Comparative Study on Cutting Performance of Conventional and Ultrasonic-assisted Bi-directional Helical Milling of CFRP

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Abstract

Compared with the conventional drilling, the helical milling has obvious advantages in making holes of Carbon Fiber Reinforced Plastic (CFRP). Nevertheless, the rapid wear of cutting edges readily causes some defects in the outlet holes, such as burrs and tearing. In order to improve the hole-making quality of CFRP, a comparative experimental study on conventional and ultrasonic-assisted bidirectional helical milling of CFRP was carried out. The wear mechanism of the forward and reverse cutting edges was analyzed in the two types of machining, and the change laws of cutting forces and hole wall quality were obtained by different machining means. The experimental results indicated that the flank face of forward and reverse cutting edges was dominated by the abrasive wear mechanism in the ultrasonic-assisted milling. With aggravation of the tool wear, no obvious coating peeled off the forward cutting edge, the reverse cutting edge remained relatively intact, and the wear form of neither cutting edge changed. Furthermore, in the ultrasonic-assisted reverse milling, the axial force and hole diameter deviation were restrained better than in the conventional milling, and especially when the tool wear occurred, the cutting force fluctuation varied slowly. In the ultrasonic-assisted milling, the shear fracture predominated over bending fracture. Meanwhile, the time variation of effective rake angles improved the chip breaking and removing performance of cutters, and thus the machining quality of hole wall was enhanced obviously.

1 Introduction

The carbon fiber reinforced composites (CFRP) have excellent physical properties of high specific strength, fatigue resistance and corrosion resistance, being widely applied to some advanced manufacturing fields such as aviation, aerospace, etc.[1, 2]. In the process of assembly, CFRP are mostly used as structural parts and need fixing and connecting by screws and rivets, and thus plenty of high-precision holes for assembly and connection need to be machined on CFRP. By contrast with the conventional drilling, the helical milling, as a new technique of machining holes, can greatly reduce the axial force and cutting temperature in the cutting process. Nonetheless, the interlaminar bonding force is weak at the outlet, and thus this causes readily some defects at the outlet [3–5]. The bi-directional helical milling has a better solution, but there are still some problems, for instance, the effective cutting distance of reverse cutting edges is short, and the wear occurs easily, etc.[6]. Consequently, the reasonable improvement in machining techniques to achieve high-quality holes and prolong the tool service life, is the key to promotion of the helical milling technology [7].

As to the helical milling, Saeid et al. [8] carried out an experimental research on CFRP laminates with tungsten carbide tool, analyzed the effect of cutting parameters on machined hole quality, and found that reduction in cutting speed and feed rate could obtain high-quality hole and good surface accuracy. Brinksmeier et al. [9] performed a comparative experiment on the conventional drilling and helical milling of aluminum, CFRP and titanium composites. The results showed that the cutting temperature and axial force in the helical milling were both lower than in the conventional drilling. Voss et al. [10] analyzed comparatively the tool wear and the hole diameter variances in the helical milling and conventional drilling. The results showed that the helical milling generated a better hole quality with smaller cutting

forces. Tanaka et al. [11] proposed the tilted planetary helical milling of CFRP, and concluded that a certain range of hole diameters could be machined and delaminations and burrs could even be avoided by adjusting the tilted angle. Yang et al. [12] proposed a new reverse helical milling method to increase the uncut thickness and restrain effectively the delamination at the outlet hole. Zhu et al. [13] presented the effect of tool geometry and cutting parameters on cutting forces and temperature, and used a response surface method to develop mathematical models for predicting the changes in cutting forces and temperature during helical milling of composites. Emad et al. [14] carried out an experimental research on the influence of cutting forces and machining parameters on delamination defects caused by the helical milling of CFRP, and found that occurrence of delamination in machining could be reduced by increasing cutting speed or decreasing feed rate. Wang et al. [15] established a cutting force prediction model for helical milling of unidirectional CFRP, and verified experimentally that the predicted values were in good accordance with the experimental values. Sakamoto et al. [16] investigated the influence of cutting rotational speed on cutting heat in helical milling of CFRP, and found that increasing the rotational speed could effectively restrain the heat from transferring to the workpiece and thus reduced cutting heat.

