to the modification of the chisel edge zone. Additionally, Durão et al. [20] evaluated the performance of five different tool geometries, including two twist drills with different point angles, a brad drill, a dagger drill, and a step drill for the drilling of fibrous composites. The work showed that the twist drill having a 120°-point angle could be used to attain minimal delamination and the step drills could also be an alternative option. Heisel and Pfeifroth [21] emphasized the importance of selecting optimized drill point angles for the reduction of thrust forces and delamination damage when drilling CFRPs. In their work, four types of drill point angles were examined and the authors pointed out that an increase in the point angle tends to increase the delamination factor at the hole exit side. Feito et al. [22] studied the feasibility of step tools for the delamination-free drilling of woven CFRPs using both experimental and numerical methods. It was found that the step drills promoted lower thrust forces and less delamination damage than the conventional twist drills, particularly when lower feed rates were used. Moreover, some other authors revealed the benefits of using special drill geometries to decrease the thrust forces and to improve the composite hole quality [23-28]. The mechanisms behind the advantages of the functionally-designed drill geometries to achieve delamination-free machining lie in their ability to possess high critical thrust forces (CTFs) [15, 16, 29-31] that stand for a high safety threshold of drilling thrust for the hole making of composites. In general, great attempts have been made in the past few decades to develop special geometrical tools for the composite drilling, and this has been a promising research direction in the field of composites machining.

Despite the advances achieved in the performance assessment of special drills for CFRPs, most of the investigations are concerned with analyzing the tool effects on the composite drilling outputs such as thrust forces, delamination extents, and surface quality attributes. Very limited studies are reported so far to quantify the wear progression of special tools following the CFRP drilling. Moreover, the wear mechanisms acting onto the special tools have not been studied comprehensively for the composites machining. Therefore, the present paper aims to carry out a comparative study focusing on the wear characteristics of two types of special drills involving the candlestick drills and step drills for the CFRP drilling. The wear progression of drill edge segments was quantified and correlated with the hole number (HN). The novelty of the present study lies in identifying the underlying mechanisms controlling the wear development of the special tools and in quantifying their wear effects on the composite machining responses. A particular focus is placed on the quantification of the interlaminar delamination extents using the three-dimensional delamination factor. Moreover, both the digital microscope and scanning electron microscope (SEM) were utilized to identify the dominant tool wear modes governing the composites machining. The results discussed in this study offer a better understanding of the wear mechanisms of special tools and

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their peculiar impacts on the composite drilling responses.

2. Experimental procedures

2.1. Composite specimens and cutting tools

In this study, the composite specimens used are CFRP laminates fabricated by the high-strength T700 carbon fibers impregnated with the FRD-YZR-03 epoxy resin. The CFRP workpieces are rectangular plates having a total size of 300 mm (length)×200 mm (width)×6.60 mm (thickness), which are multidirectional laminates subjected to the layup of $[(0°/45°/-45°/90°)_4]_s$. Two types of special drills, including the candlestick drills and step drills, were adopted for the drilling operation. Both drills are uncoated carbide tools featured by an 8.0 mm diameter, a 30° helix angle, a 90° point angle, a 10-15° rake angle, and an 8° flank angle. The detailed morphologies of the candlestick and step drills are respectively shown in Figs.1 and 2. Note that the candlestick drill is characterized by three protruding tips, including one centering tip and two peripheral tips. The functionality of the candlestick drill lies in its cut-push coupling effects accompanied by the sharp flank cutting edges. In contrast, the step drill is designed on the basis of a step-control scheme, including a first step to create a pilot hole firstly and a secondary step to ream the hole surface to the final diameter. Moreover, the examined step drill is featured by a ratio of the primary diameter (7.8 mm) to the second diameter (8.0 mm) of 0.975, as shown schematically in Fig.3(a). The pilot hole is created by the cutting edges located at the first step of the drill. Then the initially-created hole is further reamed to a nominal diameter by the cutting edges between the first and the secondary steps as shown schematically in Fig.3(b). Note that the first drilling zone occupies most of the composites to be machined and only few fiber volumes are cut by the second drilling zone, which is beneficial to the generation of high-quality hole surfaces.

2.2. Drilling tests and post-process measurements

The drilling experiments were conducted on a DMU 70V CNC machine tool as shown in Fig.4. To compare the drill performance and wear behavior, all the drilling trials were carried out under a fixed cutting speed (V_c) of 120 m/min and a fixed feed rate (f) of 0.090 mm/rev. During the composites machining, the drilling forces were measured by the KISTLER dynamometer (type 9272) connected with a KISTLER amplifier (type 5070A) and a data acquisition system. After the drilling completion, the tool wear morphologies were examined by a high-precision KEYENCE VHX-500FE digital microscope and a TESCAN VEGA3 SEM. A previous method used in Ref. [32] was adopted to quantify the tool wear progression during the CFRP machining. Since the flank wear lands were unevenly distributed along the drill edges, the secondary drill edge of each tool was uniformly divided into nine points with identical spacing as shown schematically in Fig.5. Then the flank wear width (VB) of each divided edge point was measured via the KEYENCE VHX-500FE microscope, and the acquired data were plotted in an x-y orthogonal coordinate system where the x-axis denotes the relative distance to the starting point of the examined drill edge, and the y-axis signifies the flank wear width. Additionally, the drilling-induced delamination damage was also characterized by a KSI v-400E scanning acoustic microscope (SAM) and quantified using the three-dimensional delamination factor (F_v) proposed by Xu et al. [16]. Moreover, the morphologies of cut composite hole walls were examined using both the ZEISS confocal laser scanning microscope (CLSM) and the FEI SIRION200 SEM. Eventually, the average diameters at the hole entrance, middle, and exit sides together with the cylindricity errors were measured using a SOLEX EUA coordinate measuring machine (CMM) to figure out the tool effects on the composite hole dimensional accuracy.

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3. Results and discussion

3.1. Tool wear mechanisms and development

The worn drill flank surfaces were initially examined using the digital microscope after drilling a certain number of composite holes and the obtained results are shown in Fig.6. It is clear that both the candlestick and step drills appear to exhibit smooth surfaces at the worn flank zones, irrespective of the increased number of holes. Abrasion wear due to the high abrasiveness of the reinforcing fibers tends to dominate the flank wear lands, and no evidence of adhesion wear is found through the microscopic observations due to the brittle fracture mode leading to the powdery composite chip formation. Regarding the candlestick drill, signatures of abrasion marks onto the flank surfaces are clearly observed along its drill edges due to the abrasion/erosion effects resulting from the intensified tool interaction against the hard carbon fibers. In general, abrasion wear is confirmed as the dominant wear mode for both uncoated carbide drills. The findings are consistent with the observations of Rawat and Attia [14] and Iliescu et al. [33] when drilling CFRP laminates. It is worth noting that the number of drilled holes has a significant impact on the development of drill wear. When the hole number (HN) increases from 5 to 15, an expansion of the drill flank wear land is identified according to Fig.6(c). Additionally, one of the candlestick drills seems to undergo a certain degree of edge chipping apart from the commonly-observed abrasion wear as depicted in Fig.6(d)-(f). The premature chipping failure occurs probably after the tool creates the 5th composite hole. Note that the chipped edge zone is very close to the tool peripheral region which is mainly caused due to the highest instantaneous cutting speed involved. However, microchipping seems not to occur at the two other candlestick drills. Therefore, it can be deduced that microchipping is not a common wear mechanism when machining CFRPs utilizing candlestick drills under the experimental conditions in the present paper.

