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Comparison of drill wear mechanism between rotary ultrasonic elliptical machining and conventional drilling of CFRP

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Abstract

Carbon fiber-reinforced plastic (CFRP) is widely used as aircraft structural components for its superior mechanical and physical properties. Meanwhile, the rotary ultrasonic elliptical machining (RUEM), as a new drilling method in which an elliptical ultrasonic vibration is imposed on the end of the drill, can reduce tool wear effectively. In this paper, we firstly presented an investigation on the wear mechanism of diamond core drill in RUEM of CFRP in comparison with the conventional drilling (CD). A series of drilling experiments were performed including the drilling force measurement, the observation of drill topographies, and machined hole surface. The experiment results indicated that the drill performance in RUEM of CFRP was improved significantly in comparison with that in CD. Because the length of steady region rised by 39% and the tool life increased by 28% in RUEM than those in CD, respectively. With the observation of drill surface under a microscope, it was validated that less chip adhesion and more grain micro-fracture appeared in RUEM, which had a positive effect on the better drilling performance, such as lower drilling force, smoother hole surface.

Keywords

Carbon fiber-reinforced plastic, rotary ultrasonic elliptical machining, diamond core drill wear, chip adhesion, grain micro-fracture

Introduction

In recent years, the demand for the CFRP composites is increasing greatly to meet the wide applications such as aircraft skin, wind turbine blades, robot structures and automotive parts due to their low density, high strength-to-weight ration, large stiff-to-weight ratio, high chemical and corrosion resistance, and other superior properties.[1,2] The abrasivity of the CFRP causes severe damage to the cutting tool, not only shortening the tool life but also affecting the surface quality.[2] So the cost-consuming and time-consuming machining process happens in CFRP machining.

Drilling has been employed as the most frequent method on machining CFRP owing to the assemble need of fixing the composite parts to other structures,[3,4] such as joining the CFRP skin to the titanium alloy beams in aircraft wings assembly process. Meanwhile, many typical problems exist in drilling CFRP including short tool life, delamination, burrs, swelling, splintering, fiber pullout, and low machining precision. The tool performance plays a dominant role in drilling process. In order to improve the performance of drilling tools, tools with different geometry including twist drills, saw drills, mutifacet drills, candle stick drills, core-center drills, and diamond core drills were fabricated.[4–9] Furthermore, the cutting mode in which the drill tool was assisted by ultrasonic vibration could

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improve the tool performance significantly in experiments, which indicated that the cutting mechanism was modified in this process.[10]

Ultrasonic-assisted drilling has been applied in different modes to develop cost-effective and high surface quality drilling technology, which resulted in tool life extension and drilling force decrement. As a typical one-dimensional ultrasonic-assisted drilling (UEV), rotary ultrasonic machining (RUM) is adopted extensively, in which the ultrasonic vibration applied to the drill is generated in the direction vertical to the workface.[10–12] Recently, RUM has been successfully used in drilling holes in CFRP. A comparison of RUM and twist drilling, effects of variables on output variables and temperature, and a comparison of different cooling conditions were studied.[11,13–17] However, the RUM coolant limited the RUM technology application in the aircraft assembly due to the high cost of the cutting fluid deployment, the waste cutting fluid treatment, the health and environment hazard.[11,12,14] In order to further enhance the machining efficiency and improve the quality of hole surface in ultrasonic-assisted drilling, Ma et al. proposed a two-dimensional UEV technique. He utilized a drill bit and a special aluminum alloy workpiece that ultrasonically vibrated in an elliptical mode vertical to the drill axial direction.[18] The investigation showed that the axial drilling force, the variation of the radial drilling force, and the chip thickness of drilling were reduced in UEV under dry condition. After then, the technique of UEV (later called rotary ultrasonic elliptical machining, RUEM) was successfully applied to the machining of CFRP, and the viability of RUEM on CFRP was studied for the first time by Liu et al.[12] In the experiment, the diamond core drill vibrated ultrasonically in two directions by using an elliptical ultrasonic vibrator. Dry machining was used to avoid the problems related to cutting fluids. The experimental results showed that, in comparison of CD, the tool wear and thrust force were significantly reduced, and the hole precision as well as surface quality was enhanced markedly. Therefore, RUEM was considered to be a new effective method for CFRP drilling under dry condition. However, the core drill wear in RUEM of CFRP was simply measured by the wear size of core drill, and the analysis of the ultrasonic vibration effect on tool wear was not conducted in this paper.

As for the tool wear in RUM, the ratio of the removed material weight to the tool wear weight was often used to evaluate the specific tool wear.[19] The effects of process parameters in RUM on specific tool wear were investigated experimentally, such as static load, ultrasonic vibration amplitude, diamond type, grit size, bond materials, strength, and so on.[10,11,20] However, the conventional specific tool wear measurements can reveal little about the tool wear mechanism in RUM. Based on the microscope techniques used to investigate the wear mechanism of grinding wheel, Zeng et al. studied the diamond core drill wear in RUM of advanced ceramics by examining the drill surface under a digital microscope with magnification 50.[21]

Although there were a lot of investigations on the tool wear mechanism in both CD and RUM, few studies were carried out to reveal the wear behavior in RUEM. It is well known that the investigation on the evolution of drill wear is essential to quantitatively evaluate the drill cutting ability. This paper, for the first time in the literature, presented an experimental observation and analysis on tool wear in RUEM of CFRP. The experimental investigation was conducted to study the diamond core drill wear behavior by carrying out the RUEM operations on CFRP without coolant on an ultra-precision lathe. The drill surface topographies until losing the cutting ability were used to evaluate the tool wear evolution condition. In addition, in order to deeply understand the wear behavior in RUEM, the CD experimental works in the same drilling conditions were also conducted. Finally, the experiments results in RUEM were fully analyzed to investigate the wear mechanism of diamond core drill in comparison of that in CD.

Experiment

Experimental set-up

The experimental set-up is shown in Figure 1(a). It mainly consisted of an ultra-precision lathe (a Harding lathe by Harding Co., Ltd., NY, USA), an ultrasonic drilling unit, and a data acquisition system. The ultrasonic drilling unit was composed of an elliptical ultrasonic transducer, a power supply, and a slip ring which supplied electricity to the rotary ultrasonic transducer. The fixture clamping the specimen was mounted on a 3D dynamometer fixed to the lathe working platform.