The ultrasonic-assisted machining shows obvious advantages in processing CFRP [17, 18]. Based on the ultrasonic-assisted orthogonal cutting experiment, Takeyama [19] carried out the research into chip formation, cutting forces and surface quality at different fiber cutting angles, and verified experimentally that the ultrasonic machining was effective in cutting force and surface quality. Farrukh et al. [20] researched the ultrasonic-assisted drilling of CFRP. By contrast with the conventional drilling, the axial force decreased largely and chips were characterized by the transition from brittleness to ductility in the ultrasonic-assisted drilling. Xu et al. [21] developed a reliable mechanics model, and predicted by the model that ultrasonic application could significantly reduce cutting forces, minimize fiber deformation, promote fiber fracture on the cutting interface, and thus obtain better machined surface integrity. Cong et al. [22] performed a comparative study on the tool wear in rotary ultrasonic drilling of CFRP/Ti using fixed and variable feed rate, and discovered that the tool wear resistance was better at variable feed rate than at fixed feed rate. Phadnis et al. [23] presented a finite model of ultrasonic-assisted drilling (UAD) of CFRP, explaining volumetric and thermal softening phenomena in the workpiece material, and found that UAD could make the machined surface quality much better than the conventional drilling. Geng et al. [24] proposed rotary ultrasonic helical machining (RUHM) of small-diameter CFRP holes, and concluded that compared with the conventional grinding, RUHM significantly improved the hole edge quality and surface integrity, and remarkably reduced the axial force and delamination factor. Zhang et al. [25] established a theoretical model for predicting cutting forces in ultrasonic-assisted drilling of CFRP, and verified experimentally the theoretical prediction was in good accordance with the experimental results. Moreover, it was found that in the same cutting condition, the axial force in the ultrasonic-assisted drilling was reduced by 20–30% as much as in the conventional drilling. Amin et al. [26] developed a novel cutting force prediction model for ultrasonic-assisted milling of CFRP, and proposed a method for calculating effective cutting time and friction force.

To sum up, the helical milling technique has certain advantages in making holes of composites, but it still has no good solution to the negative influence of tool wear on the hole quality of CFRP. The bi-directional

helical milling can restrain burr and delamination defects at the outlet, but some problems, such as the rapid wear of reverse cutting edges, the damage occurring easily on the junction surface of the forward and reverse machining, etc. increase the processing cost. The ultrasonic-assisted machining, a typical compound machining technique, has some advantages in reducing the axial force, weakening the tool wear, etc. [27, 28]. This paper, based on the conventional bi-directional helical milling technique, introduced ultrasonic assistance, and carried out research on the cutting performance of bi-directional helical milling of CFRP materials.

2 Experimental Design

This paper designed a comparative experiment on making holes by the conventional and ultrasonic-assisted bi-directional helical milling of CFRP with stepped bi-directional milling cutters (SBMCs) in order to obtain the wear mechanism and surface quality change law of ultrasonic-assisted SBMCs. VDL-1000E high speed milling center was selected as the machine tool, and USBT40ER32 inductive rotary ultrasonic vibration tool holder acted as the ultrasonic-assisted machining equipment. The experimental material was unidirectional CFRP laminates and the substrate material AG-80 epoxy resin. The reinforcing material was T700 carbon fiber, its volume ratio was $60 \pm 5\%$, and the workpiece size was 200mm×110mm×6mm. The SBMC for the experiment was coated with diamond, and its substrate material was YG8 cemented carbide, in which WC was main composition and the binder Co accounted for 8%. The milling cutter ranged in diameter from 4 to 6 mm, and had 4 teeth. The rake angle was 10° , the flank angle 8° , and the helical angle of helical groove 35° .

The bi-directional helical milling technique for making holes used in the experiment consisted of two stages. First, in the stage of forward machining, the eccentricity of the milling cutter was 1 mm, and when the forward machining proceeded to the hole depth of 4 mm, the eccentricity was decreased and an allowance of 0.4 mm for machining was retained, and then the whole hole was milled through. Next, in the stage of reverse machining, the eccentricity was adjusted back to 1 mm, and then the retained allowance for machining was removed by reverse machining, and finally machining a through hole of 8 mm in diameter was finished. The experimental system, along with the forward and reverse machining process is shown in Fig. 1.

