The Study of CFRP Variable Feed Drilling Method Based on Sinusoidal Curve

Shuaipu Wang
Zhengzhou University
Jie Liang (liangjie812@163.com)
Zhengzhou University

Research Article

Keywords: CFRP drilling, variable feed, delamination factor, surface roughness

Posted Date: January 7th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1222587/v1

Abstract

In order to reduce the delamination damage of carbon fiber reinforced polymer (CFRP) drilling and improve the drilling quality. A variable feed drilling method based on sinusoidal curve was proposed, that is, when the drill at a distance of 1mm from the hole exit, the feed rate of the drill would be reduced according to the rule of sinusoidal curve. The method is compared with the traditional feed drilling by experiment, and the influence of the variable feed drilling on thrust force, delamination factor, surface quality, surface roughness of hole wall and exit hole wall morphology are analyzed. The results show that compared with constant-feed drilling, the variable-feed drilling based on sinusoidal curve reduces the thrust force near the hole exit, and greatly improves the delamination factor, surface quality and hole wall morphology at the exit. But the influence on the hole wall roughness is not particularly obvious.

1. Introduction

Due to its light weight, high strength and strong impact resistance, CFRP (Carbon Fiber Reinforced Plastics) has been widely used in aircraft wings and fuselage and other main load bearing structures in recent years. With the number of CFRP holes increasing rapidly during aircraft assembly, the quality and efficiency of holes are of great significance to aircraft assembly [1].

The quality problems of drilling CFRP mainly include delamination and peel-up at the entrance and exit, fiber pulling out, oversized diameter, burr on hole edge, etc., among which delamination at the exit has the greatest influence on the quality of CFRP hole [2-3]. Jia [4] showed through simulation and experiment that thrust force was the main reason for delamination of CFRP exit, and gave the critical thrust force of CFRP drilling without delamination. Wu [5] experimentally studied the causes of delamination in the inner wall of CFRP, and believed that the internal delamination was more sensitive to the change of feed rate. The ultrasonic vibration-assisted drilling and the placement of lining plates under CFRP played a positive role in reducing delamination damage. Geier [6] drilled unidirectional CFRP using diamond-coated tools, and the results showed that the feed rate had the greatest influence on thrust force and exit delamination, while the spindle speed had a good effect on improving uncut fiber burr. Jia [7] proposed a multi-edged tool structure to drill Ti/CFRP stacks, and showed that the multi-edged tool structure could effectively reduce CFRP exit delamination and the aperture error of Ti/CFRP stacks by experimental comparison. Some other scholars [8-10] used artificial intelligence algorithm to optimize the CFRP drilling process parameters, obtained the cutting parameters corresponding to the minimum delamination damage, and found that the feed rate was positively correlated with the delamination damage.

In addition to changing cutting parameters and tool geometry, some special machining methods are also applied to CFRP holes. Chen [11] combined ultrasonic vibration with spiral milling process to reduce thrust force and cutting heat in machining and significantly reduce the phenomenon of matrix adhesion to hole wall. Islam [12] introduced EDM(electrical discharge machining) process to burr removal at CFRP exit to obtain better surface quality. Yaşarl [13] improved the delamination damage at the CFRP exit through a step-change feed drilling method. Although the special machining method achieves better machining quality, its corresponding supporting equipment is not mature yet.

In brief, existing research showed that reducing the thrust force of exit and increasing the spindle speed could suppress surface delamination damage, and then reducing the feed rate under the condition that the spindle speed was constant would reduce the machining efficiency. In the paper, a variable feed drilling method based on sinusoidal curve was proposed, which has a positive effect on reducing the thrust force of exit, surface delamination damage, the roughness of the hole wall and improving the surface morphology of hole wall by experiment comparison with traditional drilling.

2. Damage Mechanism Of Cfrp Drilling

At present, the machining damage of CFRP cannot be repaired, and the large degree of damage will directly lead to the scrapping of parts [1-2]. Therefore, the quality of assembly hole will directly affect the assembly performance and service life of structural parts. The quality evaluation of assembly holes of CFRP structural parts mainly includes the following three aspects [14]: (1) Entrance fiber peel-up and delamination; (2) Hole wall surface groove; (3) Exit push-up delamination. The analysis of the three damage formation mechanisms is as follows:

(1) Entrance fiber peel-up and delamination: Under the action of high-speed rotation and cutting force of the tool, the main cutting edge of the tool cuts off the fibers on the surface of CFRP. When the tool is about to fully enter the workpiece (As shown in Figure 1. (a)), the tool acts on the fiber at the hole edge, causing fiber twist separation (Mode III) and upward peel-up (Mode I) [5].

(2) Hole wall surface groove: With the continuous drilling of the tool, the cutting heat gradually accumulates and softens the matrix epoxy resin, which will weaken the wrapping ability of the matrix to the reinforcement fiber [3]. At the same time, the cutting force causes the carbon fiber to break and peel off from the matrix, which result in the formation of groove on the surface of the hole wall (Mode II).

(3) Exit push-up delamination: When the tool is about to drill out (as shown in Fig. 1. (b)), the uncut material bends and deforms under the action of thrust force and causes interface delamination and fiber breakage (Mode I and mode II).

In summary, the push-up delamination of CFRP exit is easy to occur, and it is also the main reason for the high scrap rate of structural parts [1-5]. Therefore, the reduction of thrust force will be an important measure to improve exit delamination damage and hole making quality.

3. Variable Feed Drilling And Design Of Experiment Scheme

3.1 Variable feed drilling method

Franck girot (Pr.) [15] studied the thrust force causing fiber delamination under different uncut material thickness. It was considered that the formation of delamination damage could be suppress if the thrust force was less than the critical force of delamination. In order to reduce the thrust force, it can be achieved by reducing the feed rate, but the sudden change of the feed rate is bound to cause the vibration of the cutting system. In addition, the step change of feed rate will also greatly reduce the machining efficiency. therefore, the flexible and smooth line of sinusoidal curve provides the possibility for the achievement of high-efficiency variable feed without vibration. The specific process of sinusoidal variable feed drilling is shown in Figure 2, details are as follows:

I: Select the sine curve of the interval in $\left[\frac{\pi}{2}, \frac{3\pi}{2}\right]$.