The ultrasonic elliptical transducer and vibration modes are shown in Figure 1(b). The designed transducer was a sandwiched piezoelectric structure which was composed of a diamond core drill, a front cylinder (titanium alloy), two groups of piezoelectric plates (PZTs), and a back cylinder (stainless steel). The bending vibrations were incited by the two orthogonal groups of PZTs. When the alternating voltages were applied to the two groups of PZTs, respectively, with the same frequency and a phase shift , two ultrasonic bending vibrations were generated in x- and y-directions simultaneously. The synthesis of the two bending vibrations generated an elliptical mode vibration in the x–y-plane at the end of the vibrator. As a diamond core

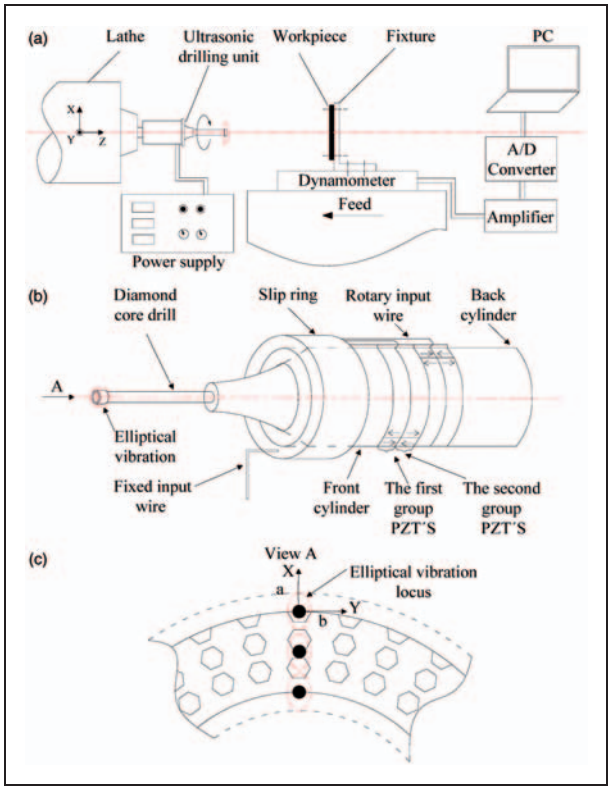

Figure 1. Experimental set-up and ultrasonic transducer of RUEM. (a) Experimental set-up of RUEM, (b) Ultrasonic elliptical transducer and (c) Partial view A of the diamond core drill.

drill was mounted onto the end of the transducer, the vibration amplitude of the diamond core drill tip was magnified by the stepped horn and reached maximized value. The elliptical vibration locus is shown in Figure 1(c). Once a feed motion was provided to the specimen fixed on the lathe platform, the diamond core drill held on the rotating spindle would remove the work material. In this case, as the elliptical ultrasonic vibration of the vibrator was applied, an RUEM operation was performed.

Measurement procedure and conditions

RUEM experiments were performed on an experimental apparatus without coolant (i.e. dry machining). The drilling force was measured by a three-dimensional (3D) piezoelectric dynamometer (9256A1 by Kistler Japan Co., Ltd., Winterthur, Switzerland), and the data acquisition system is shown in Figure 1(a). The surface roughness of the drilled holes across the axial direction was obtained using a texture measuring instrument (Surfcom408A by Tokyo Seimitsu Co. Ltd., Tokyo, Japan).

In order to obtain the elliptical ultrasonic vibration of the tool end, the frequency, the amplitude, and phase shift of the applied AC voltages were set as 20.6 kHz, 50 V and 250°, respectively. In this condition, the elliptical vibration amplitude of the drill end was measured with two

Table 1. Workpiece material properties.

Property	Unit	Value
Density	kg/m^3	155
Hardness (Rockwell)	HRB	70–75
Elasticity Modulus of epoxy	GPa	2.06–2.15
Tensile strength of epoxy	MPa	80–85
Elasticity Modulus of carbon fiber	GPa	230
Tensile strength of carbon fiber	MPa	4900

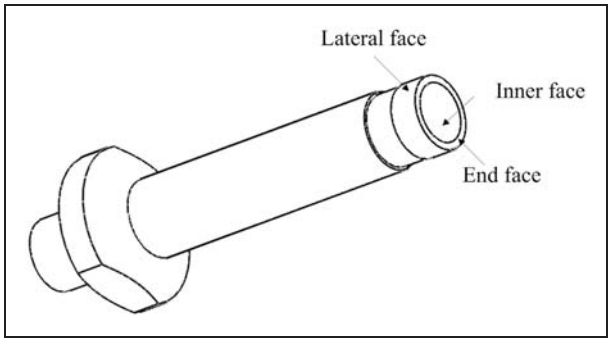

Figure 2. 3D view of the diamond core drill.

laser Doppler vibrometers (LV-1610 of Ono Sokki Co., Ltd., Yokohama, Japan), the amplitude of circular locus was 10 μm (i.e. a = b = 5 μm) (see Figure 1c).

A sample of CFRP was used as the workpiece, which was provided by Chengdu Aircraft Industrial (Group) Co., Ltd., Chengdu, China, with a dimension of 200 mm × 200 mm × 10 mm. The material properties of workpiece are shown in Table 1. The cutting tools were diamond core drills (Figure 2) provided by Beijing Aeronautical Manufacturing Technology Research Institude, Beijing, China. The grit size, the drill outer diameter, and the inner diameter were 80# (the screen hole size was 0.18 mm), 10.7 mm, and 8.1 mm, respectively. The diamond grains were welded to the tool surface by vacuum brazing process. The surface density of diamond grains on drill face was about 15 grains per unit area (i.e. $15/mm^2$) and few diamond grains existed on the drill inner face, so it could improve drill sharpness, machining quality, and prevent rod jamming effectively. Two drills were used to drill the specimen in CD and RUEM. After particular drilling tests, the diamond core drills were removed from the lathe spindle and cleaned by an ultrasonic washing machine. The surface conditions were observed using a digital optical microscope (Nikon E950 by Nikon Co., Ltd., Tokyo, Japan) to grasp the evolution of drill wear. The magnification of the microscope was 30 to 500. Once the tool was dull enough to generate severe delamination and burrs at the hole exit position, a repairing operation was needed. In this experiment, the tool life of a

Table 2. Details of experiment conditions.

Parameters (unit)	Value
Coolant	Dry condition
Input voltage amplitude (V)	$U = 50$
Input voltage frequency (kHz)	$f = 20.6$
Input voltages phase shift (°)	$\Psi = 250$
Elliptical vibration amplitude (μm)	$a = b = 5$
Rotary speed (r/min)	$v_s = 5000$
Feedrate (mm/s)	$v_f = 0.33$
Depth of drilling (mm)	$d = 10$

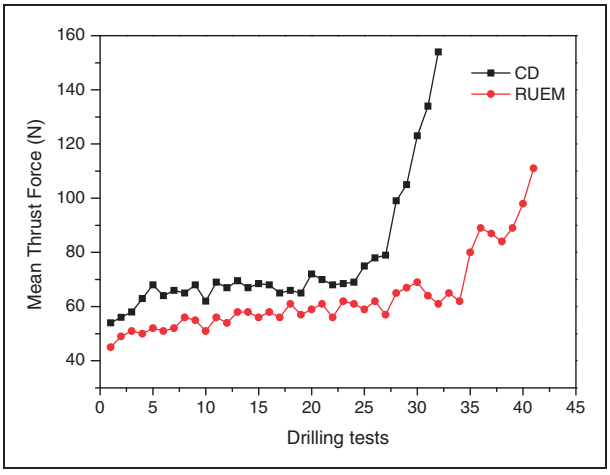

Figure 3. Mean drilling force versus the number of drilling tests.

diamond core drill was defined as the drilled hole number before repairing. The details of experiment conditions are tabulated in Table 2.

Experimental results

Drilling force

Figure 3 shows the mean drilling force along the axial direction (i.e. mean thrust force) as a function of the drilling tests number. The drilling force which is directly related to the sliding friction at the interface between the drill and the workpiece is generally a crucial factor for the evaluation of the drill wear conditions. The mean drilling force in this experiment was defined by F_m

$$F_m = \frac{\int_0^{t_i} F_{z_i} dt}{T} \quad (1)$$

where F_{z_i} is the real-time axial drilling force at t_i, and t_i and T are the real-time cutting time and the cutting duration during drilling, respectively.