To quantify the severity and progression of the drill flank wear following the CFRPs machining, the secondary drill edge of each tool was divided into nine segments (points) as detailed in Fig.5. Tables 1 and 2 summarize the correlations between the selected edge points and their relative distance to the starting point as well as the corresponding instantaneous cutting speed. The flank wear width of each selected edge point was then measured and correlated with the number of drilled CFRP holes. The obtained results are given in Fig.7. It is clear that an increase in the hole number tends to raise the flank wear width regardless of the used drills or the selected drill edge points. For instance, when drilling from the 1st hole to the 15th hole, the VB value of the No.1 edge point for the candlestick drill approximately increases by 181.75%, while for the step drill, the VB value of the No.1 edge point probably rises by 275.87% as the HN increases to 15. The phenomenon is due to the cumulative effects of abrasion wear exerted onto the tool flank surfaces as the drills consecutively cut the CFRP workpiece. Moreover, the quantitative analysis indicates that the drill flank surface shows an uneven distribution of wear signatures, which is evidenced by the different values of the flank wear widths for each edge point selected, (Ref. Fig.7). For both tools, the edge points residing far away from the inner drill center basically experience the largest extent of abrasion wear. This is due to the highest instantaneous cutting speed involved for the edge points leaving far away from the inner drill center. Moreover, the selected edge points of the step tool basically undergo a faster wear progression than those of the candlestick tool, as depicted in Fig.7. This is due to the fact that the candlestick structure combines the cutting and pushing effects of the sharp flank cutting edges that slow down the wear progression along the secondary drill edges. Normally, the cutting edges of both drills generate more cutting effects in the rotary motion and

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make more pushing effects in the feed movement. The cutting edges having larger angles than 0° with respect to the CFRP surface often contributes to the pushing effects in the feed movement. Note that the major cutting edge of the candlestick drill forms an angle about 45° to the specimen surface. Additionally, the secondary cutting edge of the candlestick drill is nearly perpendicular to the feed direction, which favors the cutting effects and reduces the wear progression generated in the feed movement. As a result, the candlestick structure slows down the wear progression along the secondary cutting edges. Note that each major cutting edge and each secondary cutting edge of the step drill forms an angle larger than 40° to the laminate surface. Therefore, the secondary cutting edge of the step drill generates more pushing effects than that of candlestick drill. Consequently, the step drill undergoes a faster wear progression.

The SEM morphologies of the worn drill surfaces for the candlestick and step tools after creating 15 holes are shown in Figs.8 and 9, respectively. The results indicate that the candlestick drill basically undergoes a minor degree of abrasion wear along its cutting edges. Some marks of debris adhesion are also identified onto the drill flank surface, being the powdery chips separated from the composite workpiece. More severe abrasion wear is noted at the tool corner zone due to the highest instantaneous cutting speed involved. In contrast, the step drills are found to undergo more serious abrasion wear when drilling the CFRP composites. For both tools, the abrasive wear surfaces are featured by the smoothly blunt and rounding zone close to the drill cutting edges. This is due to the high abrasiveness of the carbon fibers that dominates the tool-work interaction during the composite chip separation, leading to the dulling and rounding of the cutting-edge zones. Additionally, the step drill seems to undergo a large area of edge fracture within the corner zone, as shown in Fig.9. The phenomenon is due to the highest cutting speed involved in the corner zone. In sum, the candlestick drills are confirmed to exhibit higher resistance to abrasion wear and chipping failure than the step drills when drilling the CFRP composites.

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3.2. Tool wear effects on the delamination damage, hole morphologies, and dimensional accuracy

Delamination has been widely recognized as the most critical damage in drilling composite laminates as it is irreparable and accounts for a large proportion of composite part rejections in industries [34, 35]. The drilling-induced delamination is firmly associated with two types of mechanisms, including the peel-up mode and the push-out mode [16]. The push-out delamination occurring at the hole exit side is often more severe than the peel-up one [3, 36-38]. Therefore, the present work concerns only the push-out delamination damage during the CFRP drilling. Figs.10 and 11 show the SAM morphologies of the push-out delamination damage induced by the candlestick drill and the step drill after creating 15 holes, respectively. Due to the resolution limit of the SAM equipment, only six exit plies are clearly scanned. It is found that the push-out delamination initially occurs inside the interlaminar plies of the carbon fibers and then propagates rapidly toward the hole exit side following the tool advancement. The observation confirms the internal characteristics of the drilling-induced delamination for CFRP composites. Moreover, it can be seen from Figs.10 and 11 that the delaminated area along the hole circumference increases from the 6th fiber ply to the 1st fiber ply. The phenomenon is due to the decrease of the local strength of the composite laminae with the reduced number of uncut fiber plies as the drill edges start to penetrate the exit hole side.

To quantify the tool wear effects on the severity of the push-out delamination, the three-dimensional delamination factor of each drilled hole was calculated. The obtained results were then plotted in terms of the tool wear effects (*i.e.*, the HN) as shown in Fig.12(a). The results indicate that increasing the hole number tends to elevate the delamination factor irrespective of the used drills. The phenomenon is attributed to the increased drilling thrust forces as the HN increases, which is shown in Fig.12(b). Additionally, since the step drill produces much lower levels of drilling thrust forces (Ref. Fig.12(b)), it induces a relatively lower value of the push-out delamination factor than the candlestick drill, as evidenced in Fig.12(a). The results confirm the superiority of the step drill in minimizing the delamination extents when drilling the CFRP composite laminates.

Moreover, Figs.13 and 14 show the different tool effects on the machined hole morphologies for CFRP composites. The results indicate that the cut composite hole walls are constituted by alternating smooth surfaces and fiber cavities regardless of the used drill bits. The phenomena are attributed to the anisotropic behavior of the composite laminate that shows a high dependence on the fiber orientation while machining. It is worth noting that the finely-cut composite surfaces are often formed by the fiber plies having acute fiber orientations due to the dominance of the forward fiber cutting relations of mechanical interactions between the drill edges and the fiber/matrix system. In contrast, the poorly-cut composite surfaces featured by quantities of cavities at the obtuse fiber plies are mainly produced by the against fiber cutting relations that are associated with the buckling and interlaminar cracking of the fiber/matrix system resulting in the poor chip removal process. Through the CLSM and SEM examinations, the step drills promote relatively better composite hole morphologies than the candlestick ones. The phenomenon is due to the functionality of the specially-designed tool structure involving two steps of procedures dedicated to the hole-making process. Firstly, the composite is drilled to create a pilot hole by the first step edges, and then the pilot hole is reamed to the final hole dimensions by the second step edges along with the effects of smoothening the hole wall. In contrast, the candlestick drills show an inability to guarantee better composite holes than the step drills. Additionally, similar hole damage modes involving the surface cavities due to the loss of matrix, adhering debris, and fiber fractures are observed for the two types of drills.

Moreover, the tool wear effects (*i.e.*, the HN) on the average hole diameters and cylindricity errors are shown in Fig.15. It is clear that increasing the hole number (*i.e.*, the tool wear extent) tends to reduce the average diameters of the composite holes for both drills examined, as depicted in Fig.15(a). The phenomenon is due to the decrease of the sharpness of the drill edges that results in the poor cut of the fiber/matrix system. Additionally, the exit diameters appear to be closer to the nominal hole diameter than the entrance and middle ones. The step drills are found to promote more consistent hole diameters being closer to the nominal drill diameter as shown in Fig.15(a). With regard to the cylindricity errors of cut composite holes, the hole number (*i.e.*, the tool wear extent) seems to have a positive impact on the increase of the average cylindricity errors, which is due to the blunting of the drill edge that fails to achieve the precision cutting of fibers. Finally, the step drills are found to produce lower values of cylindricity errors than the candlestick drills as shown in Fig.15(b), which is due to the reaming effects of the secondary step edges that guarantee a higher cutting precision of composites.

