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ORIGINAL ARTICLE

# Effects of cooling position on tool wear reduction of secondary cutting edge corner of one-shot drill bit in drilling CFRP

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**Abstract** Drilled hole surface quality of carbon fiber reinforced polymer (CFRP) deteriorates quickly with rapid tool wear, which ultimately influences service performance of CFRP parts. For one-shot drill bit, it is the secondary cutting edge, especially its end part close to tertiary cutting edges (secondary cutting edge corner) that mainly determines drilled hole surface quality. In order to effectively reduce tool wear of the secondary cutting edge corner, minimum quantity lubrication (MQL) coolants are applied and delivered to the desired location on secondary cutting edges. And coolant supply outlets of the drill bits are specially designed at two different locations at the secondary cutting edges of separate drill bits to verify the effects of cooling position on tool wear reduction of secondary cutting edge corner. The results show that delivering MQL mist out from the end of secondary cutting edges contributes to better wear reduction than that from the front of secondary cutting edges. In addition, by compared with dry drilling, the effects of cooling supply position on tool wear reduction of desired secondary cutting edge corners are further validated. Holes drilled by the drill bit ejecting MQL mists from the end of secondary cutting edges also exhibit superior quality. The results are valuable for further research on drill bit design and process development in drilling CFRP.

**Keywords** Tool wear reduction · Secondary cutting edge corner · Drilled hole surface quality · Minimum quantity lubrication (MQL) · Location of MQL supply outlet

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## 1 Introduction

Carbon fiber reinforced polymer (CFRP) has been widely adopted to manufacture key load-bearing aeronautical parts such as center wing boxes and fuselages in the field of large airplanes due to its light weight, high strength, high resistance to corrosion, etc. [1–7]. And a large amount of bolt and rivet connections are necessary for assembling the CFRP structural parts [8]. For example, as many as 55,000 holes are generally required to be drilled in a complete single unit production of the Airbus A350 aircraft that has a high usage share of CFRP [9]. Therefore, the hole-drilling process is common in the manufacturing of CFRP parts, which is also of great importance because drilled hole quality has a direct impact on the assembly quality and the service life of final products [10].

There are many challenges in drilling CFRP parts on account of the fact that the highly abrasive carbon fiber reinforcement can cause rapid tool wear [11–13]. The rapid tool wear will induce the increase of thrust force that enlarges possibilities of delaminations [10, 14], which can cause severe risks for the CFRP parts [15–18]. Also severe tool wear deteriorates hole surface qualities by generating uncut fibers, fiber pullouts on drilled hole surface, etc. [19–22]. Despite delaminations at hole entry and hole exit, defects on drilled hole surface not only affect the assembly quality as well as initiation and propagation of fatigue cracks, but also have impacts on connection strength and fatigue life of airplane structural parts under dynamic loadings. Thus, drilled hole surface quality is crucial for the service performance of CFRP parts.

Currently, multi-edge and multi-facet drill bits such as one-shot drill bits are commonly applied for drilling CFRP parts [10, 23] to effectively reduce thrust force and improve drilled hole quality. The drilling process of the one-shot drill bit consists of several functional drilling stages [24]. The primary cutting edges perform pre-drilling and the primary cutting edge's

**Table 1** Mechanical properties of the T800 prepreg

| Density/ ($g/cm^3$) | Longitudinal young's modulus/GPa | Longitudinal shear modulus/GPa | Transverse poisson's ratio | Tensile strength/ MPa | Compressive strength/MPa |
|---|---|---|---|---|---|
| 2.7 | 160 | 6.21 | 0.36 | 2843 | 1553 |

diameter is relatively small compared to the nominal diameter of the whole drill bit. Thus, the primary cutting edges are less possible to affect the quality of drilled hole surface. However, in the counterboring and reaming process by the secondary cutting edges, the defects induced by chisel edge and primary cutting edges can be effectively removed [25, 26]. The tertiary cutting edges mainly perform smoothing and chip evacuation and do not contribute to cutting off fiber reinforcement. Therefore, for such type of drill bit, it is the secondary cutting edge that determines the hole dimensional and surface quality. And it is especially true for the end part of the secondary cutting edge close to tertiary cutting edge, which is also known as secondary cutting edge corner. As reported in previous study [27], with the wear aggravation of the secondary cutting edge corners, the cutting capability of the secondary cutting edges deteriorates quickly leading to uncut fibers at drilled hole surface. And the tool wear also subsequently induces severe denting, fiber pullouts, matrix cracks, etc. Therefore, it is necessary to reduce tool wear on the desired secondary cutting edge corners in order to improve drilled hole surface quality.

According to literature, many researchers applied coolant and lubrication during machining of difficult-to-cut material in order to reduce tool wear [28]. In the research of machining CFRP, there is a rising trend to incorporate cryogenic machining method. [29] applied chilled air to the milling tool by a vortex tube and tool wear was found less compared to that without the coolant under high feed rate and cutting speed. [30] delivered liquid nitrogen internally through the coolant holes of the drill bit in drilling CFRP. And the results demonstrated that cryogenic cooling had profound effects on reducing the cutting edge rounding of the drill bit's cutting edges. In addition, minimum quantity lubrication (MQL) is an emerging technology that has technological, economical, and environmental benefits in high-speed machining of composites. Generally speaking, flood cooling may have negative effects on shear fracture toughness of CFRP because of moisture absorption by the composite material. MQL was evaluated to be a viable alternative of flood cooling. The cutting fluid of MQL is usually lubricant oil or mixture of water and lubricant oil, and the cutting flood is disintegrated into small droplets (coolant mist) when the aerodynamic and surface shear external forces exceed surface tension forces under high spraying pressure. Small droplets have a large surface area-to-volume ratio, thus have increased heat transfer through rapid vaporization. Therefore, water that has low boiling point and high latent heat of vaporization is mixed with small amount of oil, which acts as the lubricant [31]. [31] carried out investigations on MQL parameter optimization. Compared to flood, pressurized air, and dry machining, MQL was proved to be more effective in minimizing tool wear and improving hole surface quality if optimized. Several studies also reported positive effects of MQL on tool wear reduction in drilling CFRP/metal stacks [32, 33].