It can be obtained that the mean drilling force in RUEM was much smaller than that in CD. In the study of Zeng et al.,[21] the tool wear in RUM of ceramics was divided into two stages until most of diamond grains were dislodged from the drill end face according to the wear mode. Moreover, the results confirmed an obvious relationship between the evaluation of drill wear and the maximum drilling force. Thus, according to the trend of the mean drilling force, the core drill wear process either in RUEM or CD could be divided into three stages, i.e. an initial region, a steady region, and a deteriorated region:

1. Initial region:

It covered the drilling test times <5 in CD or 3 in RUEM. In this region, the drilling force increased obviously.

2. Steady region:

It covered the drilling test times from 5 to 28 in CD or from 3 to 35 in RUEM. In this region, the drilling force in CD increased slightly with a small fluctuation. The drilling force in RUEM also increased slightly and compared with CD, the steady region in RUEM was 39% longer.

3. Deteriorated region:

This region covered the drilling test times larger than 28 in CD or 35 and RUEM, respectively. The experiments were terminated at the 32nd drilling test in CD and the 41st drilling test in RUEM due to severe delamination and burrs at hole exit position. In this region, the drilling force increased sharply with the test number both in CD and RUEM, while the increasing rate in CD was larger than that in RUEM. Moreover, it should be noted that, the tool life in RUEM and CD was 41 holes and 32 holes, respectively, and thus, the tool life in RUEM was 28% longer in comparison with that in CD.

Topographic features of drill surface

Wear of tool end face. Figures 4–8 show the images of the drill end face after the 5th, 15th, 25th and 32nd drilling test both in CD and RUEM, and the 41st drilling test in RUEM, respectively.

It can be seen that there were few visible changes of drill end faces after five times drilling tests except some grain pullout and slight grain micro-fracture both in

CD and RUEM. The number of dislodged grains in CD was obviously larger than that in RUEM, while the number of grains with slight micro-fracture in RUEM was larger than that in CD at the whole drill end face. Compared with the wear condition of other grains, the premature dislodged grains had not reached its effective working life. Although some grain pullout occurred in CD and RUEM, there were still lots of active cutting edges at the drill end face, which were considered as main cutting edges during drilling.

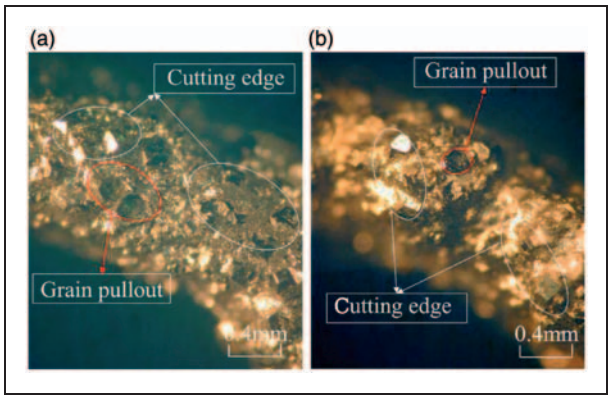

Figure 4. 2D microscopic images of drill end face after the 5th drilling tests. (a) CD and (b) RUEM.

Compared with the drill end face after five drilling test times, more grains were dislodged and more sharp cutting edges were worn significantly in mode of attritious wear after drilling 15 holes, especially in CD (see Figure 5). Both wear modes effectively decreased in active cutting edge density which was defined as the number of active cutting edges per unit area on the drill end face. The bond fracture resulting in grain pullout and slight chip adhesion in the bulky pits occurred at the edge of the drill end face in CD. Although the bond fracture, grain pullout, and cutting edges worn were also observed in RUEM, the chip adhesion rarely appeared and obvious grain micro-fracture could be found. This meant that the drill in RUEM maintained a higher drilling performance than that in CD.

As the drilling tests were raised to 25 times (see Figure 6), bond fracture and grain pullout increased markedly in CD and RUEM. However, more grain

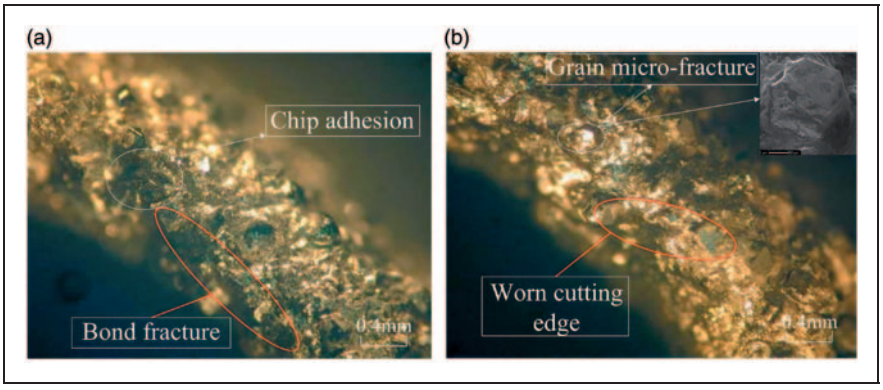

Figure 5. 2D microscopic images of drill end face after the 15th drilling tests. (a) CD and (b) RUEM.

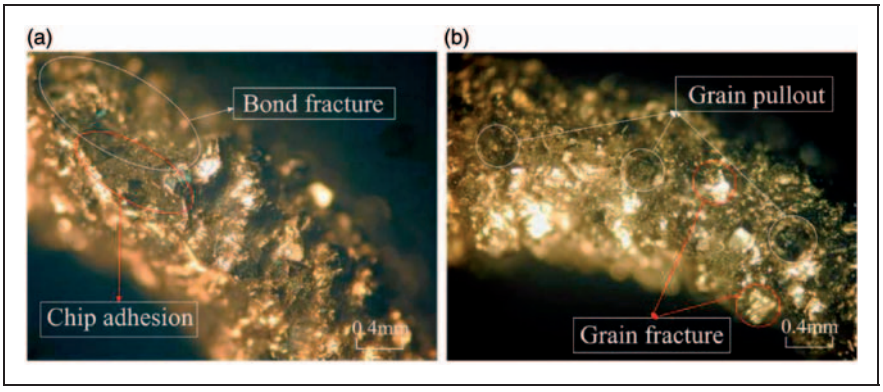

Figure 6. 2D microscopic images of drill end face after the 25th drilling test. (a) CD and (b) RUEM.

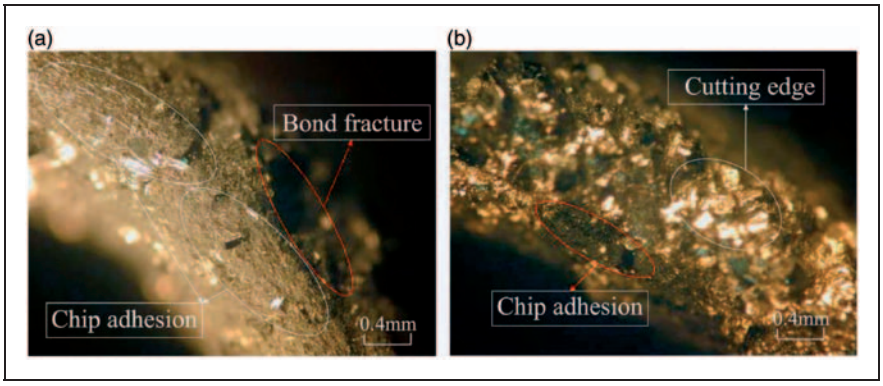

Figure 7. 2D microscopic images of drill end face after the 32nd drilling test. (a) CD and (b) RUEM.

