Experimental Investigation On Machining Performance During Orbital Drilling of CFRP

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Research Article

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Abstract

As the most promising CFRP hole making method, orbital drilling is widely concerned. This paper aims to understand the influence of the cutting parameters, tool diameters and ratio between milling and drilling ($R_{m\&d}$) on thrust force, cutting temperature, tool wear and machining quality in CFRP orbital drilling. The effects of cutting parameters on thrust force and cutting temperature were studied by orthogonal experiments, and experiments were performed to investigate the variations of tool diameters, ratio between drilling and milling on thrust force, cutting temperature, tool wear and machining quality. The experimental results show that the tangential feed rate has no apparent effects on thrust force, but it appreciably impacts on the cutting temperature. The selection of tool diameter and the $R_{m\&d}$ has specific influence on tool wear, machining quality and cutting temperature. The result is helpful for selecting cutting parameters and tool diameters for high quality holes machining in CFRP orbital drilling.

1 Introduction

Carbon fiber reinforced plastic (CFRP) is a new type of composite with high specific modulus and strength. With the characteristics such as fatigue resistance, corrosion resistance, radiation protection, low coefficient of thermal expansion and vibration absorption, CFRP is the perfect material for weight reduction in the manufacturing of high-end equipment such as rockets, missiles, aircraft and spacecraft. The CFRP parts have the characteristics of a near net shape, however the CFRP are generally used to make structural components and skin of airplane and spacecraft, and there are still a large number of connection holes with high quality requirements to be processed. As a new type of laminated material, the physical properties of CFRP are quite different from those traditional homogeneous materials. Therefore, scholars pay different attentions to the processing. The research on CFRP hole making mainly focuses on reducing the thrust force causing machining defect and improvement of the processing quality.

Drilling is the wildest used method for CFRP hole machining, scholars have done a lot of researches on the effect of cutting parameters on machining quality. To extend tool life and to improve machining quality, Iliescu et al.[1]developed a model which can be used for monitoring tool wear, and found that the thrust force is affected by feed rate, cutting speed and tool wear. SEM is used to study the tool wear when drilling CFRP/Al sticks with different tools by Montoya et al. [2], the result shows that due to the tool wear, the thrust force increases with the quantity increasement of drilled holes increase. Faraz et al. [3] introduced the latent wear characteristics - cutting edge rounding in CFRP drilling, and studied the influence on torque and thrust force. Boccarusso et al. [4] researched on an alternative drilling strategy for CFRP hole machining, the analysis showed the cutting forces are sensitive to the cutting parameters, and there is a similar trend between feed rate and delamination factor. The influence of drilling parameters on the drilling force, drilling temperature, hole diameter and hole surface quality were studied in the drilling of CFRP/Al with double point angles drill by Wang et al. [5]. Khashaba [6], Jain [7], Melentiev [8], Ha [9], Qiu [10], Biermann [11] and Kolesnyk [12] had conducted similar research with different tools and obtained similar results. It is found that in CFRP drilling, cutting parameters have a noticeable impact on thrust force, torque and machining quality.

Compared with drilling, orbital drilling can effectively reduce the thrust force generated by the tool in the machining process. Therefore, orbital drilling is applied to the hole making of CFRP to reduce the possibility of machining defect. The cutter rotates around the tool axis at high speed while moving along a helical path in the three-dimensional space. The motion of the tool in orbital drilling is composed of three independent motions: the rotation of the tool, the revolution of the tool around the axis of the machined hole and the tool linear feed along the axis of the hole. Therefore, orbital drilling can be regarded as the combined motions of drilling and milling[13]. Scholars have studied the effects of cutting parameters[14, 15] and fiber cutting angles[16] on machining performance during CFRP milling. Because of the brief applying in CFRP hole machining and the complex process, there are few studies on the influence of various parameters of orbital drilling on the process performance during CFRP machining. Ahmad et al.[17] used tools of the same size to process holes of different sizes on workpieces with different thickness, and studied the tool wear, surface roughness, and diametric error. It is found that the coated tools are better than their uncoated counterparts. Exit quality, thrust force and geometric accuracy of the two methods were compared in the process of machining 1000 holes by drilling and orbital drilling, it is found that orbital drilling is better than drilling in quality value and feed force, whereas the drilling's geometric accuracy is better[18]. Gaiyun et al. [19] studied on the helical milling of CFRP/Ti-6Al-4V, it is found that the usage of two sets of machining parameters to machine each material can get a lower thrust force, a better geometric accuracy, and a better roundness. According to the results of orbital drilling experiment of CFRP/Ti-6Al-4V, Yagishita [20] found that the geometric accuracy and the roundness of holes decreased with the quantity increasement of holes machining. Wang [21] used orbital drilling to process holes on CFRP/Ti, it can be found that because of tool wear, the cutting force increases with the increase of hole number, when the number of machining is small, the cutting force of Titanium alloy and diameter error do not change significantly. Li et al. [22] studied the orbital drilling of Ti6Al4V, it is found that with the increase of the number of processed holes, the flank wear of the tool increases continuously, affected by the tool wear, the roundness errors and surface roughness are elevated even at the end of tool life. Fernández-Vidal [23] analyzed the effects of tool wear on dry orbital drilling of Ti6Al4V, and found that the wear of the peripheral cutting edges can affect the roughness and the geometric accuracy.