With the fact that tool geometrical structures have become more and more complex in drilling CFRP, the wear characteristics along various cutting edges are different. Correspondingly, damages induced by different types of wear along various cutting edges are not identical. And for one-shot drill bit as mentioned above, the wear of secondary cutting edge corner has direct impacts on drilled hole surface quality. However, in current researches on tool wear reduction in drilling CFRP, there have not been any reports that mainly focus


**Fig. 1** One-shot drill bits with different MQL supply outlet positions (a) #1 drill bit, MQL outlets located at the front of the secondary cutting edges, (b) #2 drill bit, MQL outlets located at the end of the secondary cutting edges

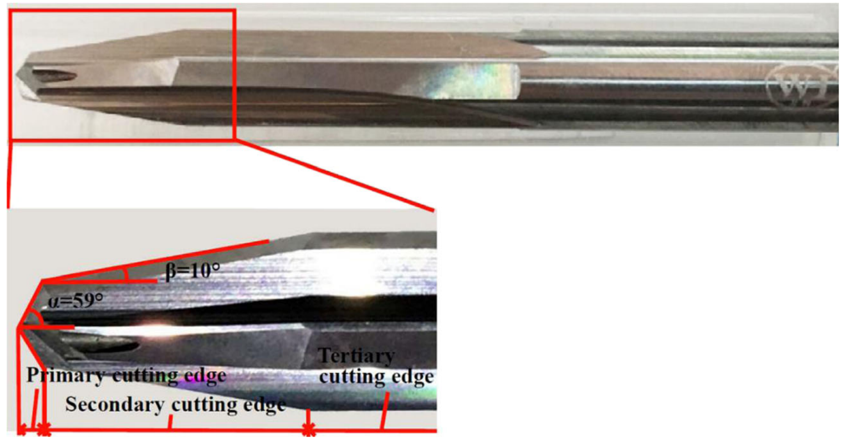



**Fig. 2** Geometrical parameters of the one-shot drill bit in the experiment

on reducing tool wear at specific positions of cutting edges to improve drilled hole quality.

This work carries out an investigation on tool wear reduction of secondary cutting edge corners of one-shot drill bit in drilling CFRP. In order to effectively reduce tool wear of the specific position of secondary cutting edges, MQL is applied as cooling and lubricating method, and MQL supply outlets of the drill bits are specially designed at two different locations at the secondary cutting edges of separate drill bits. MQL is delivered internally via coolant holes of the drill bits and ejected out from the supply outlets of the secondary cutting edges. The effects of cooling and lubricating position on tool wear reduction of desired secondary cutting edge corners are systematically studied. What's more, drilled hole surface qualities such as defects and surface roughness are measured and discussed.

## 2 Tool wear mechanism in drilling CFRP

The chip formation mechanisms in drilling CFRP are different than that in drilling metal materials. The cutting process of CFRP is entirely based on fracture, as opposed to shearing phenomenon of metals due to the presence of the fibers that impair uniform plastic deformation [13]. Mainly due to abrasive carbon fibers, the dominant wear mechanism of tungsten carbide drill bit in drilling CFRP is abrasive wear [1–6]. The abrasive carbon fibers directly scratch the cutting edge, and WC grains of the tool substrate could fall away because of brittle fractures under cyclic loadings. What's more, the abrasive carbon fibers damages the Co binder of the tool substrate as well leading to acceleration of tool wear. However, by applying MQL in the drilling process, if the coolant mist can be directed ejected to the desired cutting zone by high pressure, the friction between the contact of tool edge and workpiece can be largely improved and a thin protecting film can be generated [34] to help smooth scratching effects of carbon fibers.

For the one-shot drill bit, because of its unique geometrical structure, the defects induced by chisel edge and primary cutting edges can be effectively removed in the counterboring and reaming process by the secondary cutting edges. And it is the end part of secondary cutting edges (secondary cutting edge corner) that finally removes hole surface material and reams the holes close to the nominal diameter. Therefore, the secondary cutting edges, especially secondary cutting edge

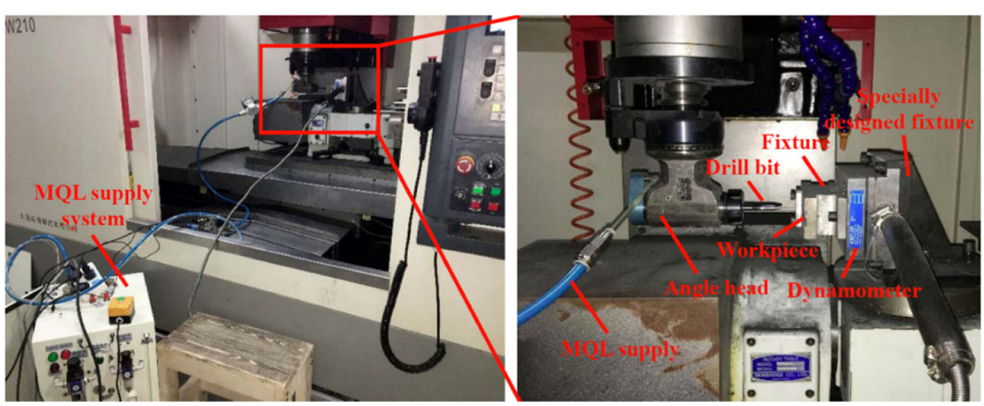



**Fig. 3** Experimental setup

corners, actually determine dimensional and surface quality of drilled holes. The rapid tool wear of secondary cutting edge corners can induce severe drilled hole surface defects [27].