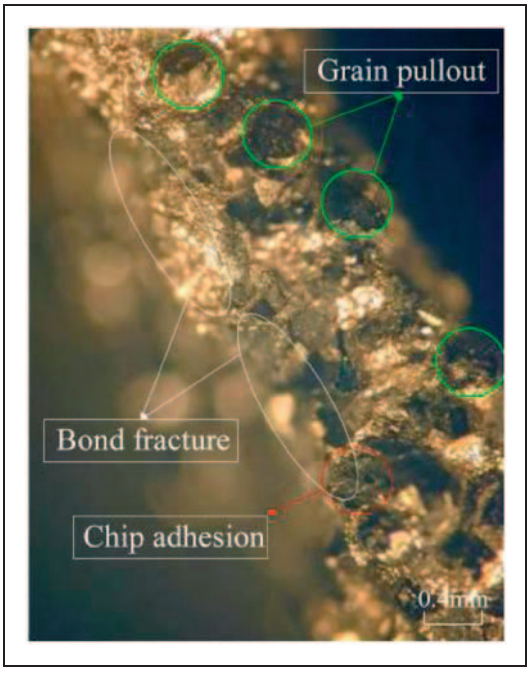

Figure 8. 2D microscopic images of drill end face after the 41st drilling test in RUEM.

micro-fracture and less chip adhesion occurred in RUEM in comparison with CD. It indicated that the core drill became poor after drilling 25 holes in CD, while the core drill was still sharp in RUEM.

After the 32nd drilling test (see Figure 7), the chip adhesion and bond fracture became severe in CD, and about 80% of the end face was blocked with adhesion layer, which was made up of the epoxy debris, the cut carbon fibers, the diamond and metal solder debris. In this situation, the cutting edge density decreased so significantly that the drilling force became large enough to produce severe delamination and burrs at the exit position of drilled holes. Thus, the drill in CD lost the cutting ability and the repairing operation was necessary. Meanwhile, in RUEM, the active cutting edges on the end face were still obvious, and slight chip adhesion was observed at the bulky pits where grains were dislodged. Therefore, the drill still owned some cutting ability in RUEM.

Once the drilling tests number was increased to 41 in RUEM (see Figure 8), grain pullout and bond fracture became so severe that there were no obvious sharp grains left on the drill end face, so the repairing operation was needed.

The microscopic features of drill end face indicated that the grain wear modes changed significantly with the increase of drilling test times. The obvious variation was the number decrement of active diamond grains and the area increment of chip adhesion on the drill end face. Active diamond grains are defined as the grains with sharp cutting edges (i.e. sharp grains). The active diamond grain number on the end face during drilling is shown in Figure 9(a). The number of active grains on the drill end face during drilling was obtained by a microscope, and then the percentage of the active diamond grain number to the total grain number on the drill initial end face was calculated. The number of active grains on the drill end face decreased with the increase of drilling test times. The descent in the initial region and the deteriorated region was sharper than that in the steady region either in CD or RUEM. The number of active grains in RUEM was always larger than that in CD during drilling. This indicated that drill dullness could be constrained effectively in RUEM.

The variation of the chip adhesion area with the drilling test number is shown in Figure 9(b). The area of chip adhesion was measured with the 2D microscopic images of drill end face and VK Analyzer software. The percentage of the chip adhesion could be calculated by the software after the area of the chip adhesion was determined. It was obvious that the chip adhesion area in CD increased significantly in steady region, and once the drilling test number exceeded 25 times, the increasing rate became much greater.

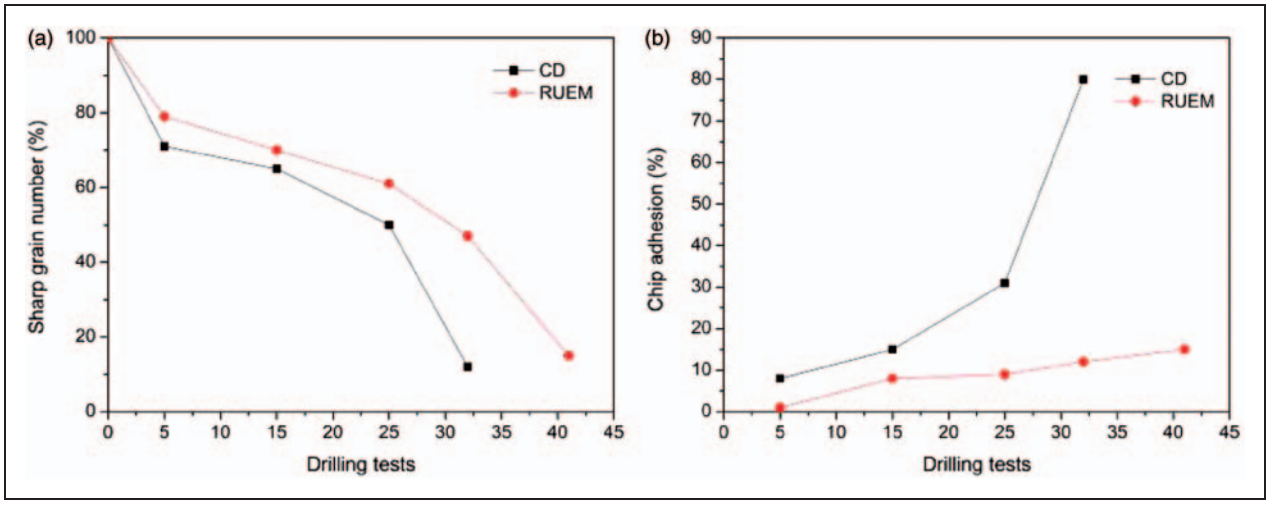

Figure 9. Variation of active diamond grains and chip adhesion during drilling. (a) active diamond grains and (b) chip adhesion.

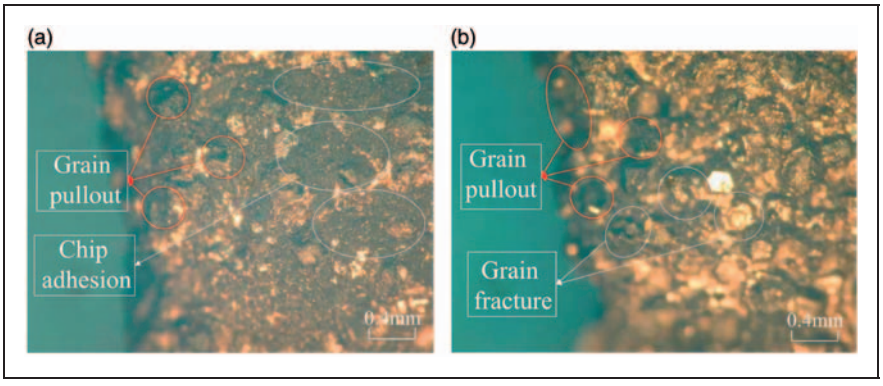

Figure 10. 2D microscopic images of the lateral face after the 15th drilling test. (a) CD and (b) RUEM.