4. Conclusions

In this paper, a comparative study on the wear behavior of two types of special drills was conducted for the drilling of CFRP composites. The wear progression of candlestick and step drills was analyzed by quantifying the wear development of their drill edge segments with the hole number. The tool wear effects on the composite drilling responses were discussed. Based on the results acquired, the following conclusions can be drawn.

- Progressive abrasion is confirmed as the dominant wear mechanism controlling the flank wear

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of both tools examined. The candlestick drills are found to exhibit higher resistance to abrasion wear and premature tool failures than the step drills. The step drill undergoes microchipping even after drilling only few CFRP holes.

- Additionally, the drill flank surfaces experience different levels of abrasion wear due to the different instantaneous cutting speeds involved. Normally, the drill edge segments residing close to the tool periphery undergo the most severe wear because of the highest instantaneous cutting speed involved.
- The tool wear (*i.e.*, the HN) has a significant impact on the development of the drilling-induced delamination for both drills used. The step drill is identified to promote 6.46-26.90% lower delamination factors than the candlestick one due to its functionally-designed tool structures benefitting the reduction of drilling thrust forces.
- Similar hole damage modes including surface cavities, adhering debris, and fiber fractures are observed for the two types of drills when drilling the CFRP laminates. The step drills are found to produce much better composite hole walls, more consistent hole diameters, and 9.84-14.34% lower values of cylindricity errors than the candlestick ones owing to the reaming effects of the secondary step edges that guarantee a higher cutting precision of composites.

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Figures

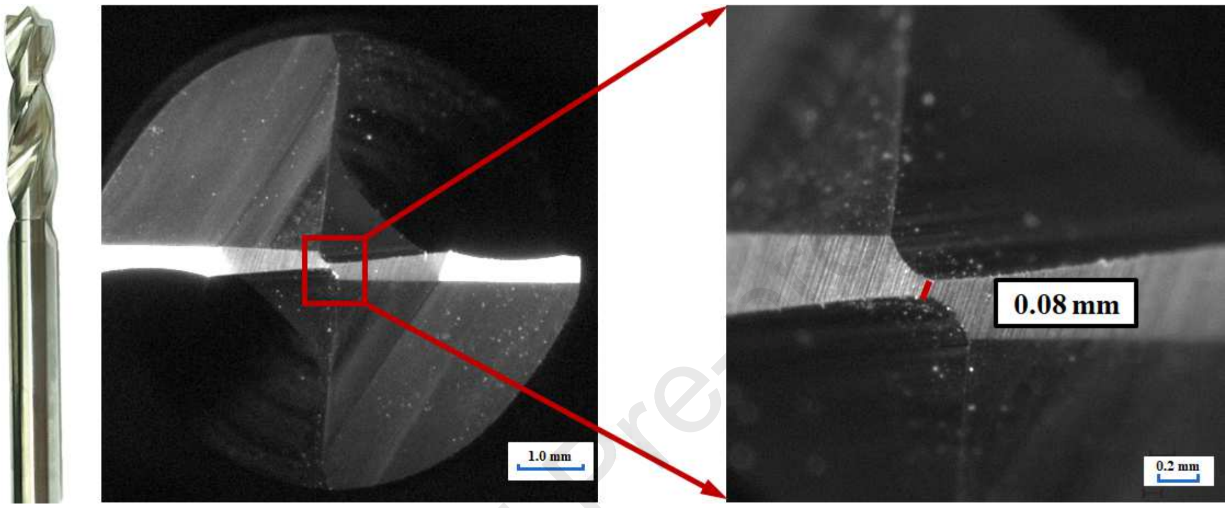

Fig.1. The morphologies of the uncoated candlestick drill before cutting.

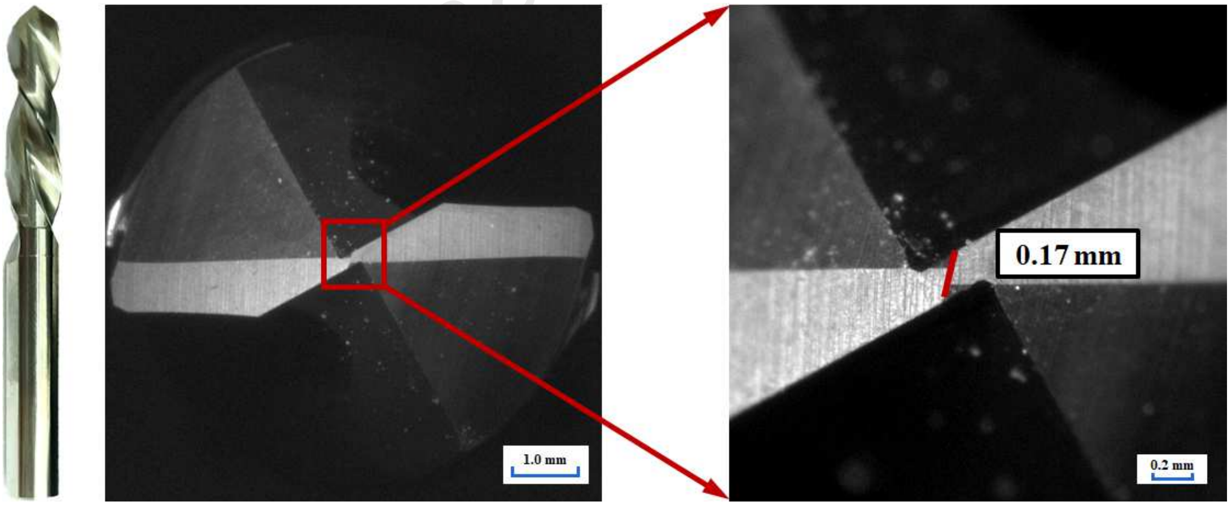

Fig.2. The morphologies of the uncoated step drill before cutting.

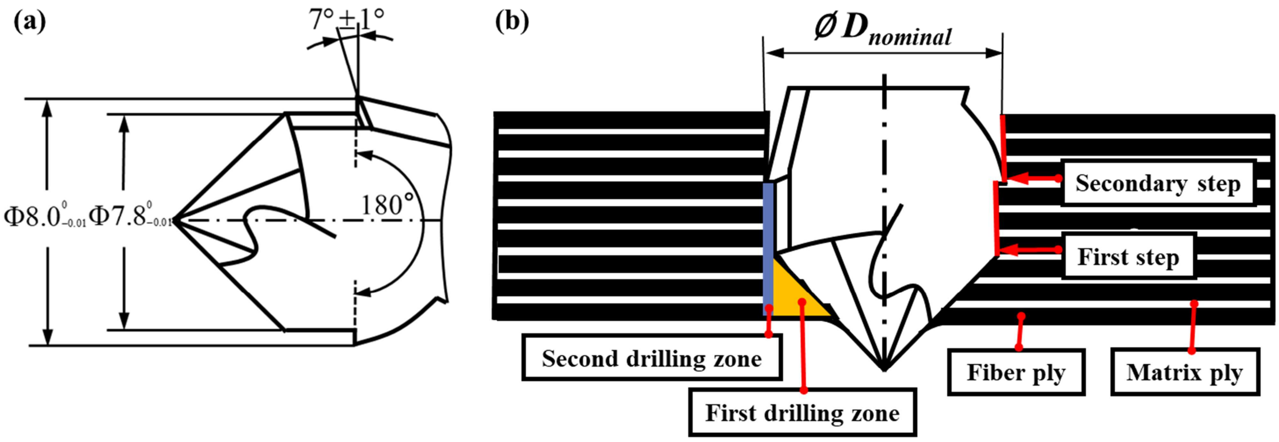

Fig.3. (a) The geometrical features and (b) the schematic drill-composite contact conditions for the step drill.