II: Considering the accuracy of the equipment, the curve obtained by I was discretized by the interval $\frac{\pi}{8}$ and the select of discrete point could be expressed as:

$$x_i = x_0 + (i\text{-}1) \times \frac{\pi}{8} \qquad (1)$$

where, $x_0 = \frac{\pi}{2}$, x_i, is the coordinate of discrete point (i=1,2…9).

III: Since the optimal feed rate of CFRP drilling is unknown, so the way that feed speed decreases by half has been applied in this paper. The discrete sample points obtained by II are correlated with the feed rate to obtain each discrete feed rate. This correlation formula can be expressed as:

$$f_i = \left(\frac{\sin(x_i)+1}{40} \times \frac{f - \frac{f}{2}}{0.05} \right) + \frac{f}{2} \qquad (2)$$

where, f is the initial feed rate(mm/r), fi is the discrete feed rate of each section (i=1,2…9).

VI: The whole drilling process was divided into two sections; one section has low damage with traditional drilling(t_0-t_1), another section has serious delamination damage with variable feed drilling(t_1-t_2).

V-VII: The feed rates distributed by VI were correlated with the corresponding spindle speed. Here, the cutting time of each discrete feed is the same by default. Therefore, the cutting time of each discrete feed can be expressed as:

$$T = \frac{60L}{\sum_{i=1}^{9} f_i \times n} \qquad (3)$$

where, n is the spindle speed(rpm), T is the cutting time(s) of each discrete feed, L is variable feed displacement (L=2mm, the distance is from the t_1 time to t_2 time).

All in, all data are stored in Mitsubishi PLC controller for calling during the drilling process.

3.2 Experimental design and conditions

The workpiece used in the trials was provided by Weihai Guangwei composite material Co., Ltd. The Carbon fiber workpiece (Brand: T300 / 7901) is overlaid by 24 layers of unidirectional prepreg within which the fiber orientations were $[45/0/-45/90]_{3S}$ directions and thermosetting to a thickness of 3.6mm. The detailed properties of unidirectional prepreg can be referred in Table 1. The size of the workpiece is 100mm×40mm×3.6mm, and the tests were carried out with uncoated solid carbide drills(K20), which are usually used to dry drilling due to their hot hardness. The drills which were used to this work have cylindrical shank, 5 mm diameter, 135°-point angle and 30° helix angle.

The general full factorial design was used to design the experiment intent. The experimental parameters are shown in Table 2, where "0" represents traditional feed strategy, and "1" represents variable feed strategy based on sine curve. It can be seen from Table 2 that the various levels of all experimental factors were combined to form 18 different experimental conditions. Two independent repeated experiments were carried out under each experimental condition. A total of 36 experiments needs to be carried out, and these experiments were performed in random order. In order to minimize the impact of tool wear, the tool was cooled and cleaned after drilling, and the tool was replaced after 10 holes. In addition, the discrete data of variable feed rate are presented in Table 3.

Table 1 Mechanical properties of unidirectional prepreg

Laminate Mechanical Properties	
Density/(g·cm^{-3})	1.6
Tensile strength/MPa	1800
Tensile modulus/GPa	115
Flexural strength/MPa	1200
Compressive strength/MPa	1000
Interlaminar shear strength/MPa	55
Fiber volume fraction (%)	70
Ply thickness (mm)	0.15

Table 2 Experimental parameters settings

Factors	Units	Values		
Drilling strategy		0	1	
Feed speed	mm/r	0.04	0.08	0.12
Spindle speed	rpm	2100	2400	2700

Table 3 The discrete data of variable feed (mm/r)

Discrete label	0.04-0.02	0.08-0.04	0.12-0.06
1	0.04	0.08	0.12
2	0.039	0.078	0.118
3	0.037	0.074	0.111
4	0.034	0.068	0.101
5	0.03	0.06	0.09
6	0.026	0.052	0.079
7	0.023	0.046	0.069
8	0.021	0.042	0.062
9	0.02	0.04	0.06

All experiments were carried out on the drilling experiment platform, which was developed by the authors' lab. The drilling experiment platform consists of the feed platform, the fixture, the tool, the workpiece and the sensor, and it can be seen in Fig. 4. The feed platform was equipped with an oriental motor servo motor (PKE569AC), which can set multiple feed speeds that are convenient for the control system to call and provide convenience for variable feed drilling process. The sensor was used to measure the thrust force in the drilling process.

After the experiment, Keyence Ultra Depth Microscope (VHX-2000) was used to measure the surface delamination damage and hole wall morphology at the exit. The surface delamination damage can be expressed by dimensionless one-dimensional delamination factor F_d [9,13] (see Fig.4) and its formula is as follow:

$$F_d = \frac{D_{\max}}{D_{nom}} \qquad (4)$$

where, $D_{\max}$ is the largest diameter including all delamination areas, D_{nom} is the nominal diameter of the hole. In order to obtain the difference in hole wall roughness of different drilling strategies. The workpiece was cut by water jet cutting machine and surface roughness Ra was measured from median line to exit (see Fig.5) with TR200 portable roughness meter (from Beijing ShiDaiZhiFeng Instrument Co., Ltd.) following the 0.8-mm stroke.

4. Results And Discussion

4.1 Comparison and analysis of thrust forces in different strategies

The thrust force is an important factor that affects the exit surface delamination, and lower thrust force helps reduce exit delamination damage [16-17]. Figure 6 shows the relationship between thrust force and feed displacement under f=0.04mm/r, n=2100rpm cutting parameters. In the figure, the thrust force at the exit of the variable feed is always lower than that of the traditional feed. The change trend of the difference between the two thrust forces at the same drilling position is: first gradually increase and then slowly decrease. The main reason is the reduction of thrust force caused by the variable feed when the tool chisel is 1mm away from the exit with a sinusoidal rule to reduce the feed rate. Unless, from the surface quality of the two different drilling strategies in the figure, it can be seen that the surface quality of variable-feed drilling (lower fiber delamination and burrs) is better than traditional drilling.