In the ultrasonic-assisted machining experiment, the cutting parameters are as follows. The rotational speed was 4500r/min, the feed per tooth 0.02mm/z, the pitch 0.2mm, the vibration frequency 28kHz and the amplitude 5μm. Kistler 9139AA piezoelectric dynamometer was used to collect the milling forces. After 5 holes were milled continuously, the cutter was removed. Then VHX-1000 super-high magnification zoom lens microscope and SU3500 scanning electron microscope were employed to detect the flank wear morphology and the micromorphology of the forward and reverse cutting edges, and meanwhile the machined holes were marked. After the experiment finished, the workpiece was removed. Then the super-high magnification zoom lens microscope was used to observe the hole diameter and the inlet and outlet morphology of the machined holes, and the scanning electron microscope was further used to observe the micromorphology of hole wall.

3 Experimental Results And Discussion

3.1 Comparison of tool wear mechanism

As the cutting proceeded, obvious wear bands occurred on the flank face of the forward cutting edge in both conventional and ultrasonic-assisted milling, and it was mainly the coating material wear. When the 30th hole was machined, the grooves on the flank wear band became deeper in the conventional milling, shown in Fig. 2(a), than in the ultrasonic-assisted milling, shown in Fig. 2(b), and the fiber particles bonded evidently together in the former milling because a small number of fiber particles were softened by the accumulation of cutting heat in machining, thus causing adhesive wear. By contrast, in the ultrasonic-assisted milling, the grooves on the flank wear zone were shallow and well distributed in width and depth, and neither residual fiber particles nor adhesion existed.

With aggravation of the tool wear, the diamond coating on the surface of the forward cutting edge gradually became thin, and the adhesion between the coating and cemented carbide substrate was decreased obviously by constant impact load and friction. When the 80th hole was machined, evident coating shedding occurred on the flank surface in the conventional milling, and the tool substrate was exposed, shown in Fig. 3(a). Subsequently, the energy spectrum analysis of the material composition was made in the edge wear area, and it was found that the oxygen content reached 5.19%, which indicated that strong friction generated high cutting heat, partly oxidizing the cutting tool. As is shown in Fig. 3(b), in the ultrasonic-assisted milling, the coating wear on the flank surface expanded, but no extensive coating peeled off, and so the edge still kept sharp. This is because the separate cutting by ultrasonic vibration shortens the tool-fiber contact time within the same machining distance, and thus well-distributed impact kinetic energy and extrusion load are exerted on the cutting edge, making the forward cutting edge worn slowly.

In the initial stage of machining, there were no obvious differences in the wear morphology of the reverse cutting edges between the two types of machining, and the wear area concentrated on the cutting edge, dominated mainly by the parallel scratches in the cutting direction, as is shown in Fig. 4. The wear morphology on the cutting edge did not start to change until the 30th hole was machined. Figure 4(a) shows that because of the mechanical and thermal impact, the reverse cutting edge coating in the conventional milling peeled intermittently in the shape of strip, and notches occurred on the local cutting edge. As is shown in Fig. 4(b), the cutting edge in the ultrasonic-assisted milling remained in good condition, mainly because ultrasonic introduction promoted the chip removal in the reverse cutting, reduced the friction between the cutting edge and chip, and thus improved the cutting performance of the reverse cutting edge.

As is shown in Fig. 5(a), when the 80th hole was machined, the reverse cutting edge coating in the conventional milling further peeled, and here a large tangential stress was generated by the cyclic contact load at the notches of the cutting edge, and then some microcracks occurred in the weak area of the cutting edge. With expansion of the microcracks, the fatigue wear gradually predominated, presented as

unevenness of the cutting edge and further expansion of the notches. Figure 5(b) shows that by contrast only tiny notches occurred on the reverse cutting edge due to ultrasonic introduction, and the edge shape did not change obviously. It was found by the further energy spectrum analysis of the cutting edge composition that the oxygen content only accounted for 0.63%, and this indicated that no obvious oxidation occurred in the ultrasonic-assisted milling. The main reason is that ultrasonic assistance avoids effectively chip accumulation in the reverse machining and accelerates the edge wear. At the moment no other wear forms occurred on the reverse cutting edge.