In current tool wear researches in drilling CFRP, there lacks studies on how to reduce tool wear on specific positions of cutting edges. Therefore, the following sections in this paper focus on how to effectively reduce tool wear of the desired end part of secondary cutting edges (secondary cutting edge corners). MQL is applied as cooling and lubricating method and MQL supply outlets of the drill bits are specially designed at two different locations at the secondary cutting edges of separate drill bits. The effects of cooling and lubrication position on tool wear reduction of desired secondary cutting edge corners are systematically studied.

## 3 Materials and experimental methods

### 3.1 Workpiece and drill bits

In this work, the aerospace grade T800 CFRP is utilized as workpiece material. And the workpiece is manufactured by prepregs in the layout of $[(-45/90/45/0)_2/90/90/90/90/90/(-45/90/45/0)_2]$. The workpiece is cured under high pressure in autoclave at Shenyang Aviation Industry Corporation. The fiber volume of the prepreg is around 60%, and detailed physical properties are listed in Table 1. The dimension of the workpiece is 150mm × 20mm × 4 mm, and three pieces of such laminated workpiece panels are used in the experiment. The one-shot drill bits utilized in the experiment have the diameter of 7.98 mm. The drill bit substrate is K40UF tungsten carbide (WC) without coating. Two different MQL supply outlets are designed on the secondary cutting edges as shown in Fig. 1. One type of one-shot drill bit has the MQL supply outlets located at the front of secondary cutting edges (#1), while the other type has the MQL supply outlets located at the end of the secondary cutting edges (#2). And the one-shot drill bit without using MQL (dry drilling, #3) is added in the experiment for comparison, and geometrical structure of drill bit (#3) is identical to that of #1 drill bit. The geometrical parameters of all drill bits utilized in the study are identical except for the MQL outlet position. The geometrical parameters of the one-shot drill bit are illustrated in Fig. 2.

### 3.2 Experimental setup and drilling parameters

The experimental setup is illustrated in Fig. 3. The drilling experiment is carried out on GONA 5 axis machine center with the maximum spindle speed of 8000 rpm. The Parlec angle head is mounted on the spindle, which transforms the vertical drilling to horizontal drilling while keeping the transmission ratio at 1:1. The MQL is supplied by Armroine 0oW129I system. The cutting flood of MQL is Microlube 2000 provided by Armroine Machinery Manufacturing Technology Co., Ltd. And high pressurized air is pumped in to generate lubricant droplets (coolant mist) and the diameters of the droplets are within 1 to 3 μm. The supply of MQL is directly connected to the angle head, then MQL is finally delivered via internal coolant supply holes of the drill bits and ejected out from the outlets of the secondary cutting edges. The MQL pressure pumped to the angle head is controlled at 0.3 MPa while the cutting flood flow rate is set at approximately 60 ml/h. The CFRP workpiece is clamped on the fixture which is mounted by 2 fastening bolts on the dynamometer. Since the support at hole exit could affect CFRP drilled hole quality, the fixture has pre-drilled holes with the diameter of 14 mm, which helps to ensure the support of the workpiece panel and eliminate the unnecessary influence factors. Kistler 9257B dynamometer is used to measure cutting force signal, and the cutting force signal goes through charge amplifier and AD conversion, then the signal is transmitted to a laptop for data acquisition. The sampling rate is set at 3 kHz. The dynamometer is vertically bolted on a specially designed fixture, which ensures drilling is stable enough. In drilling

**Table 2** Cutting edge rounding (CER)

| Number of drilled holes | Cutting edge rounding/μm | | |
|---|---|---|---|
| | #1 drill bit (MQL) | #2 drill bit (MQL) | #3 drill bit (dry drilling) |
| 0 | 5.4925 | 5.4032 | 5.7658 |
| 2 | 8.8609 | 5.6153 | 7.9194 |
| 4 | 8.9592 | 5.7022 | 9.6101 |
| 6 | 10.8103 | 7.4922 | 9.8543 |
| 8 | 10.2034 | 8.1958 | 9.1461 |
| 10 | 8.8327 | 6.4492 | 8.1873 |

**Table 3** Flank wear (VB)

| Number of drilled holes | Flank wear/μm | | |
|---|---|---|---|
| | #1 drill bit (MQL) | #2 drill bit (MQL) | #3 drill bit (dry drilling) |
| 0 | 9.6113 | 9.3568 | 9.8223 |
| 2 | 17.8114 | 11.2961 | 15.937 |
| 4 | 22.8303 | 12.7314 | 20.1901 |
| 6 | 31.144 | 17.8494 | 25.2097 |
| 8 | 44.7495 | 23.5913 | 36.0463 |
| 10 | 54.1183 | 34.6463 | 41.1881 |