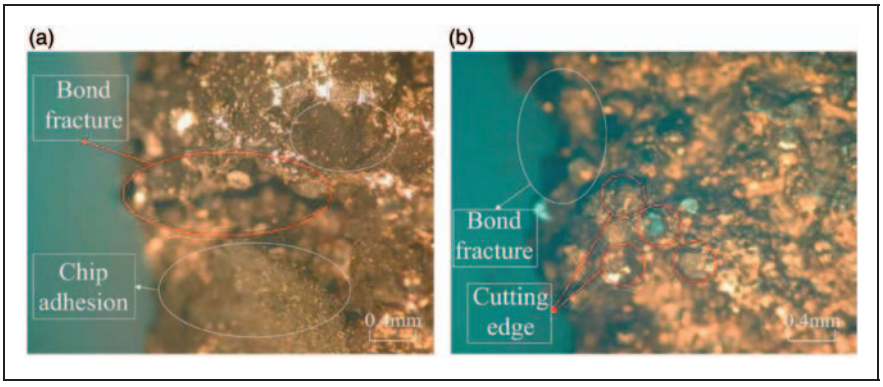

Figure 11. 2D microscopic images of the lateral face after the 32nd drilling test. (a) CD and (b) RUEM.

By contrast, the chip adhesion area in RUEM increased slightly and was much less than that in CD, which indicated that better chip removal condition could be achieved in RUEM.

Wear of tool lateral face. Figures 10 and 11 show the images of the drill lateral face after the 15th and 32nd drilling tests, respectively. Figure 10 shows that some grain pullout occurred in CD or RUEM after 15 drilling test times, especially at the edge. Obvious chip adhesion occurred in the hollow space in CD while some grain micro-fracture was observed in RUEM. It indicated that the drill lateral face in RUEM kept a better cutting ability compared with that in CD.

After the 32nd drilling test (Figure 11) in CD, the severe chip adhesion and bond fracture occurred due to the poor chip removal character and great friction between the drill and the workpiece. In RUEM, although the bond fracture and grain pullout also occurred at the lateral face, obvious chip adhesion did not appear. It was mainly attributed to the better chip removal and heat conduction in RUEM.[12]

Machined surface quality. The topographic features of the machined surface at the entrance as well as the exit location both in CD and RUEM after 15 and 32 drilling test times are shown in Figures 12 and 13, respectively. It could be obtained that the hole surface quality in RUEM was much better than that in CD at the entrance or the exit position during drilling. Moreover, in CD, the hole surface quality after 32 drilling test times became much worse than that after 15 drilling test times, especially at the exit position, due to obvious delamination and marked surface roughness. Conversely, in RUEM, the hole surface quality either at the entrance or the exit location had a less worsening trend after 32 drilling test times compared with that after 15 drilling test times.

The variations of machined surface roughness at the exit and entrance location during drilling both in CD and RUEM are shown in Figure 14. It was obtained that the machined surface roughness in RUEM was obviously better than that in CD, especially at the exit location. For the roughness at the exit location (Figure 14a), it could be seen that the hole surface roughness increased rapidly in the initial region, and then decreased slightly in steady region with some fluctuation, and finally it had a steady increasing trend in the deteriorate region. In contrast, although the hole surface roughness at the exit position in the deteriorated region rose obviously, the roughness in the initial or steady regions was lower in RUEM than that in CD. As for the roughness variation trends at the entrance location (Figure 14b), it could be seen that the entrance surface roughness was increasing slightly with small fluctuation in all the regions of the two drilling process, and the roughness in RUEM was also better than that in CD. The difference of surface roughness in the two drilling process showed that the drill wear during RUEM had a positive effect on maintaining the high surface quality.

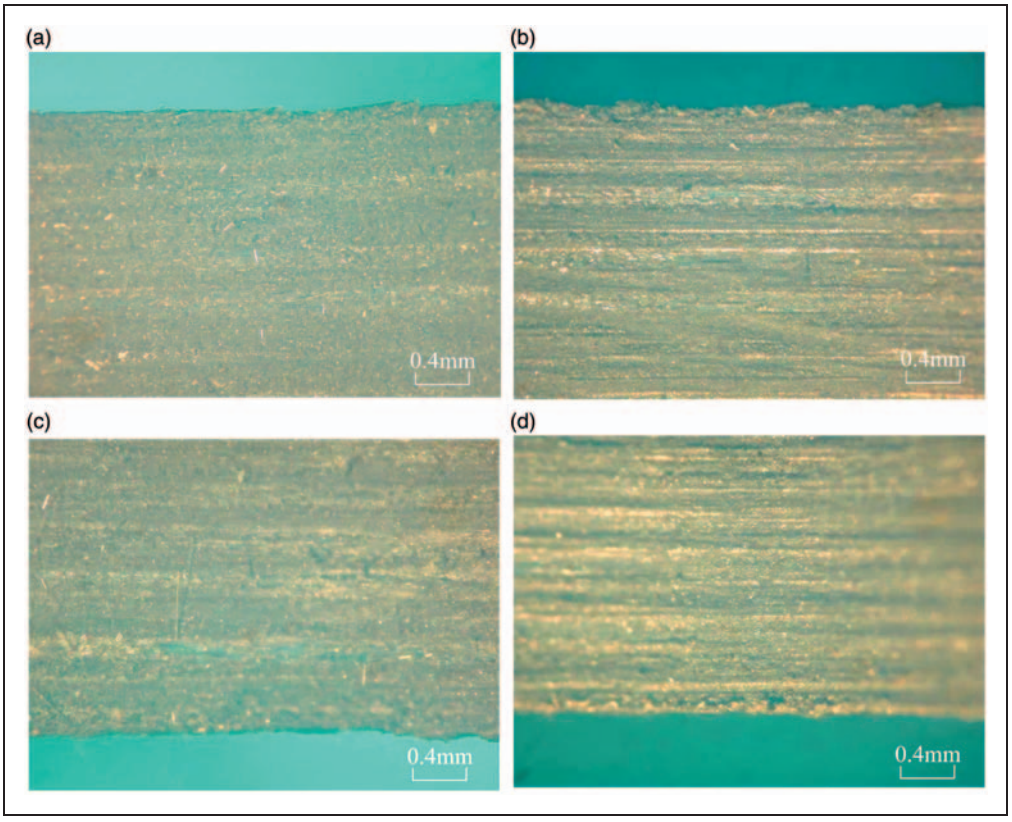

Figure 12. Topographic features of the machined surface after 15 drilling test times. (a) entrance in CD, (b) entrance in RUEM, (c) exit in CD, and (d) exit in RUEM.