3.2 Effect of tool wear on cutting forces and hole quality

The reverse machining process of bi-directional helical milling determines the machining quality of outlet holes of CFRP. Therefore, the variation law of the axial force generated in the reverse machining was analyzed. As is shown in Fig. 6, as the cutting proceeded, the axial forces on the reverse cutting edge increased to a certain extent in both conventional and ultrasonic-assisted milling. By contrast, the axial force generated in the ultrasonic-assisted milling was smaller than in the conventional milling because the frequent separation between the cutting edge and fiber caused by ultrasonic vibration improved the chip removal state of the reverse cutting edge, and thus decreased the friction resistance between the flank face and chip. After machining 30 holes, there was an obvious difference in the increase of axial forces between the two types of milling. In the conventional milling, the cutting edge coating started to wear and so the cutting edge became blunt. Consequently, the cutting performance came to decline. As the machined hole number increased, the reverse cutting edge wear worsened, and evident coating shedding occurred at the edge. Furthermore, the cutting mechanism for fiber materials changed from shear to extrusion, causing rapid increase of the axial force. When the 80th hole was machined, the axial forces in the two types of milling both increased evidently, and here the cutting edge in the ultrasonic-assisted milling also wore to some extent. Nonetheless, even in the later stage of machining, the axial force in the ultrasonic-assisted machining was still 30% or so less than in the conventional milling.

Figure 7 reveals a comparative analysis of the hole diameter deviation and the surface quality at the reverse inlet hole in the conventional and ultrasonic-assisted reverse milling when the machined hole number was different. At the early stage of milling, the machined hole diameter was close to the standard hole diameter, and there were no obvious differences in the hole diameter deviation between the two types of machining. After the 30th hole was machined, the hole diameter deviations both increased to some extent. In the conventional milling, the hole diameter deviation was relatively large, and tiny burrs occurred at the reverse inlet hole, while in the ultrasonic-assisted milling, not only was the hole diameter deviation relatively small, but also no obvious defects appeared at the inlet hole.

In the conventional milling, as the milling proceeded until the 80th hole was machined, the cutting edge coating started to peel extensively, and so the fiber bundles could not be cut off effectively. The fiber resilience narrowed the hole diameter, and meanwhile the cutting mechanism changed from shear to a mixture of shear and extrusion, and caused the fiber to twist and tear. Consequently, some machining defects such as burrs occurred in the inlet area. By comparison, the ultrasonic assistance advanced the chip removal and reduced the heat from chip blockage, and thus the flank wear of the reverse cutting

edge was decreased, keeping the reverse cutting edge sharp. At the moment, the cutting mechanism in the ultrasonic-assisted milling was mainly shear, and the axial force was relatively small. This inhibited effectively the deformation and resilience of fiber. Thus, the defects at the inlet were obviously improved. Not until the 100th hole was machined did the hole diameter deviation increase obviously in both types of milling, but the hole diameter deviation was inhibited better in the ultrasonic-assisted milling than in the conventional milling.

3.3 Comparison of the hole wall morphology on the junction surface

Figure 8 shows the hole wall morphology on the junction surface of the forward and reverse milling when the 30th hole was machined. As is shown in Fig. 8(a) and 8(b), in both conventional and ultrasonic-assisted forward milling, fewer machining defects appeared in the inlet hole, while obvious delamination occurred in the outlet hole. This is because the inadequacy of supporting materials at the outlet makes the interlaminar adhesive strength larger than the resin substrate strength, and causes interlaminar separation. As is shown in Fig. 8(c) and 8(d), in neither type of reverse milling, obvious delamination was found in the outlet hole because the supporting role of uncut material in the reverse machining restrains effectively the delamination in the outlet hole.

In the conventional milling, an obvious damage zone existed on the junction surface of the forward and reverse machining, shown in Fig. 8(c). One reason is that the fiber bundle is lack of supporting materials when the reverse machining proceeds to the junction surface, and the other reason is that the fiber stress on the junction surface is in the opposite direction of forward machining, and thus the fiber fracture in different directions interferes with each other. Comparatively in the ultrasonic-assisted milling, no obvious machining defects appeared on the junction surface, shown in Fig. 8(d). This is because the ultrasonic assistance changes the cutting state and strengthens the shear effect of reverse cutting edge. Moreover, the reciprocating movement under the influence of vibration strengthens the ironing effect of the flank face on fiber, and thus reduces the machining damage caused by the insufficient support of fiber bundles.

3.4 Comparison of the hole wall micromorphology in the inlet and outlet area

Figure 9 defines the fiber cutting angle β as the included angle between fiber and cutting speed directions, varying with rotation of the milling cutter. In order to compare the machining quality of hole walls in the conventional and ultrasonic-assisted milling, the micromorphology was extracted from the areas near four typical fiber cutting angles (0° , 45° , 90° and 135°) to be analyzed.