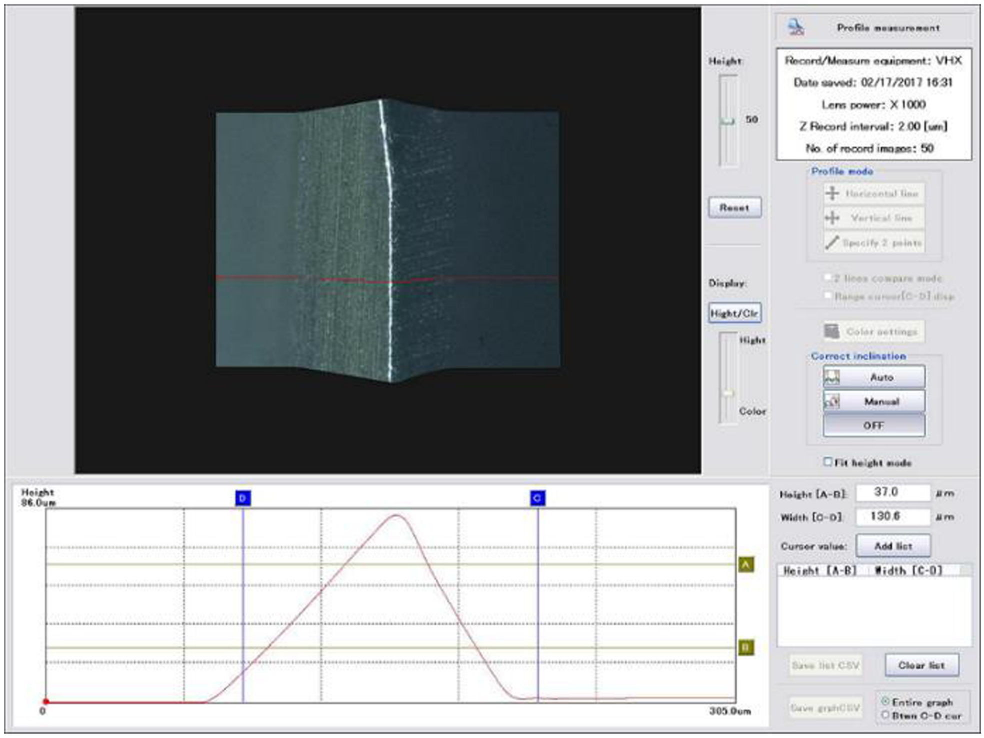



**Fig. 4** 2D profile of secondary cutting edge obtained by microscope

process, the spindle speed is set at 3000 r/min ($V_c$ = 75 m/min), and the feed rate is set at 100 mm/min ($f$ = 0.033 mm/r).

### 3.3 Quantification of tool wear and measurement of hole quality

Cutting edge rounding (CER) has been widely accepted as the representation of cutting edge dullness in tool wear researches [22, 35]. And CER can provide researchers with more information in the research of wear of complex drilling tools. This work utilizes CER to evaluate the dullness of the secondary cutting edge corner and VB is applied to represent the flank wear of the secondary cutting edge corner. In the experiment, 10 holes are drilled for each drill bit, and secondary cutting edge wear is examined off-line every 2 holes on the Keyence microscope (VHX600). The CER is measured and calculated by referencing [36]. At first, the 3D profile of the secondary cutting edge is obtained by using the depth composition function of the microscope. Then, 2D profile of the cutting edge is extracted by the microscope's internal software on the basis of the 3D profile, as shown in Fig. 4. Finally, the data of 2D profile are used to fit the CER, and the influence of flank wear on the cutting edge rounding calculation can be minimized using iterative fitting by implementing the method in the reference mentioned above. Flank wear VB measurement is

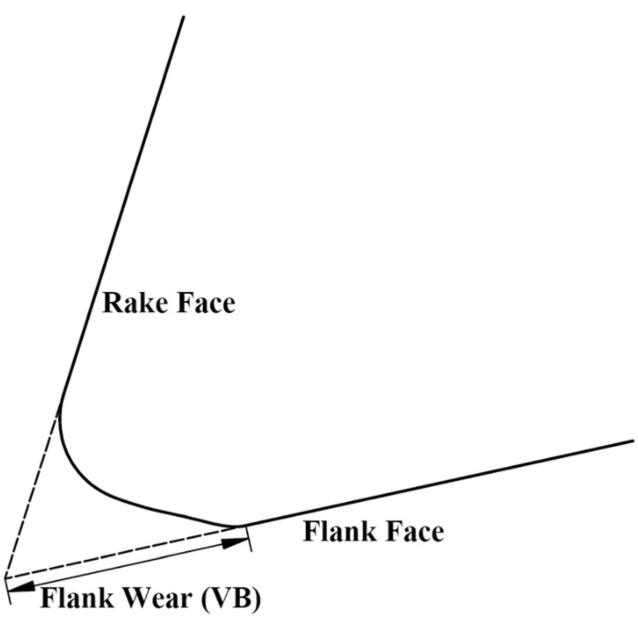



**Fig. 5** Measurement of flank wear VB

**Table 4** Maximum drilling torque

| Number of drilled holes | Maximum drilling torque/Nm | | |
|---|---|---|---|
| | #1 drill bit (MQL) | #2 drill bit (MQL) | #3 drill bit (dry drilling) |
| 2 | 0.2304 | 0.1892 | 0.1826 |
| 4 | 0.2685 | 0.2298 | 0.211 |
| 6 | 0.3125 | 0.2384 | 0.2303 |
| 8 | 0.2934 | 0.2824 | 0.2504 |
| 10 | 0.3341 | 0.2535 | 0.2507 |