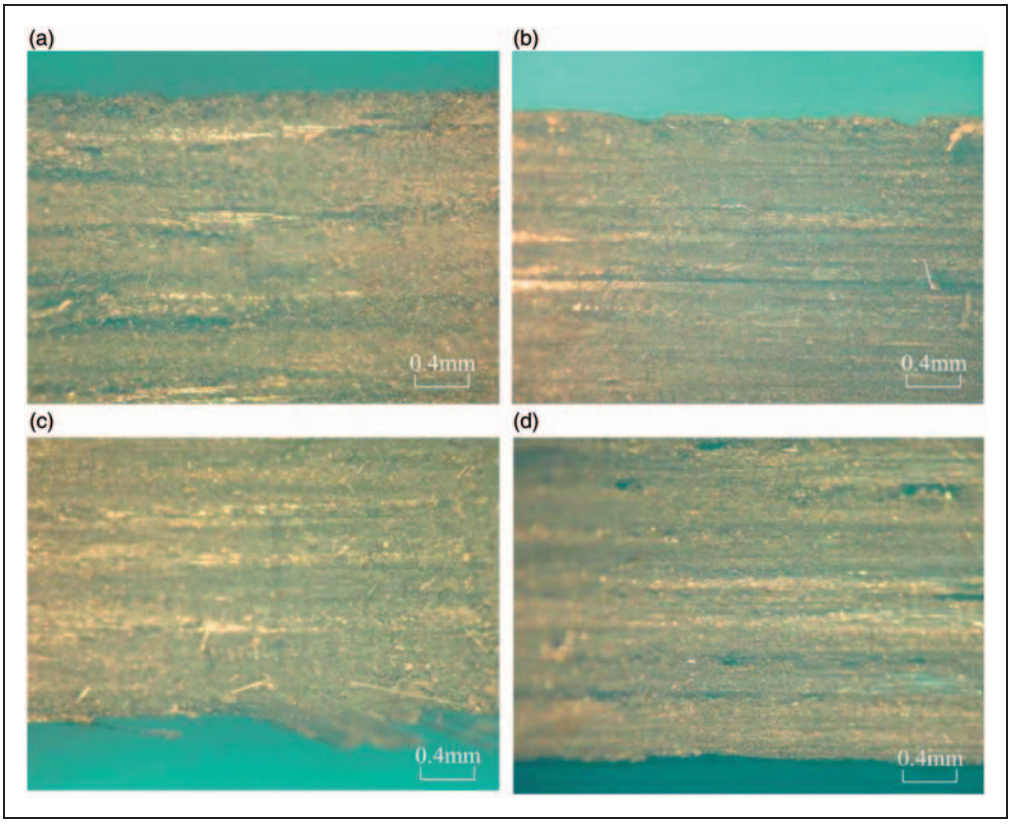

Figure 13. Topographic features of the machined surface after 32 drilling test times. (a) entrance in CD, (b) entrance in RUEM, (c) exit in CD, and (d) exit in RUEM.

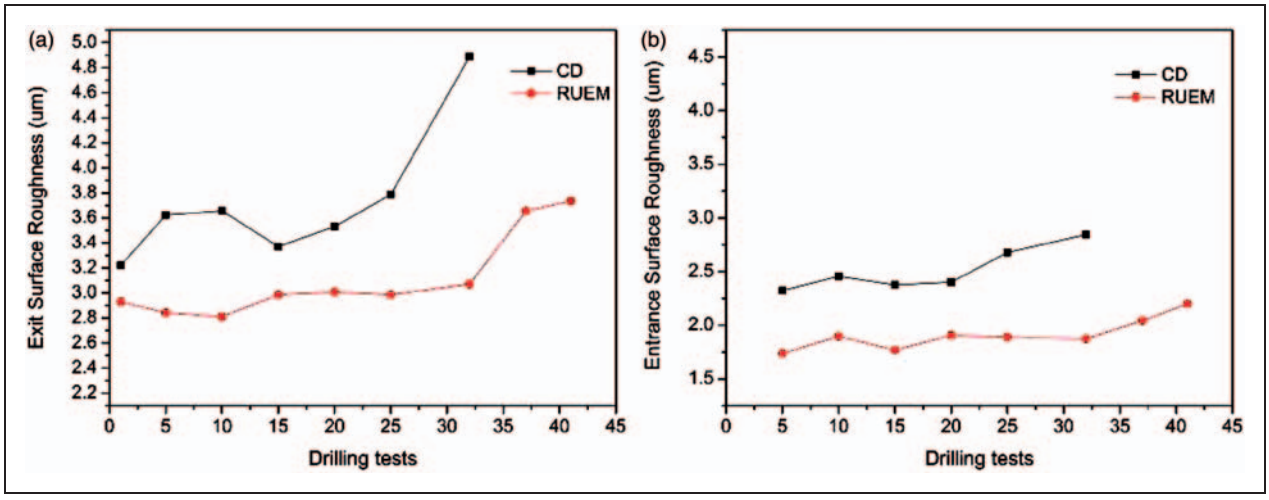

Figure 14. Variation of surface roughness during drilling. (a) at the exit location and (b) at the entrance location.

Discussion

As described earlier, the diamond core drill wear behavior either in CD or RUEM can be divided into three stages: the initial region, the steady region, and the deteriorated region, according to the obtained drilling force and drill surface topographic features.

Since RUEM is a hybrid machining process of grinding and ultrasonic machining, the wheel wear mechanism in grinding is the basis to understand tool wear mechanisms in RUEM. The research conducted by

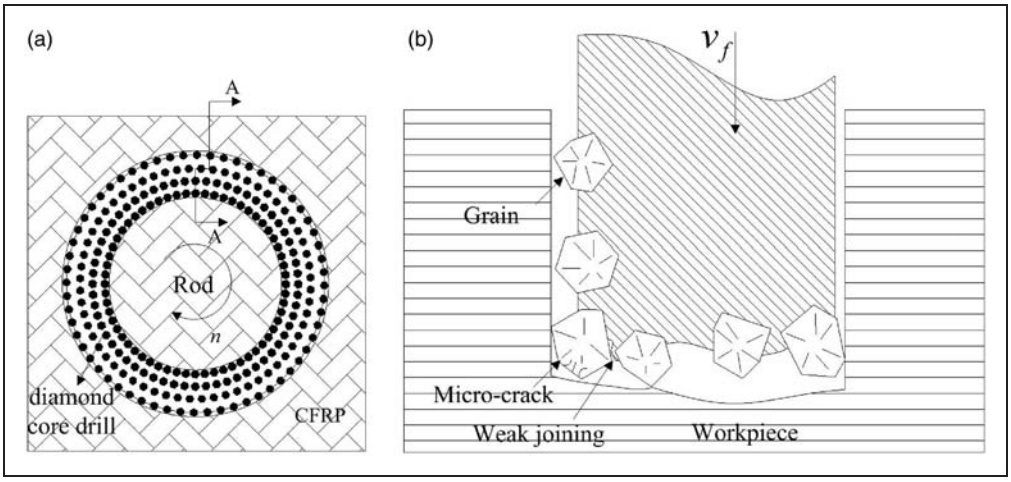

Figure 15. The end face and sectional view of core drill. (a)the core drill end face and (b) the initial drill topography before drilling.

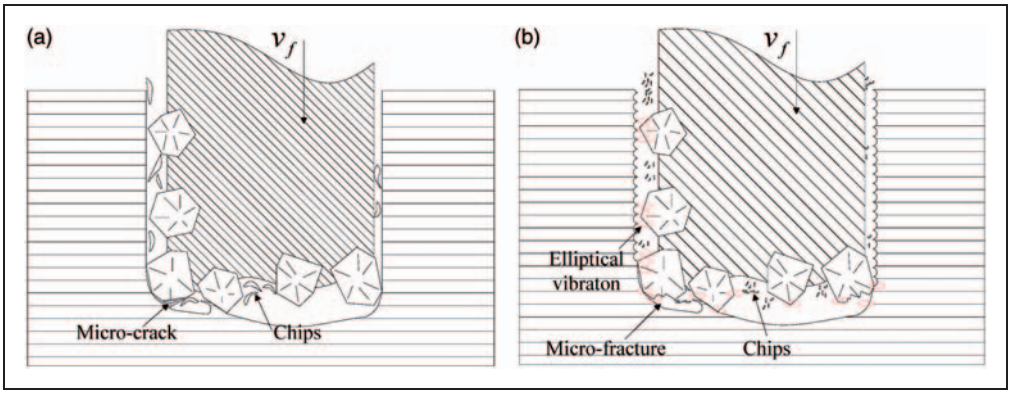

Figure 16. Mechanism of core drill wear in the initial region. (a) CD and (b) RUEM.