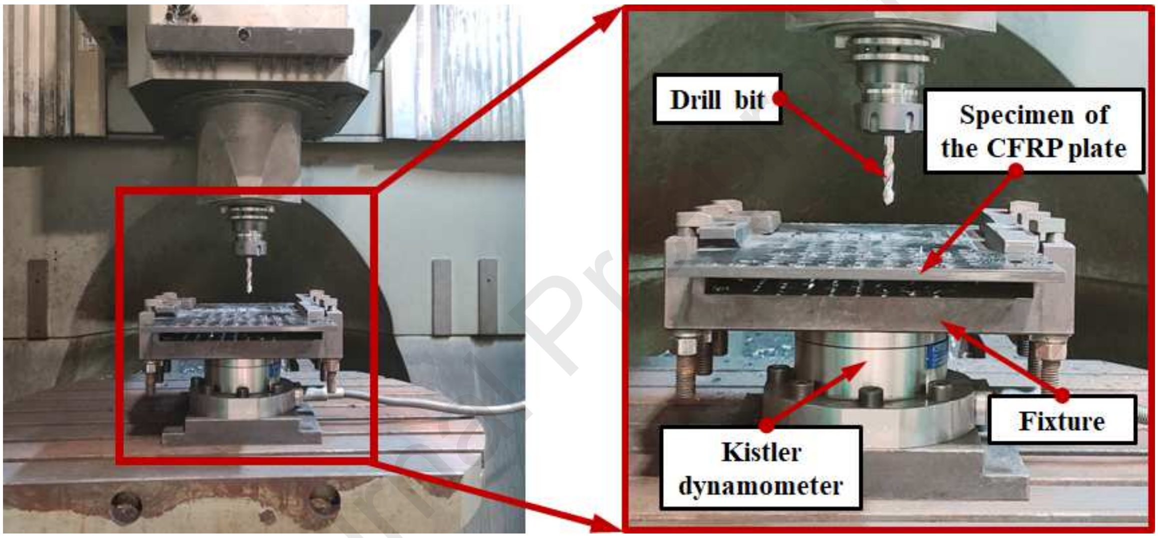

Fig.4. Experimental setup for the drilling of CFRP laminates.

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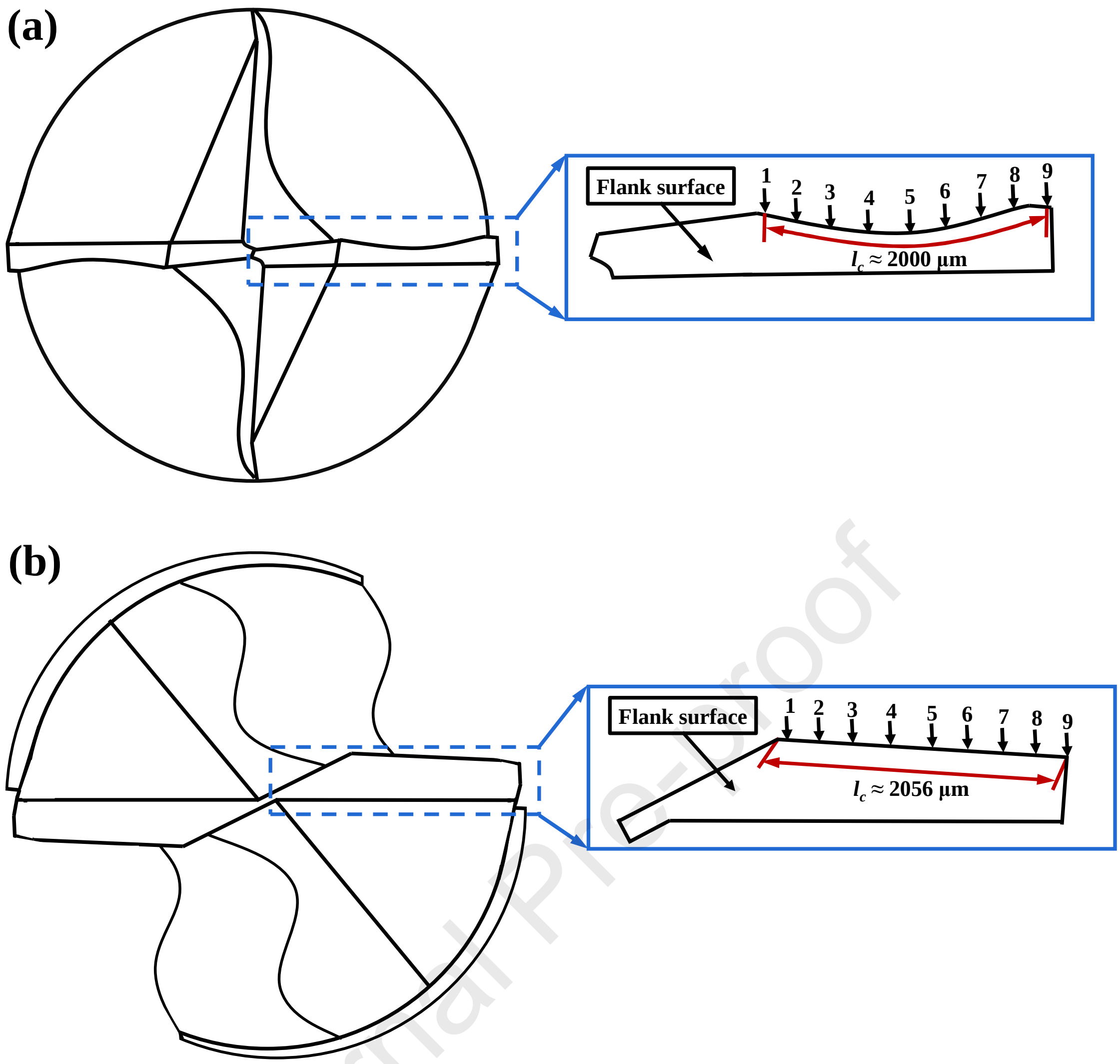

Fig.5. Schematic illustration of division of the drill secondary edges: (a) candlestick drill and (b) step drill.