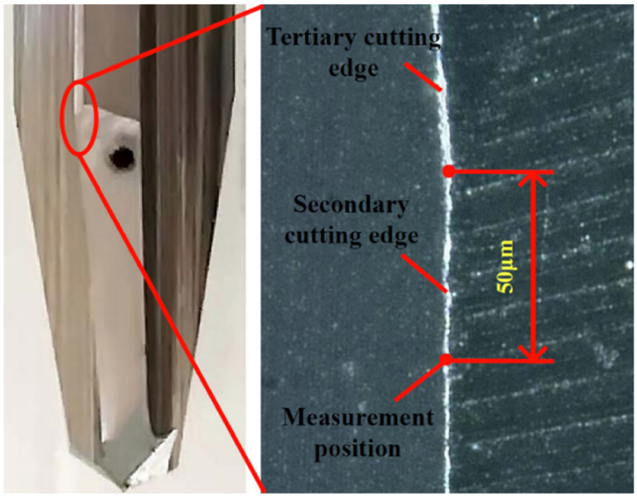



**Fig. 6** Wear measurement position of secondary cutting edge

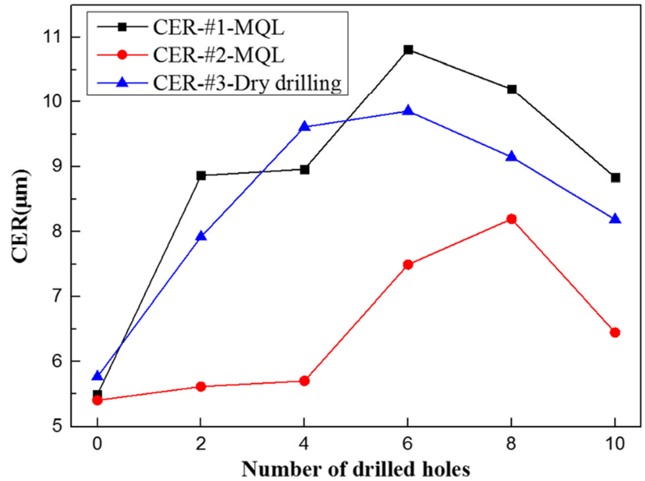



**Fig. 7** Cutting edge rounding with number of drilled holes

performed by referencing [37], and details are shown in Fig. 5. The calculation of flank wear is carried out also based on the data of 2D profile of the secondary cutting edge. The wear measurement position on the secondary cutting edge is shown in Fig. 6. The measurement position is located 50 μm away from the tertiary cutting edge, and it is known as secondary cutting edge corner.

The measurement of hole surface roughness is performed on the surface profiler (Taylor Hobson PGI840), and the measurement of drilled hole diameter is carried out on the three-coordinate measuring machine (Zeiss Prismo). SEM (FEI Q45) helps to achieve the micro-observation of drilled hole surface.

## 4 Results and discussion

### 4.1 Effects of cooling and lubricating position on tool wear of secondary cutting edge corners

Measured cutting edge rounding CER with the number of drilled holes in Table 2 is illustrated in Fig. 7. As compared with #1 drill bit, the MQL mist delivered out from the outlets located at the end of the secondary cutting edge (#2 drill bit) effectively reduces the dullness of the edges. Especially at the first few holes, it is noted that the progression of cutting edge rounding of #2 drill bit is much slower than that of #1 drill bit. Additionally, the CER value of #2 drill bit under MQL condition is substantially lower compared with that of #3 drill bit under dry drilling. Flank wear of secondary cutting edges with the number of drilled holes in Table 3 is shown in Fig. 8. In contrast with #1 drill bit and #3 drill bit, the #2 drill bit also exhibits significant flank wear reduction of the secondary cutting edge corner.

As mention above in Section 2, in drilling CFRP, the abrasive carbon fibers directly scratch the cutting edge. Thus dynamic stresses are generated, which could result in initiation of micro cracks on the tool edge since the edge is sharp and not strong enough to bear heavy cyclic loading. And WC grains of the tool substrate may fall away because of brittle

**Table 5** Surface roughness, Ra

| Number of drilled holes | Surface roughness/μm | | |
|---|---|---|---|
| | #1 drill bit (MQL) | #2 drill bit (MQL) | #3 drill bit (dry drilling) |
| 2 | 0.4441 | 0.3209 | 0.4841 |
| 4 | 0.6702 | 0.5426 | 0.7462 |
| 6 | 0.9708 | 0.7928 | 0.9201 |
| 8 | 1.1514 | 0.8903 | 1.1837 |
| 10 | 1.2978 | 0.906 | 1.3472 |

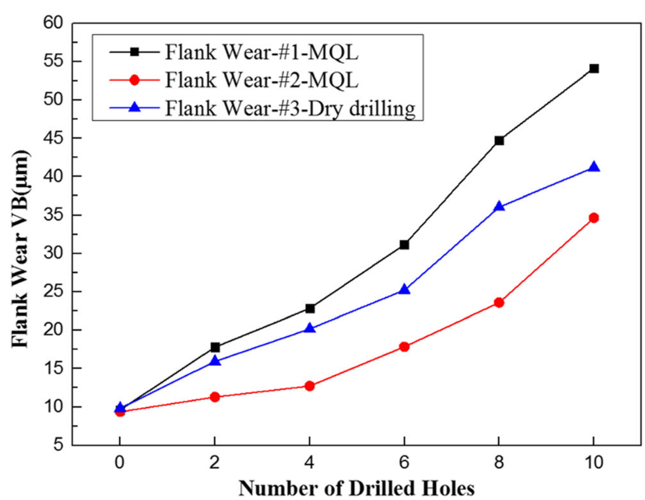



**Fig. 8** Flank wear with number of drilled holes

fractures. Such kind of mechanism leads to a large increase of CER in drilling the first few holes. What's more, the fiber reinforcement damages the soft Co binder in the abrasion process and weakens the tool substrate. Meanwhile, the aerospace grade T800 carbon fiber is more abrasive on account of its high hardness. The carbon fiber chips, WC grains, and the fiber reinforcement become abradants all together to scratch the tool edge, which accelerates the dulling of secondary cutting edge corners when it is under dry drilling.

However, in the drilling of #2 drill bit under minimum quantity lubrication, the coolant droplets (coolant mist) generated by high pumping pressure are sprayed to the cutting zone to enhance the lubricity of the tribological system between the cutting edge and the CFRP material. Due to the fact that the coolant is oil based, the small droplets generated and ejected to the cutting zone can form thin film on the tool-workpiece contact surface [34], which smooth the sliding as well as decrease the friction. Therefore, MQL improves the tool-workpiece contact durability. What's more, the high pressurized air ejected from the outlets of the secondary cutting edges can help to remove CFRP chips from the drilled hole, which avoids heat accumulation. Also, the evaporation of coolant mist and the high flow rate of pressurized air can help to achieve better heat transfer. All the improvements by MQL contribute to the significant slower progression of CER and flank wear VB.