Malkin et al. indicated that there were three main modes of wheel wear: attritious wear, grain micro-fracture, and bond fracture.[22] Attritious wear included the dulling of abrasive grains and the growth of wear flats owing to rubbing against the workpiece by grains. Grain micro-fracture involved the removal of abrasive fragments by fractures within the grains. Bond fracture causes dislodging of grains from the binder. It was validated that attritious wear and grain micro-fracture resulted in only a few percent of the tool weight loss while bond fracture was mainly responsible for the loss in the wheel radius. However, the attritious wear led to the increase of flat area and determined the magnitude of the grinding force and the quality of machined surface, while the grain micro-fracture and bond fracture exposed new cutting edges to be responsible for the self-sharping of grinding wheels.[23,24]

Figure 15(a) shows the full view of drill end face which is the initial drill topography before drilling and Figure 15(b) is the sectional view (e.g. A-A) of the diamond core drill. Some fragile grains were created due to the abrasive grain primary cracks and some weak joining of abrasive grains. It was difficult to avoid the weak joining during vacuum brazing process in manufacturing of diamond core drills. The typical mechanism of drill wear for different regions in CD and RUEM are summarized as the models from Figures 16 to 18.

In the initial wear region, the wear patterns in CD included grain pullout and slight grain micro-fracture (see Figure 16(a)), while the wear patterns in RUEM included slighter grain pullout and more obvious grain micro-fracture (see Figure 16(b)) due to the smaller drilling force and greater impulse impacts by elliptical ultrasonic vibration in RUEM. The fragile grains did not adhere to the solder firmly, which made these grains lower mechanical strength than others. Thus in the initial wear region, the drill end face was worn easily, caused a rapid increasing cutting force either in CD or RUEM. Furthermore, the initial wear region of

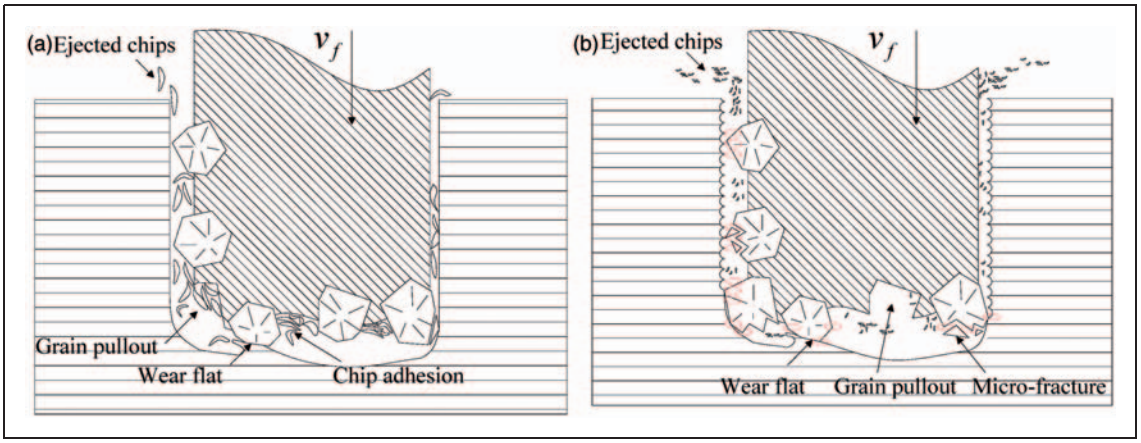

Figure 17. Mechanism of core drill wear in the steady region. (a) CD and (b) RUEM.

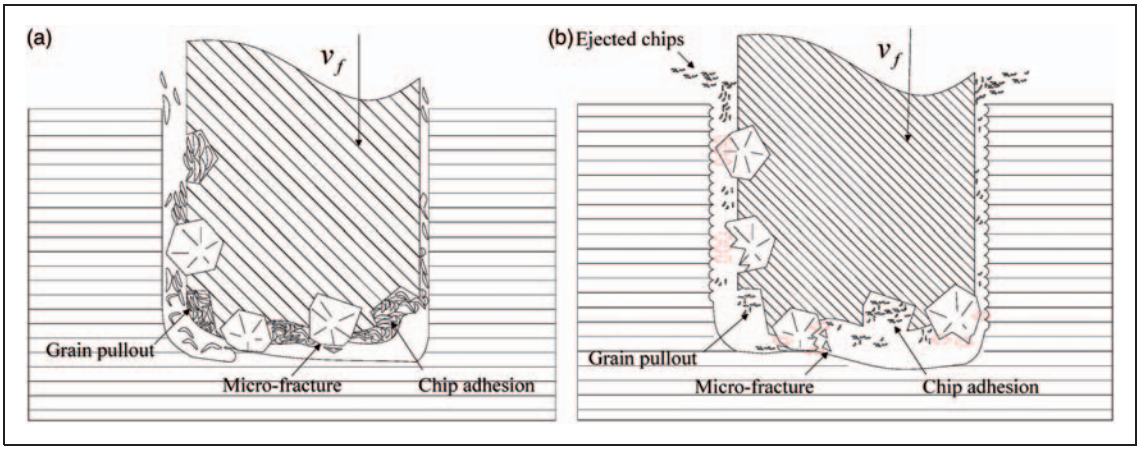

Figure 18. Mechanism of core drill wear in the deteriorated region. (a) CD and (b) RUEM.

RUEM was shorter than that of CD, and the reason was the impulse impacts on the grains which resulted in the faster drill wear.

In the steady wear region, the drill end face wear in CD could be mainly characterized by the following modes: attritious wear, chip adhesion, and grain pullout, as shown in Figure 17(a). And the drill end face wear in RUEM could be characterized by three patterns: attritious wear, grain micro-fracture, and grain pullout, as shown in Figure 17(b). These drill wear modes are completely determined by the interaction between the grains and the workpiece, such as grain cutting action, chip deformation, friction effect, and other factors. The wear mechanism of drill end face is modified by the elliptical ultrasonic vibration of grains on the drill end face.

Firstly, the grain cutting action is changed by using elliptical ultrasonic vibration. The orientation of the grain cutting edges in CD is consistent with the direction of the cutting velocity, so only the same cutting edges are employed to cut the workpiece until the edges are worn. However, the cutting edges are always changing in RUEM due to the continuous variable cutting direction along the spiral cutting path of the grains. As the grain position and cutting direction in RUEM is changed, the negative rake angle and the interaction area between the grain and the workpiece are also changed. Therefore, with the aid of elliptical ultrasonic vibration, the attritious wear of grains at the drill end face is restrained to some extent, the sharpness of grains was maintained in RUEM.

Secondly, the grain micro-fracture appears easier due to the continuous impacts of elliptical ultrasonic vibration on grain cutting edges, resulting in higher cutting edge density in RUEM. However, it is not consistent with the observations reported for RUM of advanced ceramics by Zeng et al.[22] They concluded that, in RUM of advanced ceramics, the tool wear pattern of grain micro-fracture which was commonly seen in metal grinding and conventional grinding (CG) of

ceramic materials was not observed. The reason for the different observation results is the difference of workpiece material, the tool type, and the ultrasonic vibration mode. The higher cutting edge density is considered as one of the positive factors for the improvement of surface quality and the drilling force decrement in RUEM.