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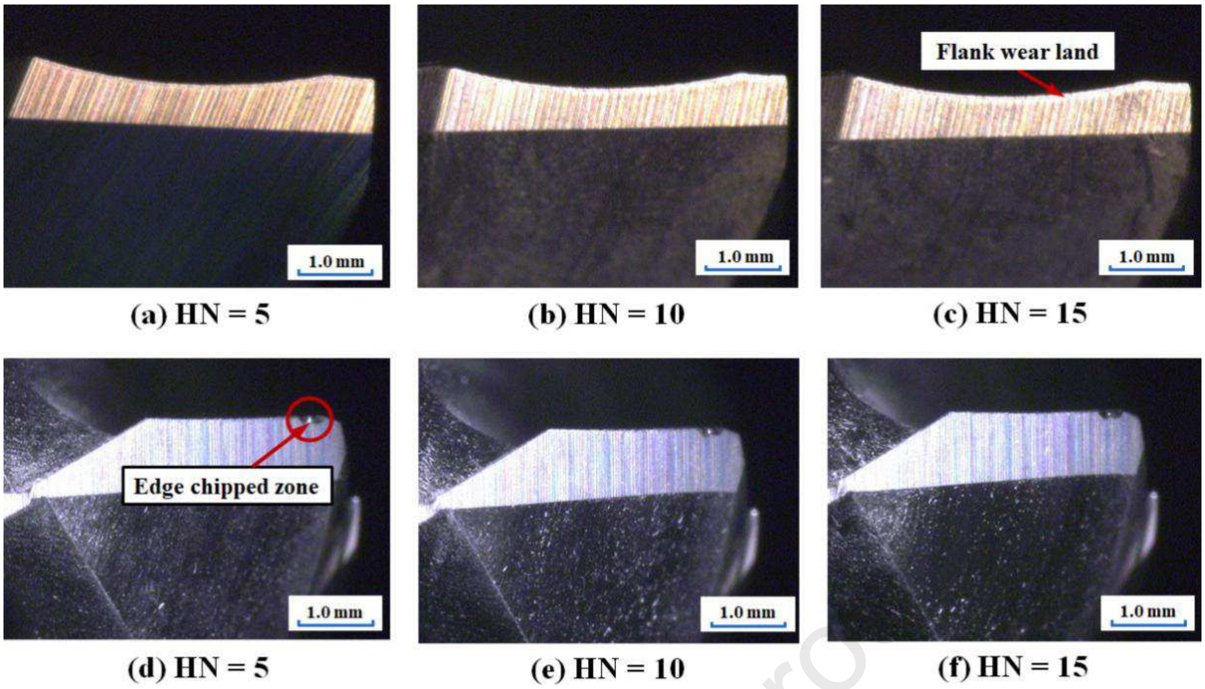

(a) HN = 5 (b) HN = 10 (c) HN = 15

(d) HN = 5 (e) HN = 10 (f) HN = 15

Fig.6. Microscopic morphologies of the worn drill flank surfaces: (a)-(c) candlestick drills and (d)-(f) step drills.

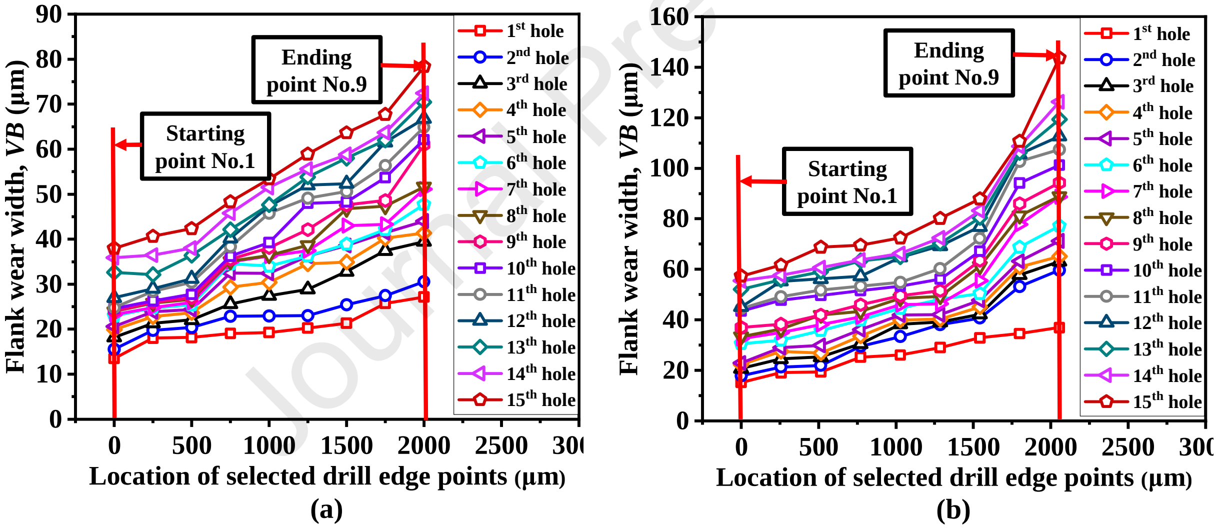

Fig.7. Progression of the flank wear width (VB) of selected drill edge points during the drilling of CFRPs with the HN: (a) the candlestick drill and (b) the step drill.

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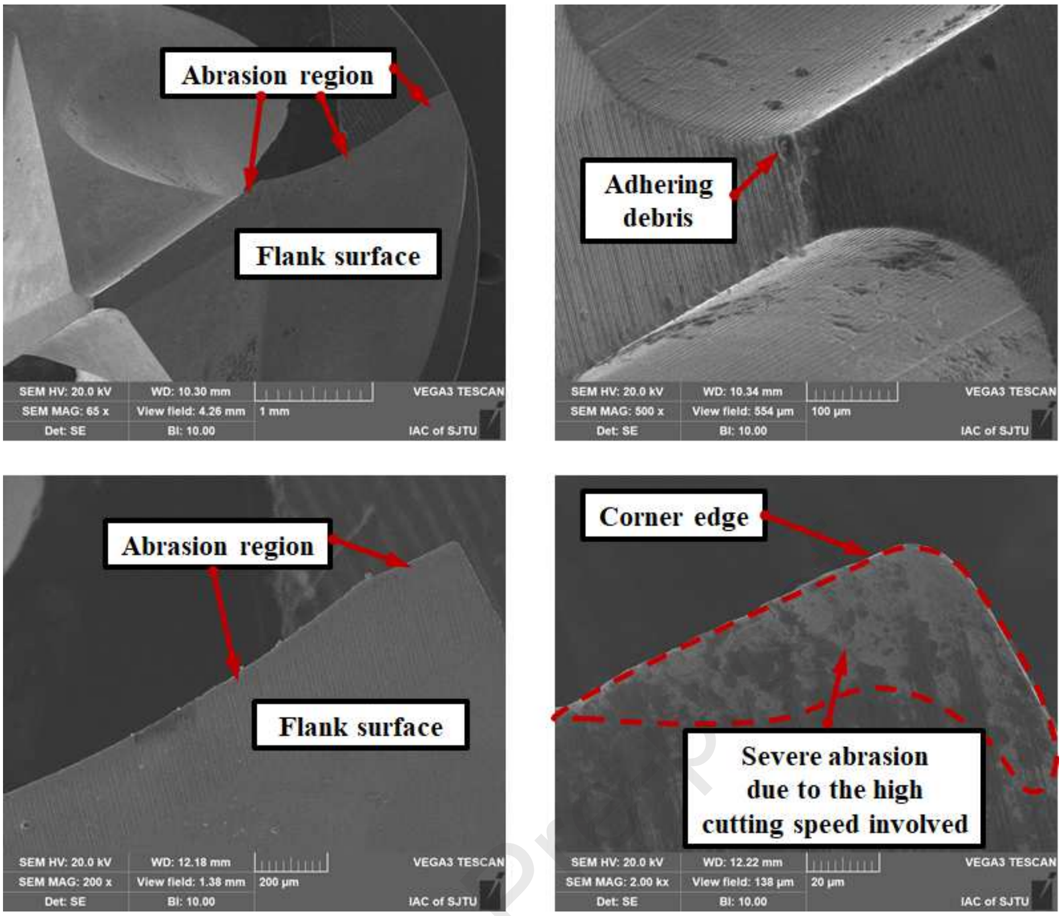

Fig.8. SEM morphologies of the worn candlestick drill after making 15 CFRP holes.