The coolant mist delivered out from the outlets located at the end of the secondary cutting edge has greater chance to be directed ejected to the desired cutting zone by high pressurized air. But the coolant mist delivered out from the outlets located at the front of the secondary cutting edges may not effectively reach the end part of the secondary cutting edges because the material removal process is under high contacting pressure, and it prevents the coolant mist from spraying and diffusing effectively combined with the blocking effects of CFRP chips. Thus, the wear reduction effects of #1 drill bit under MQL is far worse than that of #2 drill bit.

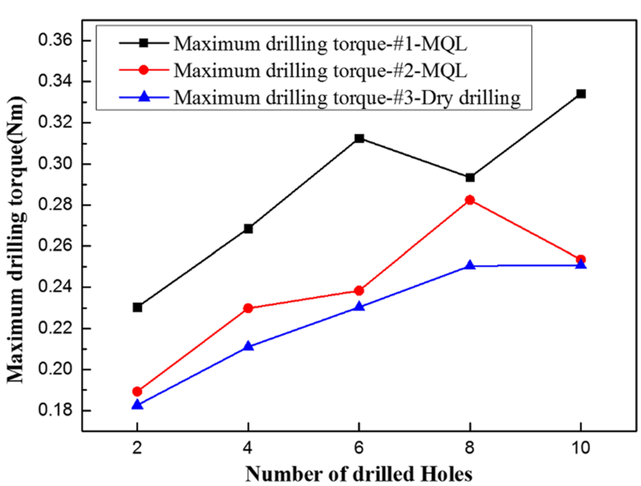



**Fig. 9** Maximum drilling torque with number of drilled holes

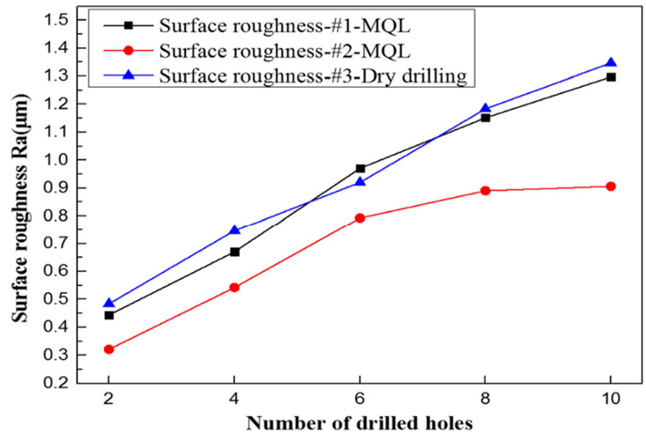



**Fig. 10** Surface roughness with number of drilled holes

The dulling of secondary cutting edge corners leads to the fact that the edge is not sharp enough to effectively cut off carbon fibers under certain acute fiber cutting angles [27]. As reported in the previous study [27], uncut fibers along with WC grains and CFRP chips slide over flank face. Thus, in this case, scratching effects cause severe flank wear and induce regrinding of cutting edges. The regrinding effects of flank wear leads to decreases of CER after 6 holes in the drilling process of #1 drill bit and #3 drill bit. But in contrast, CER of #2 drill bit drops after 8 holes due to lower flank wear.

### 4.2 Maximum drilling torque

Based on the geometrical structure of one-shot drill bit, the secondary cutting edge contributes a large part of the drilling torque in the drilling and reaming processes [27]. The

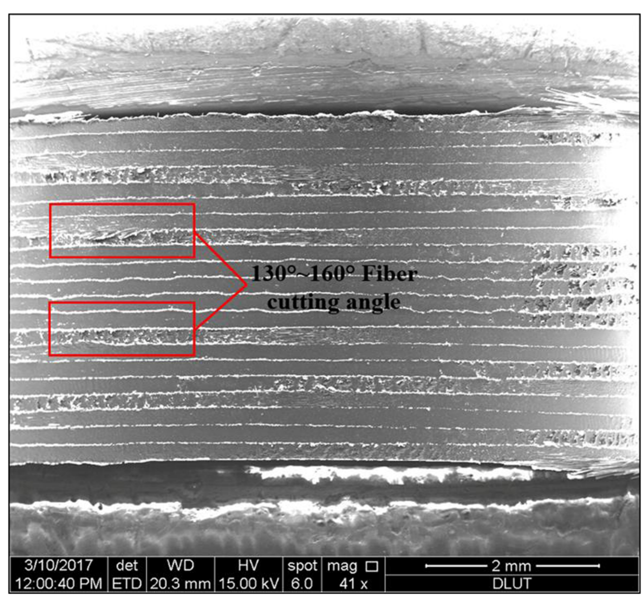
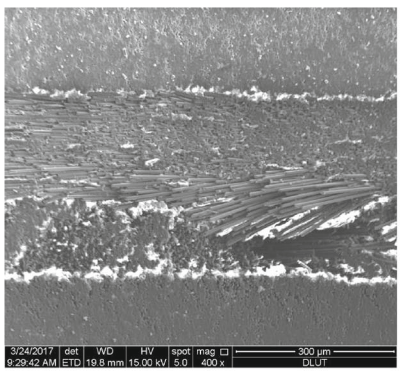
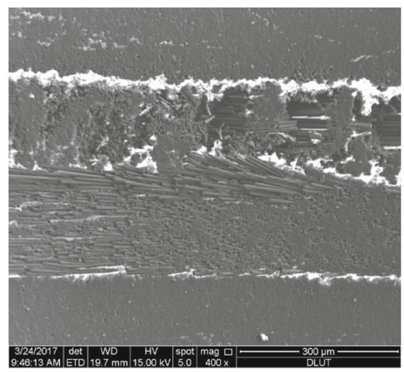
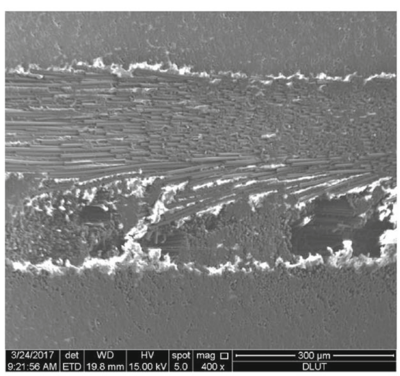
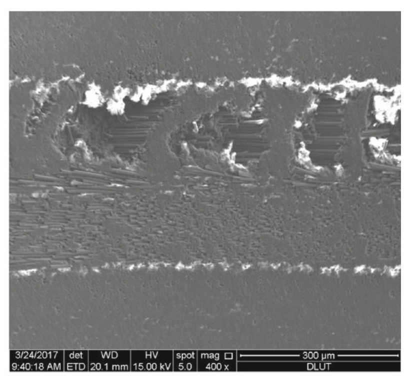
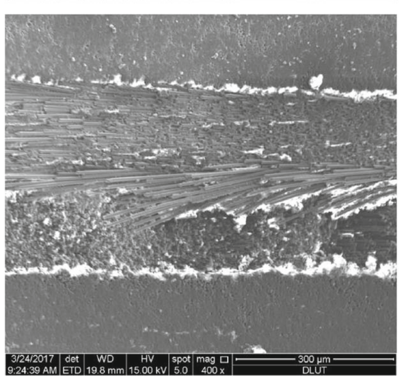
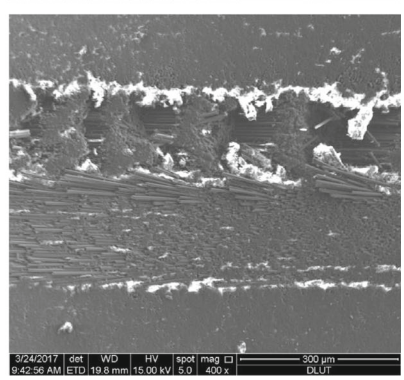