Figure 10 presents the hole wall micromorphology at different cutting angles when the 60th hole was machined in the conventional milling. Fiber debonding, subsurface substrate damage, fiber pull-out and fiber stripping can all be observed clearly from the figure. Especially in the reverse cutting of fiber at a cutting angle of 135° , shown in Fig. 10(d), the hole wall was comparatively rough, plenty of fiber bundles different in length resulted from fiber resilience, and here the tensile fiber fracture predominated.

As is shown in Fig. 11, the hole wall micromorphology was relatively smooth thanks to the ultrasonic assistance, and by contrast with the conventional milling, the surface quality was still much improved even at the fiber cutting angle of 135°. For one reason, in the ultrasonic-assisted milling, the effective rake angle of cutting tools has time variation, improving the chip breaking and removing performance of cutters, and thus the tool wear is reduced. For the other reason, the shear fracture predominates over the bending fracture in the ultrasonic-assisted machining, and so the regular fracture morphology occurs on the machined surface, effectively inhibiting the fiber resilience and improving the hole wall quality.

3.5 Analysis and discussion

Figure 12 shows a comparison of the chip removal in the conventional and ultrasonic-assisted reverse milling. In the latter milling, the cutting state of cutters was changed by the reciprocating ultrasonic vibration, so that the chips were easier to be removed. This largely reduced the friction between the cutter and blocked chips and thus enhanced the tool durability and the hole wall quality.

In order to characterize the chip removal performance in the ultrasonic-assisted and conventional reverse milling, the chip flow velocity V_0 is defined as the evaluation index, expressed as:

$$V_0 = \frac{V_R K_v}{\cos \beta_0} \quad (1)$$

In the expression, K_v stands for the chip volume coefficient, K_f the ratio of the sectional area of cutters to the sectional area of helical grooves, and β_0 the helix angle of cutters. In given milling conditions, K_v , K_f and β_0 are fixed values. The synthetic cutting speed V_R differs in the conventional and ultrasonic-assisted milling, respectively expressed as Exps. (2) and (3).

$$V_{Rc} = \sqrt{V_s^2 + V_f^2} = \sqrt{\left(\frac{\pi d n_s}{60}\right)^2 + \left(\frac{\pi d f_a}{60}\right)^2} \quad (2)$$

$$V_{Ru} = \sqrt{V_s^2 + (V_f + V_F)^2} = \sqrt{\left(\frac{\pi d n_s}{60}\right)^2 + \left(\frac{\pi d f_a}{60} + 2\pi A f \cos(2\pi f t)\right)^2} \quad (3)$$

In the expressions, V_{Rc} and V_{Ru} stand respectively for the compound cutting velocity (mm/s) in the conventional and ultrasonic-assisted milling, V_s the tangential moving velocity (mm/s), V_f the axial feed rate (mm/s), V_F the reciprocating axial feed rate with ultrasonic assistance (mm/s), the maximum diameter of reverse cutting edge, f_a the axial feed (mm), n_s the rotary velocity of cutters (r/min), the amplitude (μm), and the vibration frequency (Hz).

It can be learned from Exps. (1)-(3) that the reciprocating axial feed rate V_F with the ultrasonic assistance brought about the cyclic motion of contact and separation between the reverse cutting edge and the workpiece, and thus the chip flow velocity V_0 was changed. This has solved the problem of chip blockage

in the conventional milling caused by gradual drop in the chip flow velocity, resulting from the friction resistance between helical grooves and hole walls.

Figure 13 depicts the time-varying effect in the ultrasonic-assisted milling of CFRP. Namely, the instantaneous cutting velocity of the cutting edge and the effective rake angle of the cutter both varied cyclically in a vibration cycle. In the figure, γ_0 stands for the rake angle, $\Delta\gamma$ the time-varying increment of the rake angle, γ_e the effective rake angle, α_0 the flank angle, ψ_i the included angle between the tool path and tangential velocity, V_z the compound velocity of V_f and V_F , and P_n the plane perpendicular to the cutting edge.

In the ultrasonic-assisted milling, the cutting velocity V_z varies cyclically along with the tool path, and so the effective rake angle is time-varying, differing from the effective rake angle keeping fixed in the conventional milling. Here the effective rake angle is expressed as Exps. (4) and (5).