Thirdly, the chip formation is changed in RUEM. It was observed that the carbon fiber that cut off in RUEM was smaller under the microscope in this experiment due to the discontinuous grain cutting action. This is consistent with the researches conducted by Ma and Liang et al.[12,22] Ma et al. found that the chip thickness was reduced significantly in drilling aluminum alloy assisted by UEV. Liang et al. examined the grinding chips generated in both elliptical ultrasonic assisted grinding (EUAG) and CG of monocrystal silicon and validated that the grinding chips in EUAG were much smaller than that in CG.[24] The chip removal condition is improved in RUEM. The drill in RUEM is vibrated in an elliptical mode along the hole radical direction during drilling, so the larger instantaneous radial clearance between the drill and the workpiece can be obtained in RUEM. As a result, compared with CD, smaller chips are able to be rejected in larger radial clearance easily, and less chip adhesion would happen in RUEM. In addition, the ultrasonic impulse energy provides the ultrasonic cleaning function at the end of the core drill in RUEM, which not only helps to effectively remove the adherent chip on the drill surface but also keeps the sharpness of diamond abrasive. By comparison, chips are hard to be rejected in radial clearance effectively and timely in CD, resulting in an obvious increase of chip adhesion on the drill surface.

In the deteriorated wear region, severe grain pullout and bond fracture occurred in RUEM or CD due to the large drilling force (see Figure 18). And severe chip adhesion happened in CD due to poor chip removal condition and high drilling temperature. In contrast, for RUEM, the excellent chip removal condition and the heat conduction weakened the chip adhesion effectively.[12] In this region, the cutting ability of diamond core drill either in CD or RUEM became much poor due to the large drilling force and high drilling heat. Thus, the following repairing operation was needed to restore the drill performance in the deteriorated region.

Conclusions

A series of drilling experiments were carried out with and without the assistance of elliptical ultrasonic vibration, and the wear mechanism of diamond core drill in RUEM of CFRP was analyzed in comparison with that in CD. The following conclusions are drawn from this study:

1. The drill wear process can be divided into three regions either in RUEM or CD of CFRP. The steady region and tool life can be performed up to 39% and 28% longer in RUEM compared with that in CD, respectively.
2. More micro-fracture of diamond grains generated in RUEM leads to a longer sharpness maintaining time and smaller drilling force in RUEM than that in CD.
3. In contrast to CD, the higher active cutting edge density in RUEM due to less chip adhesion and more grain micro-fracture has a positive effect on the improvement of the machined surface quality.

The above study demonstrates that the performance of diamond core drill is improved significantly in RUEM of CFRP in comparison with that in CD.

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Conflict of Interest

None declared.

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References

1. Kim PJ, Lee DG and Choi JK. Grinding characteristics of carbon fiber epoxy composite hollow shafts. *J Compos Mater* 2000; 34: 2016–2035.
2. Ucar M and Wang Y. End-milling machinability of a carbon fiber reinforced laminated composite. *J Adv Mater* 2005; 37: 46–52.
3. Abrao M, Faria PE, Campos Rubio JC, et al. Drilling of fiber reinforced plastics: a review. *J Mater Process Technol* 2007; 186: 1–7.
4. Hocheng H and Tsao CC. Preliminary study of ultrasonic drilling of fiber-reinforced plastics. *J Mater Process Technol* 1995; 48: 255–266.
5. Hocheng H and Tsao CC. The path towards delamination-free drilling of composite materials. *J Mater Process Technol* 2005; 167: 251–264.
6. Hocheng H and Dharan CKH. Delamination during drilling in composite laminates. *ASME J Eng Ind* 1990; 112: 236–239.
7. Tsao CC and Hocheng H. Analysis of delamination in drilling composite materials using core-center drill. In: *11th ICCE*, Hilton Head, SC, USA, 2004.

8. Hocheng H and Tsao CC. Comprehensive analysis of delamination in drilling of composite materials with various drill bits. *J Mater Process Technol* 2003; 140: 335–339.
9. Tsao CC and Hocheng H. Effect of eccentricity of twist drill and candle stick drill on delamination in drilling composite materials. *Int J Mach Tools Manuf* 2005; 45: 125–130.
10. Kubota M, Tamura Y and Shimamura N. Ultrasonic machining with a diamond impregnated tool. *Bull Japan Soc Precision Eng* 1977; 11: 127–132.
11. Feng Q, Cong WL, Pei ZJ, et al. Rotary ultrasonic machining of carbon fiber-reinforced polymer: feasibility study. *Machining Sci Technol* 2012; 16: 380–398.
12. Jing L, Deyuan Z, Longgang Q, et al. Feasibility study of the rotary ultrasonic elliptical machining of carbon fiber reinforced plastics(CFRP). *Int J Mach Tools Manuf* 2012; 53: 141–150.
13. Cong WL, Feng Q, Pei ZJ, et al. Dry machining of carbon fiber reinforced plastic composite by rotary ultrasonic machining: effects of machining variables. In: *Proceedings of the ASME 2011 international manufacturing science and engineering conference*, 13–17 June 2011, Corvallis, OR, USA.
14. Cong WL, Feng Q, Pei ZJ, et al. Rotary ultrasonic machining of CFRP using cold air as coolant: feasible regions. *J Reinf Plastics Compos* 2011; 30: 899–906.
15. Cong WL, Zou X, Deines TW, et al. Rotary ultrasonic machining of carbon fiber reinforced plastic composites: an experimental study on cutting temperature. *J Reinf Plastics Compos* 2012; 31: 1516–1525.
16. Cong WL, Feng Q, Pei ZJ, et al. Rotary ultrasonic machining of carbon fiber-reinforced plastic composites: using cutting fluid vs. cold air as coolant. *J Compos Mater* 2012; 46: 1745–1753.
17. Cong WL, Pei ZJ, Deines TW, et al. Rotary ultrasonic machining of CFRP using cold air as coolant: feasible regions. *J Reinf Plastics Compos* 2011; 30: 899–906.
18. Ma CX, Shamoto E and Moriwaki T. Drilling assisted by ultrasonic elliptical vibration. *Key Eng Mater* 2005; 291: 443–446.
19. Petrukha PG. Ultrasonic diamond drilling of deep holes in brittle materials. *Russian Eng J* 1970; 50: 70–74.
20. Lia ZC, Jiao Y, Deines TW, et al. Rotary ultrasonic machining of ceramic matrix composites: feasibility study and designed experiments. *Int J Mach Tools Manuf* 2005; 45: 1402–1411.
21. Zeng WM, Li ZC, Pei ZJ, et al. Experimental observation of tool wear in rotary ultrasonic machining of advanced ceramics. *Int J Mach Tools Manuf* 2005; 45: 1468–1473.
22. Malkin S. *Grinding technology: theory and applications of machining with abrasives*. Chichester: Ellis Horwood, 1989, pp.197–221.
23. Fathima K, Kumar AS, Rahman M, et al. A study on wear mechanism and wear reduction strategies in grinding wheels used for ELID grinding. *Wear* 2003; 254: 1247–1255.
24. Liang Z, Wu Y, Wang X, et al. Two-dimensional ultrasonically assisted grinding technique of monocrystal silicon. In: *Proceedings of the 5th international conference on leading edge manufacturing in 21st century*, 2009, Osaka, Japan, pp. 535–540.