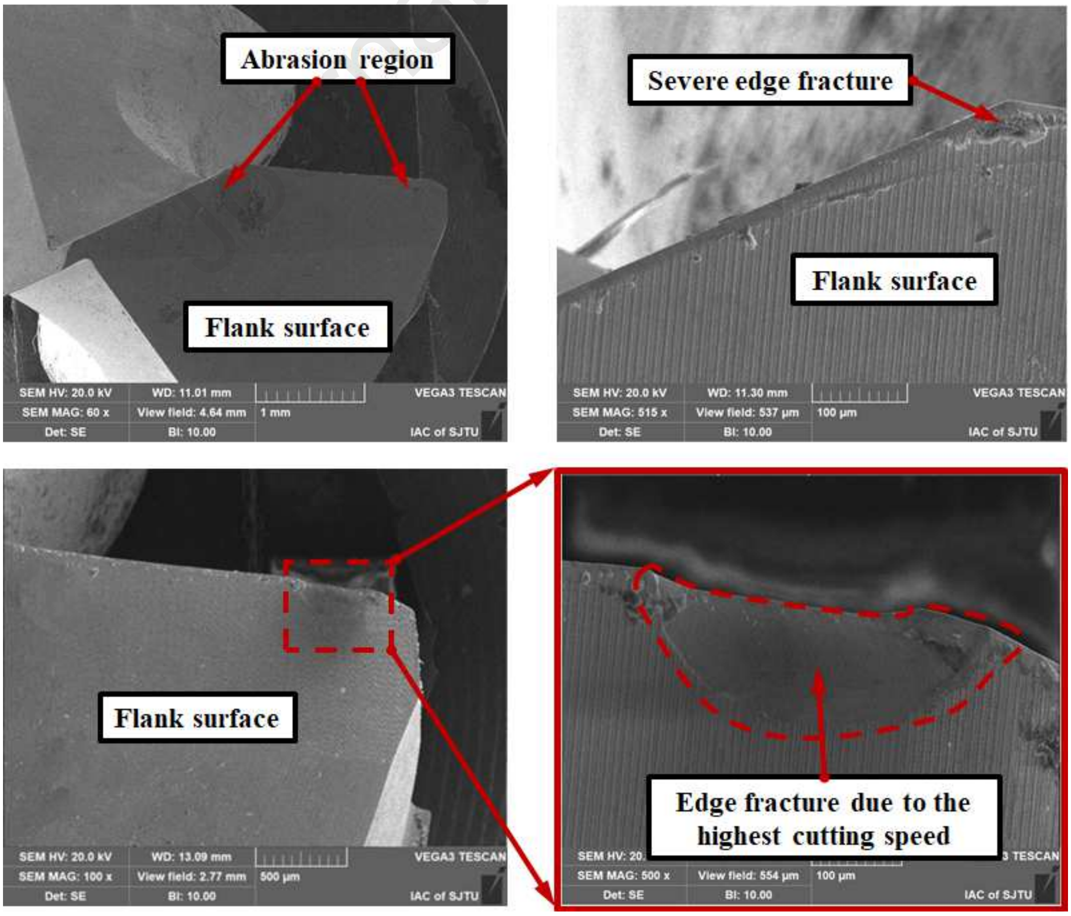

Fig.9. SEM morphologies of the worn step drill after making 15 CFRP holes.

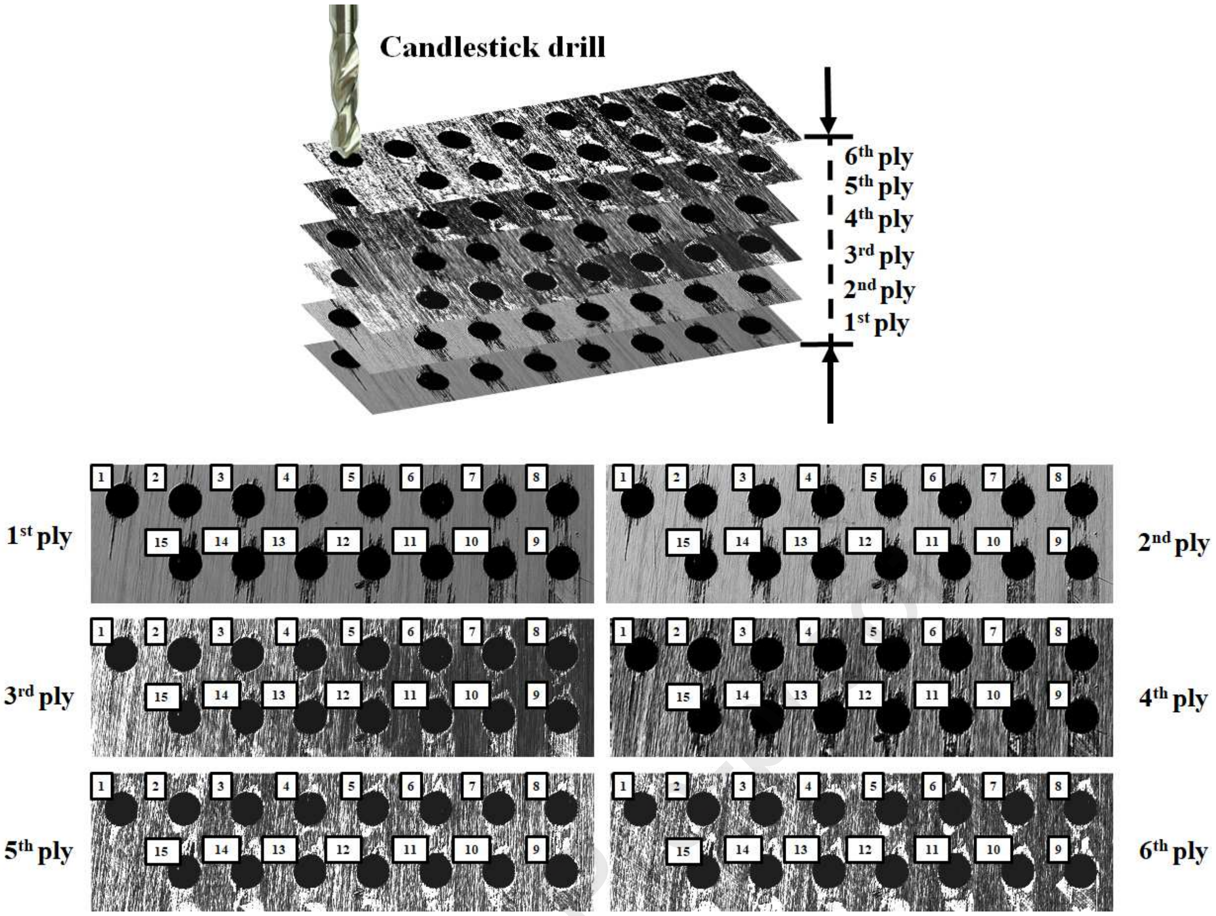

Fig.10. SAM scanned morphologies of the push-out delamination damage induced by the candlestick drill (HN = 15).