$\gamma_e = \gamma_0 + \Delta\gamma = \gamma_0 + \psi_i \quad (4)$
$\tan \psi_i = V_z / V_s \quad (5)$

The time variation resulting from ultrasonic assistance enhances successfully the contact conditions in machining so that the fiber materials can be removed more easily by the cutting edge, and thus the chip breaking and removing performance is improved in the reverse milling. Consequently cutting forces are decreased effectively and the reverse cutting edge wear is slowed down.

4 Conclusion

In this paper, a comparative study was conducted on the cutting performance in the conventional and ultrasonic-assisted bidirectional milling of CFRP using the cutter coated with diamond, and an analysis was made of the tool wear, the machined hole quality and the hole wall accuracy. The conclusions are drawn as follows.

1. In the ultrasonic-assisted milling, both forward and reverse cutting edge wear is dominated mainly by the abrasive wear mechanism. With aggravation of the tool wear, the same adhesive wear and coating shedding as that in the conventional milling never occur on the forward cutting edge, and the reverse cutting edge also keeps relatively intact.
2. By contrast with the conventional milling, the axial force produced in the ultrasonic- assisted reverse milling is comparatively small. With increase of the hole number, the ultrasonic-assisted machining presents more obvious advantages. Both the machining defects in the inlet hole and the hole diameter deviation are effectively inhibited.
3. The cyclically reciprocating motion of cutters resulting from ultrasonic assistance changes successfully the cutting state of fiber bundles, and strengthens the shear effect of the reverse cutting

edge. Consequently, the machining damage caused in the conventional milling due to insufficient support of fiber bundles in the outlet, is effectively restrained, and thus the machining quality of the forward and reverse machining junction is improved better.

4. In the ultrasonic-assisted milling, the time variation of the effective rake angle enhances the chip breaking and removing performance of cutters, and reduces the axial cutting force. This has effectively solved the problem of chip blockage in the reverse milling. Thus the tool wear is slowed down and the machining quality of hole wall is improve obviously.

Declarations

Ethical Approval The research does not involve human participants or animals and the authors warrant that the paper fulfills the ethical standards of the journal.

Consent to Participate It is confirmed that all the authors are aware and satisfied of the authorship order and correspondence of the paper.

Consent to Publish All the authors are satisfied that the last revised version of the paper is published without any change.

Author contributions Chen Tao, has organized the project, designed the experiments, and written the manuscript; Wang Yongsheng, has designed the experiments, analyzed and arranged data, and written the manuscript; Lu Yujiang, has conducted the experiments, and collected and analyzed data; Liu Gang: has conducted the experiments, and collected and analyzed data; Liu Guangjun, has reviewed the manuscript.

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Competing Interests The authors declare that they have no competing interests.

Availability of data and materials The raw/processed data required to reproduce these findings cannot be shared for the time being. Data will be made available upon request.

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Figures

Figure 1

The experimental system and the forward and reverse machining process

(a) Conventional milling

(b) Ultrasonic-assisted milling

Figure 2

The flank Wear morphology of the forward cutting edge after machining the 30th hole

(a) Conventional milling

(b) Ultrasonic-assisted milling

Figure 3

The flank wear morphology of the forward cutting edge after machining the 80th hole

(a) Conventional milling

(b) Ultrasonic-assisted milling

Figure 4

The flank wear morphology of the reverse cutting edge after machining the 30th hole

(a) Conventional milling

(b) Ultrasonic-assisted milling

Figure 5

The flank wear morphology of the reverse cutting edge after machining the 80th hole

Figure 6

Comparison of the axial forces in the reverse machining stage in the two-type milling

Figure 7

Comparison of the inlet hole diameter deviations in the two-type reverse machining

(a) Conventional forward milling

(b) Ultrasonic-assisted forward milling

(c) Conventional reverse milling

(d) Ultrasonic-assisted reverse milling

Figure 8

The hole wall morphology on the of forward and reverse milling

Figure 9

Variation of the fiber cutting angle with rotation of the milling cutter

Figure 10

The hole wall micromorphology in conventional milling of the 60th hole

Figure 11

The hole wall micromorphology in ultrasonic-assisted milling of the 60th hole

(a) Conventional milling

(b) Ultrasonic-assisted milling

Figure 12

Comparison of the chip removal in conventional and ultrasonic-assisted reverse milling

Figure 13

The time-varying effect in the ultrasonic-assisted milling of CFRP