**Fig. 11** Drilled hole surface morphology

diameter at the end of the secondary cutting edge is close to the final hole diameter, and the drilling torque reaches its maximum value there. The maximum drilling torque variation in Table 4 is illustrated in Fig. 9. In general, the maximum drilling torques under MQL condition are higher than maximum drilling torques under dry machining. The experimental results correlate well with previously reports where cryogenic cooling generally increases the forces in machining process as compared to dry machining [30]. As stated in previous researches, possibly it is due to the fact cooling assistance lowers the temperature of work material within the cutting zone, and Young's modulus of CFRP increase as the temperature decreases. Besides, thermomechanical properties of composite materials, such as transverse modulus, shear modulus, transverse shear modulus, and transverse strength are increased when the temperature is reduced [30]. All the factors mentioned above contribute to larger tangential component of cutting force, which ultimately leads to higher maximum drilling torques.

Also, there is a large gap between maximum drilling torques of #1 drill bit and #2 drill bit. The MQL from the end of the secondary cutting edge of #2 drill bit helps to

**Table 6** Hole surface defects

| Hole surface defects | | |
|---|---|---|
| Drill bit | Hole surface defects | |
| #1 |  |  |
| #2 |  |  |
| #3 |  |  |

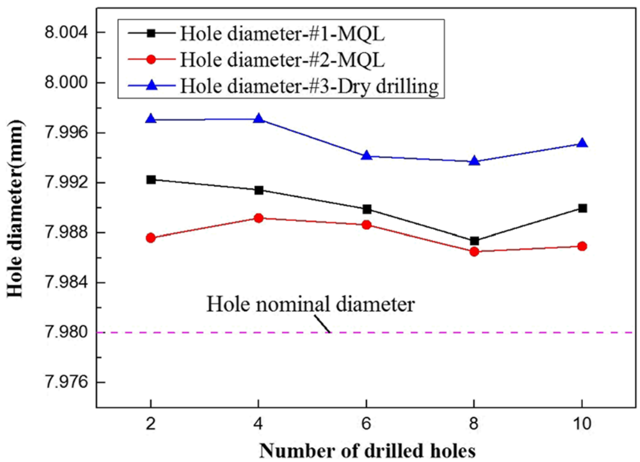



**Fig. 12** Measured hole diameter variation

achieve better tribological condition as well as better wear reduction than #1 drill bit, which therefore may contribute to the fact that the maximum drilling torques of #2 drill bit are lower than maximum drilling torques of #1 drill bit.

### 4.3 Drilled hole surface quality

The secondary cutting edge especially its end part (secondary cutting edge corner) mainly determines the drilled hole surface quality [27]. The surface roughness variations with number of drilled holes in Table 5 are depicted in Fig. 10. By comparison with #3 dry drilling, the #2 drill bit under MQL condition achieves better surface roughness as well. The surface roughness of holes drilled by #1 drill bit is at the same level as that of holes drilled by #3 drill bit. The wear of secondary cutting edge corners characterized by CER and VB of #1 drill bit and #3 drill bit are also roughly the same. Although #1 drill bit applies MQL in the drilling process, it does not show improvement of surface roughness of drilled holes.

Hole surface defects easily occur around 135° fiber cutting angle after rapid tool wear [27]. Two surface zones with fiber cutting angle of 130° ~ 160° are selected based on the drilled hole surface morphology illustrated in Fig. 11. And surface morphologies of the two zones of Hole 10 drilled by #1, #2, #3 drill bits are listed in Table 6, respectively. Compared with surface morphologies of the #2 drill bit, there are evident uncut fibers within both selected zones of the #1 drill bit. The secondary cutting edges of #1 drill bit are more prone to dulling and flank wear, and the cutting edges become no longer sharp thus leading to more uncut fibers. Due to severe tool wear, the hole surface defects such as uncut fiber and denting on surface zones of the #3 drill bit are also worse than defects on hole surface of the #2 drill bit.