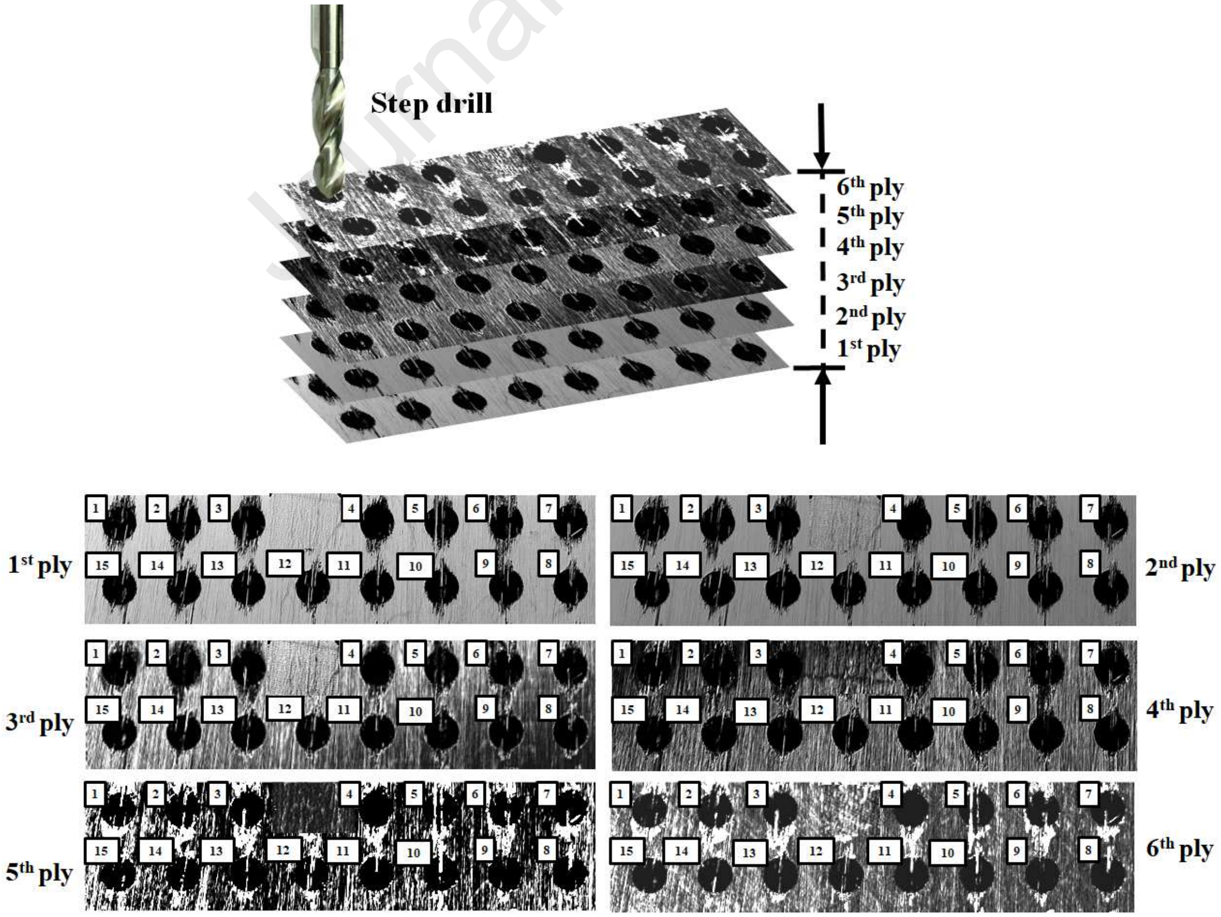

Fig.11. SAM scanned morphologies of the push-out delamination damage induced by the step drill (HN = 15).

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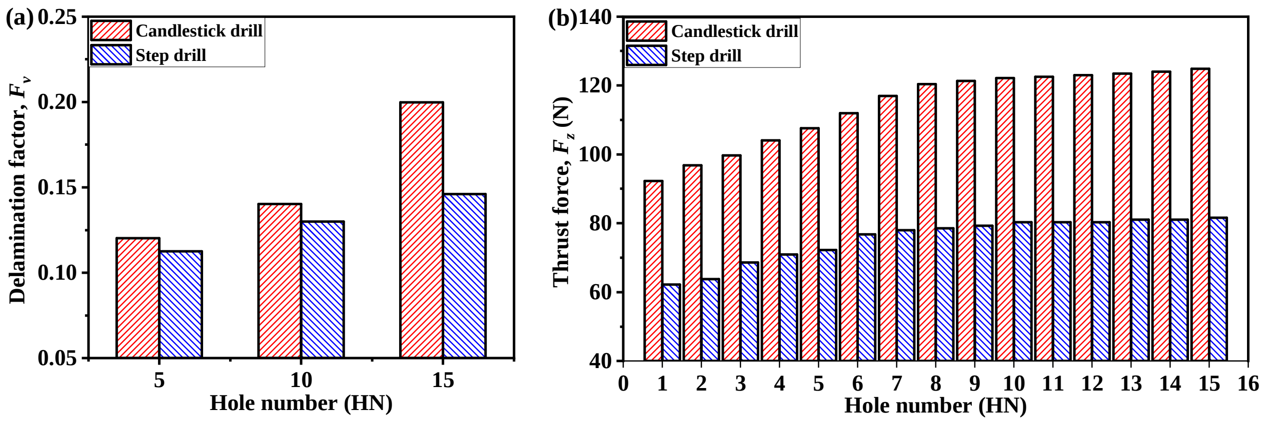

Fig.12. Effects of the tool wear progression (*i.e.*, the HN) on (a) the push-out delamination and (b) the thrust forces.

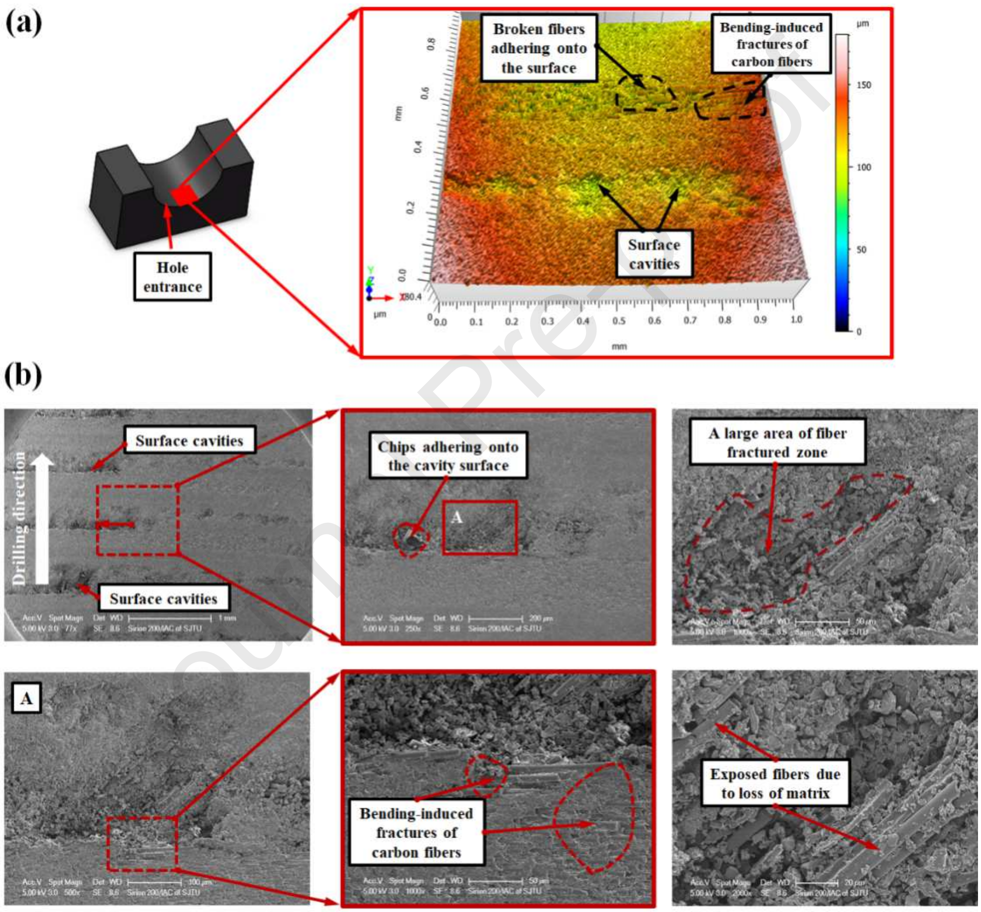

Fig.13. (a) CLSM and (b) SEM morphologies of the 15th composite hole machined by the candlestick drill.