In summary, the change rule of the sine curve (trend: small-large-small) is consistent with the change of the thrust force difference between the two-drilling strategies, which verifies the correctness of the application of the proposed method on processing equipment. In addition, the excellent surface quality of the variable feed achieves the expectation of reducing the delamination damage on the exit by reducing the thrust force.

4.2 Delamination factor comparative analysis

Figure 7 shows the measurement results of the delamination factor. It can be seen that the delamination factor increases with the increase in the feed rate, and an appropriate spindle speed is also beneficial to reducing the delamination factor. In addition, the relative errors of the delamination factors under the two different drilling strategies are basically positively correlated with feed rate, which indicates that the variable feed drilling method has a better performance at a higher material removal rate.

We also noticed that under the cutting conditions: n=2400rpm, f=0.08mm/r. The delamination factor of traditional feed drilling is lower than that of variable feed. At n=2400rpm, the effect of feed rate on the delamination factor is not particularly significant than others. This is mainly because n=2400rpm is the optimal speed (see Fig. 8) and the thrust force is smaller than the critical thrust force at different feed rates, which results in the delamination factor of traditional drilling and variable-feed drilling having not an obvious difference.

Figure 8 is the main effect plot of the delamination factor. It can be seen from the figure that the parameter that has the greatest influence on the mean value of the delamination factor is the feed rate, followed by the drilling strategy. The variable feed hole making process reduces the delamination factor from 1.6 to 1.3. The influence of cutting parameters on the delamination factor is as follows. The feed rate was reduced in a sinusoidal rule at the exit, which reduce the cutting thickness of each tooth of the tool, and weak the effect of thrust force on the uncut material. The action will reduce the delamination tear damage along the surface of the hole. In addition, the spindle speed increases the friction between the tool and the composite material and generates a large amount of cutting heat; as the tool feeds, the cutting heat gradually accumulates, which causes the resin to soften and reduce the effect of the thrust force.

4.3 Analysis of exit surface morphology

The main surface damages in CFRP processing are: delamination, fiber tearing, and burrs (see Fig. 9) [18]. Delamination is caused by fiber cracking at the hole edge due to the thrust force being greater than the critical force between the CFRP layers; fiber tearing is the surface damage caused by the delamination and cracking of the fiber along the fiber direction under the action of thrust force; burrs are left because the material at the edge of the exit hole cannot be effectively cut. Therefore, the difference of surface damage represents the bearing capacity of the hole and service life [19].

Figure 10 is a comparison of the surface morphology of different drilling strategies. It can be seen from the figure that for traditional feed, as the feed rate increases, the surface tearing and delamination become more serious and the damage area gradually increases. The increase of the spindle speed can effectively remove the burrs on the hole edge, but it cannot reduce the fiber tearing and delamination of the exit. In general, a better surface quality requires a lower feed rate and an appropriate spindle speed.

For variable feed, the overall surface topography quality is better than traditional feed, but the feed rate is still the main factor that determines the drilling damage of exit. The drilling damage at the variable feed exit is mainly uncut burrs, small-scale fiber tearing and low delamination. The main reason is that the feed rate was reduced in a sine curve, so that the thrust force of exit was less than the critical force of delamination, which avoids serious delamination damage at the exit.

The following explains the mechanism of the effect of the thrust force on the surface damage of the two drilling strategies. As shown in Fig. 11, under the action of the cutting heat, the thrust force of the tool's chisel edge separates the reinforcement fiber from the matrix, resulting in delamination between uncut material and cut material. Variable feed because the thrust force at the same cutting position is lower than the traditional feed (), so the delamination damage diameter is smaller (). Therefore, the surface quality formed by variable feed drilling exceeds traditional drilling.

4.4 Surface roughness of hole wall

Damage to the surface of the hole wall will lead to uneven stress distribution during the connection of the components, resulting in a decrease in the load-bearing capacity [16-17]. Due to the different cutting mechanisms of different fiber angles in CFRP (see Fig. 12), CFRP hole wall roughness is often poor and difficult to measure [8]. The roughness measurement result (see Fig. 13) shows that two drilling strategies under different feed rates have a minor difference on the roughness.

Combined with the main effect plot of roughness (Figure 14), it can be seen that the increase of the feed rate results in an increase in the roughness of the hole wall. The feed rate increases from 0.08mm/r to 0.12mm/r, and the average roughness increases greatly. The main reason is that the higher cutting force of the tool causes the severe peeling of the fiber from the resin matrix, resulting in the worse hole wall roughness [1,3]. The increase of the spindle speed results in an increase in the roughness of the hole wall (see Fig. 14). The main reason is that the increase of the tool spindle speed leads to a sharp increase in cutting heat, which exceeds the resin curing temperature and forms defects such as fiber pullout and matrix cracks under the action of force [11]. In addition, under the action of cutting heat, the fiber debris adheres to the hole wall to form plow-shaped particles, resulting in poor hole wall roughness [13].

In summary, the factors that have a greater impact on roughness are: feed rate> spindle speed> drilling strategy. Combining Figures 13 and 14, it can be concluded that the variable-feed drilling process has a positive effect on the improvement of the surface roughness of the CFRP hole wall compared to the traditional feed.

4.5 Comparative analysis of hole wall morphology

The composition of the composite material and the cutting mechanism determine that it is a difficult-to-machine brittle material, and the hole wall morphology also has a greater impact on the assembly performance of CFRP components [19-20]. The main defects of CFRP hole wall morphology are: exit fiber delamination, hole wall surface groove and fiber pull-out [5,14]. The fiber delamination is mainly caused by the excessive thrust force of the chisel blade. Surface cavities are caused by fiber breakage and peeling due to the angle of -45° between the tool and the fiber direction (see Fig. 15). The fiber pull-out is due to the combined action of the thrust force and the cutting heat, the fiber is separated from the matrix, leaving a rough surface with fiber pull-out.