**Table 7** Drilled hole diameter

| Number of drilled holes | Drilled hole diameter/mm | | |
|---|---|---|---|
| | #1 drill bit (MQL) | #2 drill bit (MQL) | #3 drill bit (dry drilling) |
| 2 | 7.99227 | 7.9876 | 7.99707 |
| 4 | 7.99144 | 7.98917 | 7.9971 |
| 6 | 7.9899 | 7.98863 | 7.99413 |
| 8 | 7.98737 | 7.9865 | 7.9937 |
| 10 | 7.98997 | 7.98693 | 7.99513 |

### 4.4 Drilled hole diameter

The hole diameter variation with number of drilled holes in Table 7 is illustrated in Fig. 12. The measurement shows that the drilled holes are oversized under both dry drilling and MQL conditions (drill bit diameter is 7.98 mm). Similar trends were reported in the literature where holes were drilled under both cryogenic and dry conditions [30]. The oversized holes produced in drilling CFRP are most likely because of thermal expansion of the matrix from increased cutting temperatures caused by the lack of lubricant/coolant access and poor chip evacuation [30]. In the results of this paper, the holes drilled under MQL condition have smaller diameters than those drilled under dry drilling. And the holes drilled by #2 drill bit have even slightly smaller diameters compared with holes drilled by #1 drill bit. The above results are probably due to better tribological condition in the drilling of #2 drill bit and less defects interference on drilled hole surfaces.

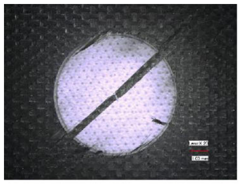
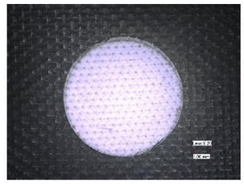
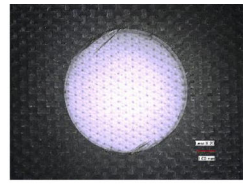
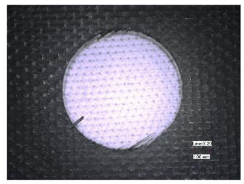
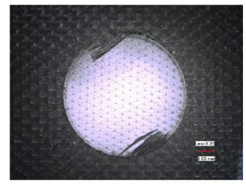
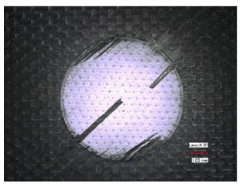
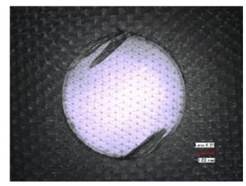
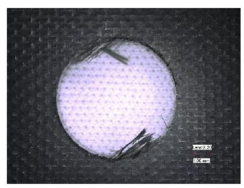
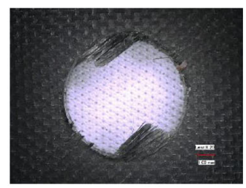
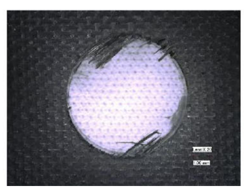
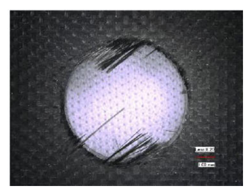
### 4.5 Quality of drilled hole exits

Table 8 compares the quality of drilled hole exits under dry drilling and MQL conditions. Evident burrs occur under fiber cutting angle range of approximately 15° to 80° after rapid tool wear. In contrast with holes produced by dry drilling and #1 drill bit, hole exits by #2 drill bit exhibit best quality with fewest burrs. It is noteworthy that holes produced by #1 drill bit under MQL condition shows worst burrs and even significant delaminations at hole exits. The result is probably due to the fact that when delivered out from the outlets located at the front of the secondary cutting edges, the coolant mist is directly ejected to hole exits, which thus leads to high thrust force and weak support in drilling of the last few plied at the hole exit. This mechanism could induce subsequent drilling damages such as burrs and delaminations.

## 5 Conclusion

This paper carries out investigations on effects of cooling and lubricating locations on tool wear reduction of the secondary cutting edge corners in drilling CFRP by one-shot drill bit.

**Table 8** Quality of drilled hole exits

| Drilled hole No. | Quality of drilled hole exits<br>Hole exit-#1-MQL | Hole exit-#2-MQL | Hole exit-#3-dry drilling |
|---|---|---|---|
| 2 |  |  |  |
| 4 |  |  |  |
| 6 |  |  |  |
| 8 |  |  |  |
| 10 |  |  |  |

Two different locations of MQL supply outlets are designed on the secondary cutting edges of separate one-shot drill bits, which helps to study the effects of cooling location on tool wear reduction of the desired tool edge corner. And dry drilling is added for comparison as well. In terms of drilled hole qualities, surface roughness and drilled hole surface defects are measured. The results of the paper are valuable for further technical study in improving drilled hole quality by one-shot drill bits. From the results of investigations and their analyses, the following conclusions are drawn:

(1) Delivering coolant mist (MQL) out from the outlets located at the end of the secondary cutting edges (#2 drill bit) contributes to better tool wear reduction of secondary cutting edge corner than delivering coolant mist out from the outlets located at the front of the secondary cutting edges (#1 drill bit). However, by comparison with dry drilling, tool wear of secondary cutting edge corners of #1 drill bit is roughly at the same level as that of dry drilling (#3 drill bit).

(2) Delivering MQL coolant mist out from the end of the secondary cutting edges (#2 drill bit) produces smaller maximum drilling torque than that of delivering MQL out from the front of the secondary cutting edges (#3 drill bit).

(3) Holes drilled #2 drill bit (delivering MQL coolant mist out from the end of the secondary cutting edges) exhibit superior hole quality in terms of surface roughness, hole surface and exit defects compared to the conditions of #1 drill bit and dry drilling, respectively. But the holes drilled by #2 drill bit have the smallest hole diameters in contrast with other drilling conditions.

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