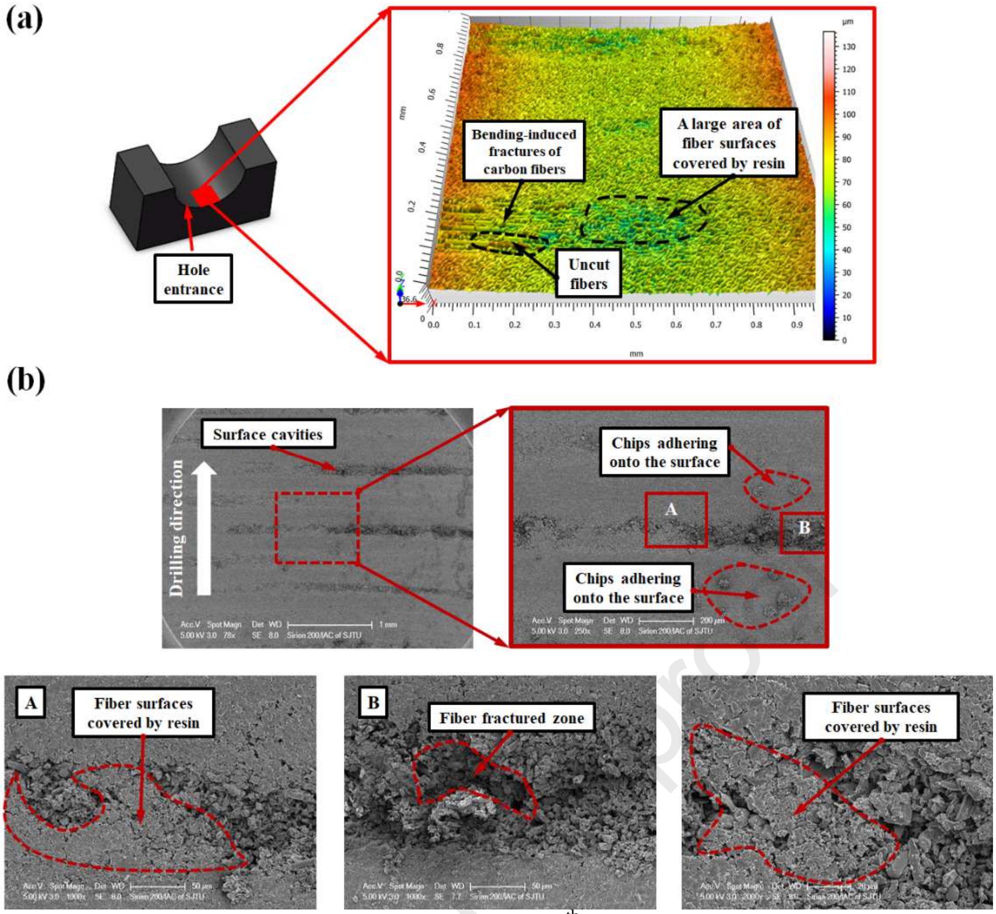

Fig.14. (a) CLSM and (b) SEM morphologies of the 15th composite hole machined by the step drill.

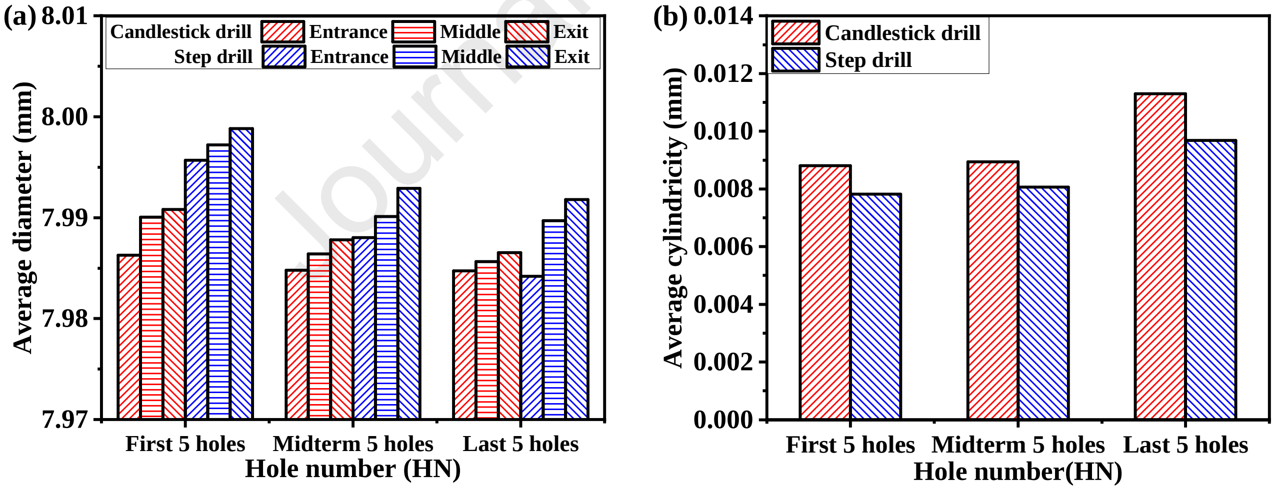

Fig.15. Effects of the tool wear progression (*i.e.*, the HN) on (a) the hole diameters and (b) the cylindricity errors.

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Tables

Table 1. Correlations between the selected candlestick drill edge points and the instantaneous cutting speed.

Point No.	1	2	3	4	5	6	7	8	9
Relative distance to the starting point of the secondary drill edge (μm)	0	250	500	7520	1000	1250	1500	1750	2000
Instantaneous cutting speed (m/min)	57.0	64.5	72.0	79.5	87.0	94.5	102.0	109.5	117.0

Table 2. Correlations between the selected step drill edge points and the instantaneous cutting speed.

Point No.	1	2	3	4	5	6	7	8	9
Relative distance to the starting point of the secondary drill edge (μm)	0	257	514	771	1028	1285	1542	1799	2056
Instantaneous cutting speed (m/min)	49.5	57.3	65.1	72.9	80.8	88.6	96.4	104.2	112.0

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Highlights

- The wear mechanisms and progression of special drills were quantified when drilling the high-strength CFRP laminates.
- The tool wear effects on the drilling responses of CFRPs such as delamination extents, hole morphologies and dimensional accuracy were investigated.
- Progressive abrasion is confirmed as the dominant wear mechanism controlling the flank wear for both the candlestick and step drills.
- The drill flank surfaces experience different levels of abrasion wear due to the different instantaneous cutting speeds involved.
- The candlestick drills exhibit much higher resistance to abrasion wear and chipping failure than the step drills.

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