Figure 16 is a comparison diagram of the morphology of the hole wall exit. It can be seen that the feed rate has a greater impact on the damage of the CFRP hole wall, and the increase of the spindle speed improves the improvement of surface cavitation, fiber pull-out and delamination damage. Observation of the morphology shows that the quality of the hole wall obtained under the condition of n=0.04mm/r is better than other conditions as a whole. Therefore, choosing a lower feed rate and a higher spindle speed when drilling carbon fiber composite materials will effectively reduce hole wall defects (delamination damage, surface cavities and fiber pull-out) and improve drilling quality.

In addition, it can be seen in Figure 16 that the variable-feed drilling process has better performance in reducing exit delamination and fiber pull-out compared to traditional-feeding, but the surface cavities are not significantly improved, which Mainly because -45 cutting mechanism cannot be eliminated between the tool and the fiber direction. It can also be seen from Fig. 16 that variable feed drilling has tolerance behavior for drilling with larger feeds (that is, better exit quality can be maintained under larger feeds).

In brief, no matter what kind of drilling strategy, it cannot completely eliminate the drilling damage at the exit of the composite material. The thrust force is still the key factor for the damage of delamination. The variable feed drilling strategy, which reduces the exit feed rate and thereby reduces the thrust force, provides a new idea for improving the drilling quality of composite materials in reducing less processing efficiency.

5. Conclusion

In this paper, the damage mechanism and factors affecting the quality of CFRP drilling were analyzed. The influence of feed rate, spindle speed, and drilling strategy on the factors of hole quality (thrust force, delamination factor, surface roughness and hole wall surface morphology) were focused on. conclusion as below:

1. In order to reduce the thrust force of the exit, a variable feed drilling method based on the sinusoidal curve setting feed rate is proposed, that is, the feed rate is set according to the sinusoidal law at a distance of 1mm from the tool to the exit. The variable-feed drilling strategy was carried out and compared with traditional drilling in the hole wall roughness and the surface delamination damage on the exit.
2. It can be seen from the thrust force of the tool at the same position that the thrust force of the variable feed is lower than that of the traditional feed, which verifies the correctness of the application of the proposed method. Through the quantitative analysis of the delamination factor and hole wall roughness, it can be known that the variable feed drilling process has a more

significant increase in the delamination factor than the traditional feed, but the difference on the roughness is not particularly obvious.

3. By comparing the surface of the exit and the morphology of the hole wall, it can be known that the variable feed process can effectively improve the surface drilling quality (delamination, fiber tearing, burr) of the composite material to obtain a smooth hole wall. Overall, under the premise of reducing the small processing efficiency, the variable feed drilling method provides a new idea for improving the drilling quality of composite materials.

Declarations

Funding: The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Conflicts of interest: The authors have no relevant financial or non-financial interests to disclose.

Availability of data and material: All data generated or analyzed during this study are included in this published article.

Code availability: Not applicable.

Ethics approval: Not applicable.

Consent to participate: Not applicable.

Consent for publication: Not applicable.

Authors' contributions: Material preparation, data collection and analysis were performed by Wang Shuaipu and Liang Jie. The first draft of the manuscript was written by Wang Shuaipu and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

References

1. Fu Pengqiang, Jiang Yinhong, Wang Yiwen, et al (2019) Research progress and perspective trend of drilling technology for carbon fiber reinforced polymer. Journal of Aeronautical Materials 39(06):32-45.
2. Geng Da-xi, Liu Yi-hang, Shao Zhen-yu et al (2019) Delamination formation, evaluation and suppression during drilling of composite laminates: A review. *Composite Structures* 216:168-186.
3. Jinyang Xu, Mohamed El Mansori (2016) Experimental study on drilling mechanisms and strategies of hybrid CFRP/Ti stacks. Compos Struct 157:461-482.
4. Zhenyuan Jia, Chen Chen, Fuji Wang, et al (2020) Analytical study of delamination damage and delamination-free drilling method of CFRP composite. J Mater Process Technol 282:116665.

5. Chao Qun Wu, Guang Lei Gao, Hao Nan Li , et al (2019) Effects of machining conditions on the hole wall delamination in both conventional and ultrasonic-assisted CFRP drilling. Int J Adv Manuf Tech 104(5):2301-2315.
6. GEIER N, SZALAY T (2017) Optimization of process parameters for the orbital and conventional drilling of unidirectional carbon fiber-reinforced polymers (UD-CFRP). Measurement 110:319-334.
7. Zhenyuan Jia, Chong Zhang, Fuji Wang, et al (2020) Multi-margin drill structure for improving hole quality and dimensional consistency in drilling Ti/CFRP stacks. Journal of Materials Processing Tech 276:116405.
8. Qian Wang, Xialiang Jia (2020) Multi-objective optimization of CFRP drilling parameters with a hybrid method integrating the ANN, NSGA-II and fuzzy C-means. Compos Struct 235:111803.
9. Byeong-chan Kwon, Ngoc Dai Duong Mai, Eun Soo Cheon, et al (2020) Development of a step drill for minimization of delamination and uncut in drilling carbon fiber reinforced plastics (CFRP). Int J Adv Manuf Tech 106(1): 1291-1301.
10. Tran Q P, Le D M, Huang S C (2020) Optimization of CFRP Drilling Process with Multi-Criteria 2Using TGRA. IEEE Eurasia Conf. IOT, Commun. Eng., ECICE 1(1): 334-337.
11. Chen Guang, Liu Jian, Ge Jia-ying et al (2021) Experimental Study on Ultrasonic Vibration Helical Milling of CFRP Based on Kinematic and Thermal-mechanical Analysis. *Journal of Mechanical Engineering* 57(01):199-209.
12. ISLAM M M, LI C-P, WON S-J et al (2017) A deburring strategy in drilled hole of CFRP composites using EDM process. Journal of Alloys and Compounds 703:477-485.
13. YASAR N, GUNNY M (2019) Experimental investigation on novel drilling strategy of CFRP laminates using variable feed rate. Journal of the Brazilian Society of Mechanical Sciences and Engineering 41(3).
14. MONYAYA M, CALAMAZ M, GEHIN D et al (2013) Evaluation of the performance of coated and uncoated carbide tools in drilling thick CFRP/aluminum alloy stacks. The International Journal of Advanced Manufacturing Technology 68:9-12.
15. Franck Girot (Pr.), Frédéric Dau, Mª Esther Gutiérrez-Orrantia (2017) New analytical model for delamination of CFRP during drilling. Journal of Materials Processing Technology 240:332–343.
16. Wang Xiao-da, Wang Fu-ji, Li Shen-kai et al (2020) Research on variable parameter hole-making process of large-thickness carbon fiber reinforced plastic. Journal of Dalian University of Technology 60:591-598.
17. MUND M, LIPPKY K, BLASS D et al (2019) Influence of production-based surface topography and release agent amount on bonding properties of CFRP. Composite Structures 216:104-111.
18. Zhang Hua-wei, Wu Jia-lu (2021) Failure Simulation Analysis of Carbon Fiber Reinforced Polymer Laminate with a Hole in Axial Tension Process. Journal of Northeastern University (Natural Science) 42(01):91-95.

19. Ministry of Aerospace Industry of the People's Republic of China. Hole-making technology of carbon fiber composite members: HB/Z 189-91[S]. Beijing: China Standard Press,1991.
20. Qiu Xing-yi, Li Peng-nan, Li Chang-ping et al (2018) Study on chisel edge drilling behavior and step drill structure on delamination in drilling CFRP. Composite Structure 203:404–413.

Figures

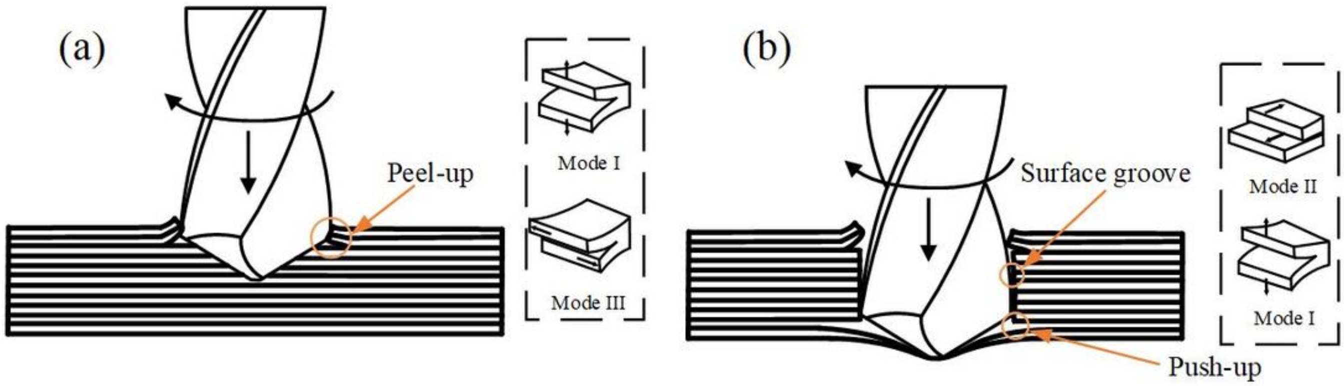

Figure 1

Damage mechanism of CFRP hole making

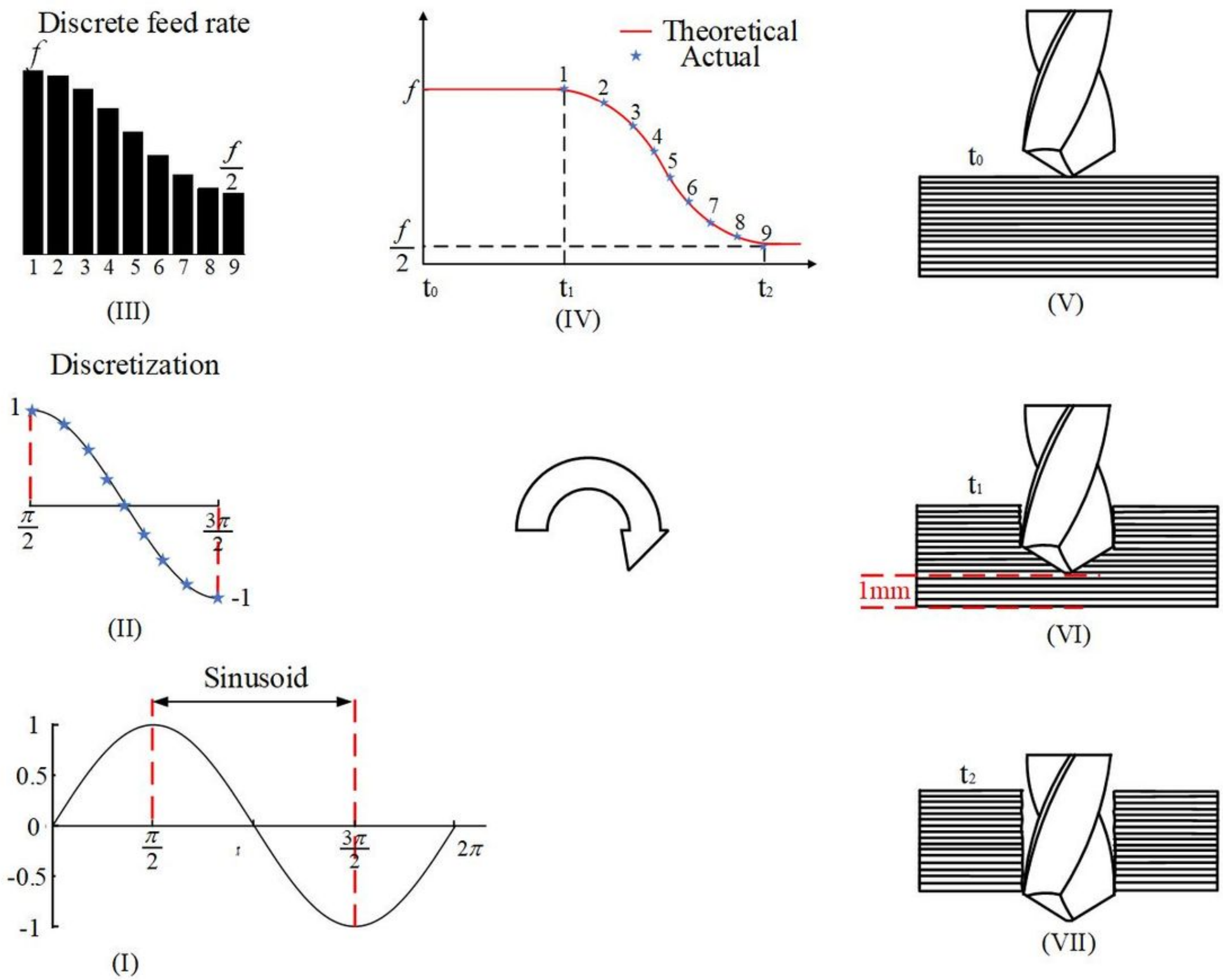

Figure 2

Variable feed drilling method association process

Figure 3

The drilling experiment platform

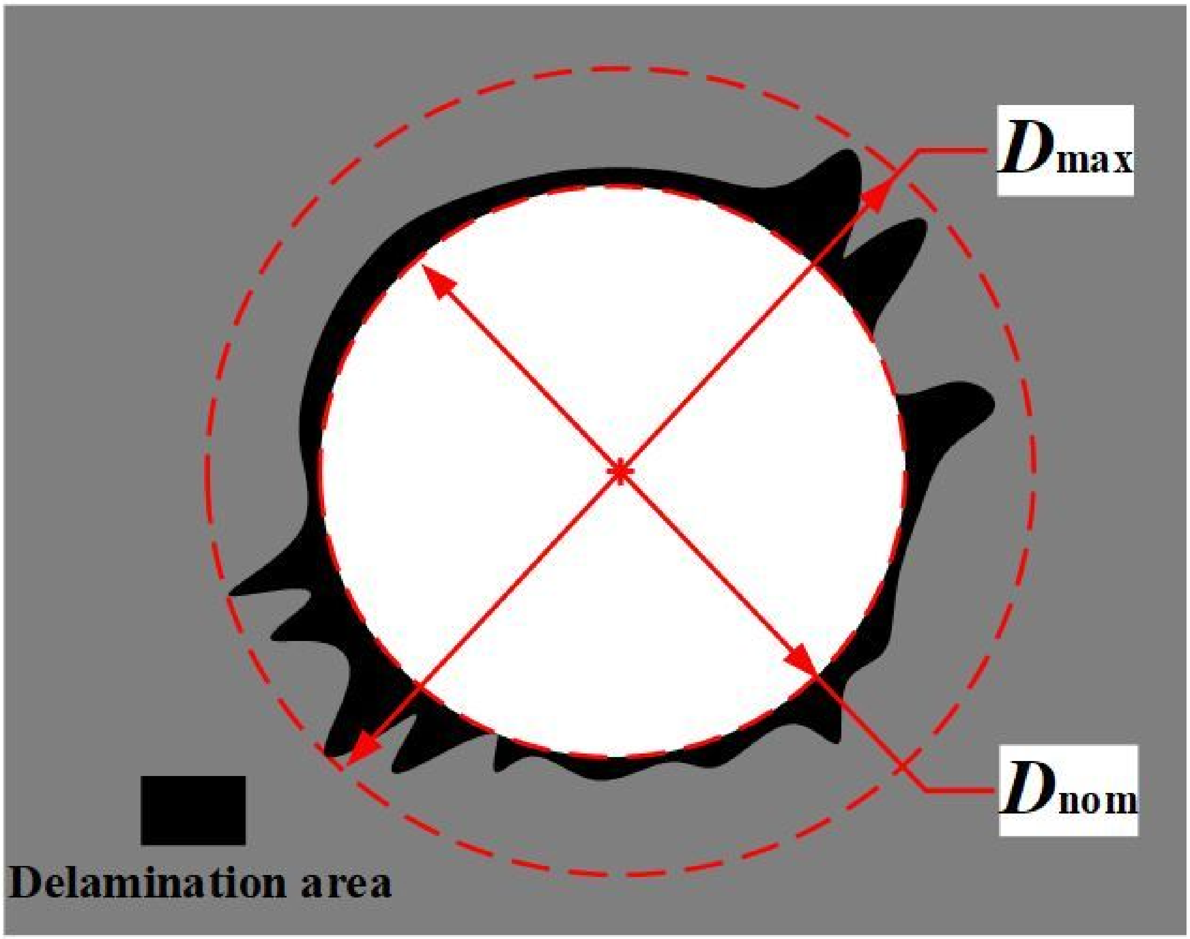

Figure 4

The measurement method of F_d

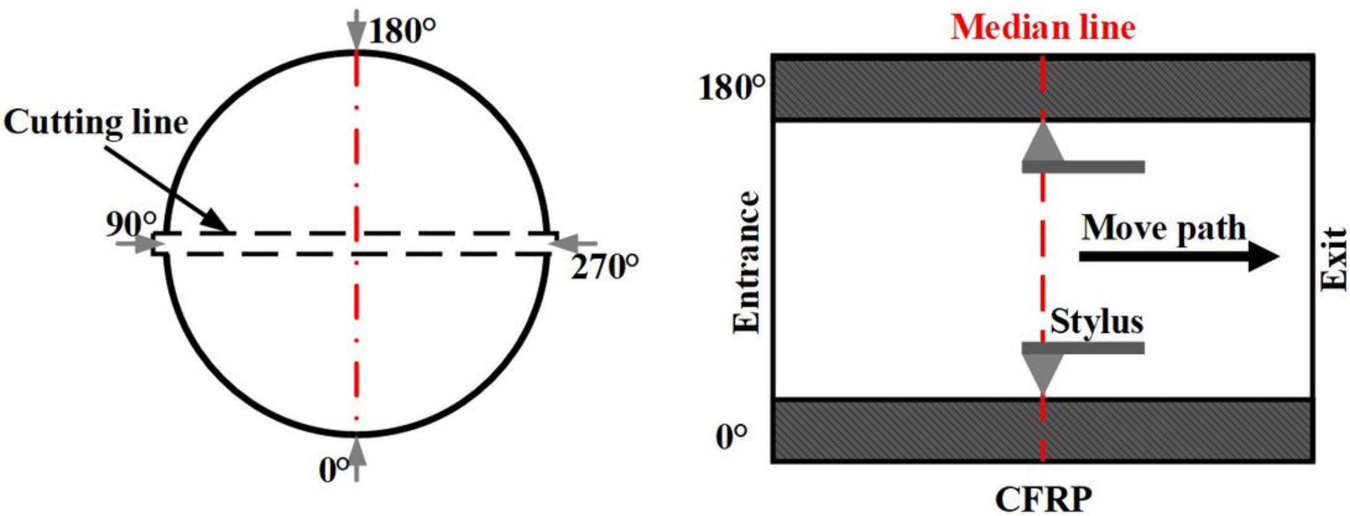

Figure 5

Measurement of hole wall surface roughness

Figure 6

Thrust force change under the cutting condition: *f*=0.04mm/r, *n*=2100rpm

Figure 7

The measurement results of delamination factor

Figure 8

The main effect plot of delamination factor

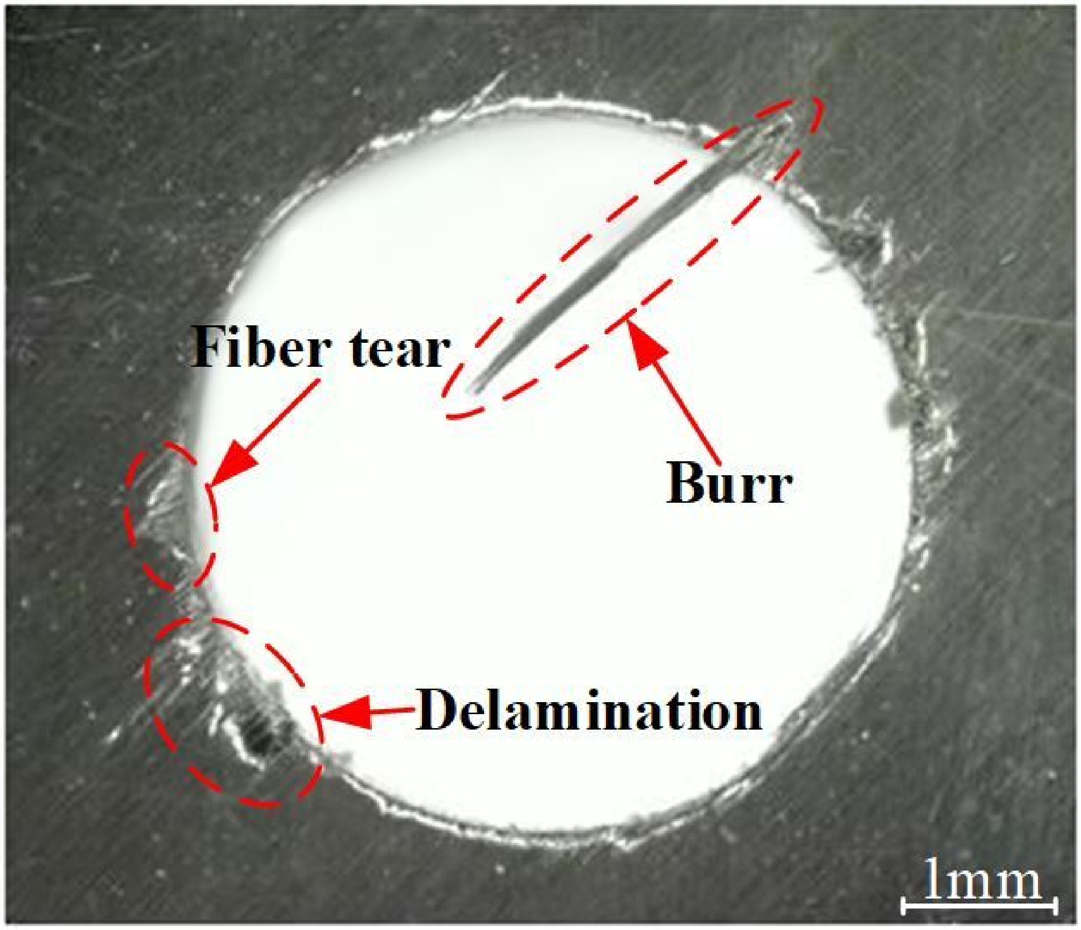

Figure 9

The surface damage of exit

Figure 10

Comparison of surface morphology of different cutting strategies

Figure 11

Comparison of damage mechanism of different cutting processes

Figure 12

Different fiber angle cutting mechanism

Figure 13

The measurement results of Surface roughness

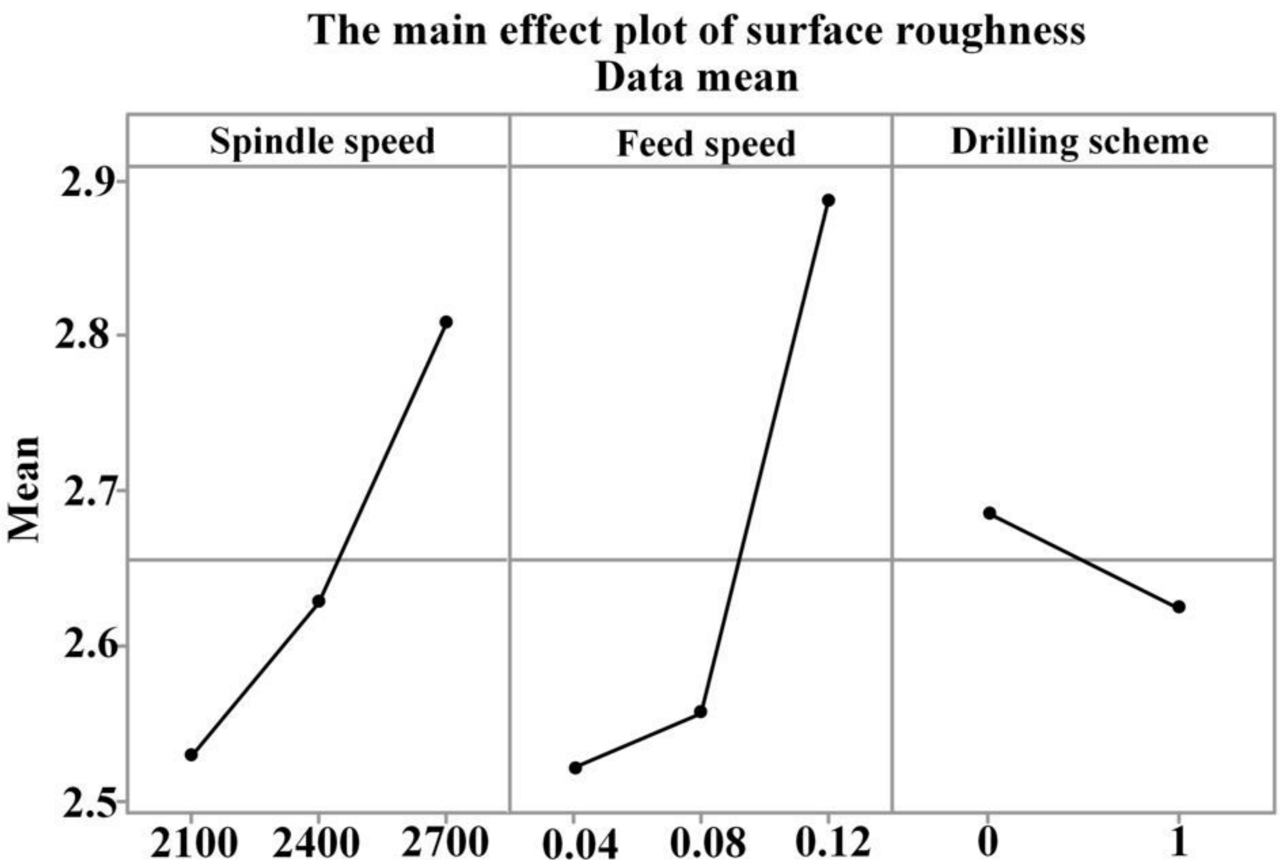

Figure 14

The main effect plot of surface roughness

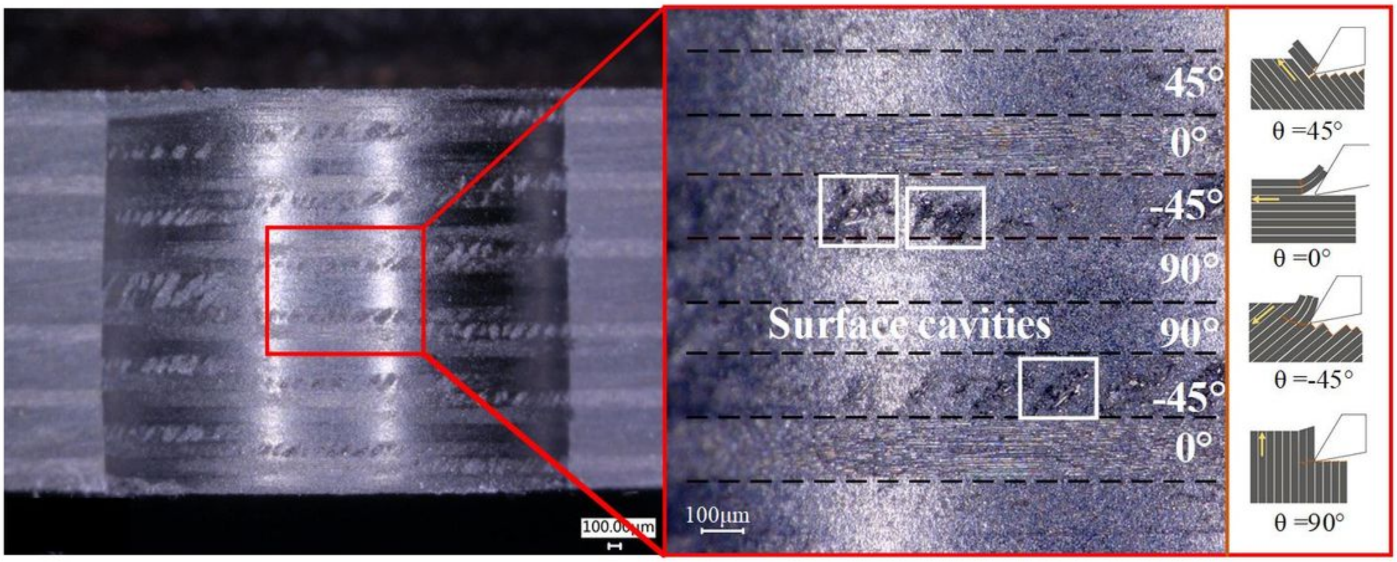

Figure 15

Drilling quality of different fiber angles

Figure 16

Exit hole wall morphology