It can be seen that the research on the influence of cutting parameters on the machining performance in CFRP mainly focuses on drilling. While the research on orbital drilling is rare and the research content is relatively concentrated, and the influencing factors in orbital drilling cannot be comprehensively studied. Orbital drilling is a method with a bit of machining flexibility, by adjusting the eccentricity of the spiral path, holes of different sizes can be machined with the same tool. Compared with other machining methods, the machining performance of orbital drilling is affected by more factors. However, the reports on the tool diameter and cutting parameter selection in CFRP orbital drilling are scarce.

This study aims to investigate the performance of CFRP orbital drilling subjected to cutting parameters, tool size and the selection of the $R_{m\&d}$. It is expected that the experiment results in this study will facilitate the selection of arguments and enhance the effect of orbital drilling in CFRP machining.

2 Experimental Works

2.1 Experiment setup

A multi-directional CFRP plate was applied in this research with the carbon fiber and epoxy resin volume fractions of 60% and 40%. After compression molding and high-temperature curing, 3-k plain unidirectional prepreg (TAIRYFIL TC-33 3k, PAN-based carbon fiber; tensile modulus, 230 GPa; tensile strength, 3450 GPa.; density, 1.8 g/cm3) was made into composite. 72 unidirectional plies with a symmetrical layout [0°/+45°/90°/-45°] were in the middle of the composite, two plies of woven prepregs were made as the top and bottom of the plate, and the plate was cut into the pieces with the size of 90mm×90mm×10mm.

The machining experiments were conducted on a VM7032 three-axis vertical machining center with the maximum spindle speed of 8000rpm. Kistler 9257B dynamometer and Kistler 5070 amplifier were used to record cutting forces generated during machining. The temperature of hole wall during processing was measured with a FLIR A315 thermal infrared imager and a close-up lens 4X. Five kinds of TiAlN coated cemented carbide end mills with diameters of 5mm, 6mm, 7mm, 8mm, 9mm were used in the experiment. All tools have the same rake angle and clearance angle, and the helix angle are 30°. In this research, Anyty 3R-WM401 portable digital microscope was used to measure the tool wear and exit quality, and the geometric accuracy was measured by a three-contact internal micrometer.

All the experiments were executed without compound or vacuum cleaner. The experiment setup is shown in Fig. 1

2.2 Experiment principle

Three groups of experiments were conducted in this study. Firstly, the influence of cutting parameters on thrust force and cutting temperature in CFRP orbital drilling was studied. The cutting parameters involved in orbital drilling are obviously more than those in other hole machining methods. Commonly, the sizes of the hole to be machined and the tool will be determined at first, then the helical path of the tool is controlled by the spindle speed, tangential feed rate and axial feed rate. The orthogonal test of three levels and three factors was carried out to find out the influence of these factors on the thrust force and cutting temperature. In the experiment, a tool with a diameter of 8mm was selected to process a hole with a diameter of 10mm. The factor level table is shown in Table 1.

Table 1
Factor level table of test 1

Levels	Factors		
	Spindle speed (rpm)	Tangential feed rate (mm/rev)	Axial feed rate (mm/rev)
1	1000	0.063	0.01
2	2000	0.126	0.015
3	3000	0.188	0.02

The axial force and hole wall temperature were measured by dynamometer and infrared thermal imager during machining. To ensure the integrity of the hole and truly display of cutting temperature changes, the holes with radius of 5mm were processed 6mm away from the workpiece boundary, and the infrared thermal imager was used to observe the side wall of the workpiece, as shown in Fig. 1b. Two points are marked in the infrared image: Sp1 is the ambient temperature, and Sp2 is the temperature of the point 1.5mm from the bottom on the side wall.

The second group of tests studied the influence of tool diameter on thrust force, tool wear and geometric accuracy when machining holes of the same size. Tools with diameters of 5mm, 6mm, 7mm, 8mm and 9mm were used to process holes of 10mm. The machining condition in this test included a spindle speed of n=2000rpm, a screw pitch of a_p = 1mm, an axial feed rate of fa =0.01mm/rev. The thrust force, geometric accuracy, flank wear on the bottom edges and peripheral cutting edges were measured every 10 holes, and each tool was tested for 100 bores.

The research about the influence of the $R_{m\&d}$ on the thrust force, exit quality and cutting temperature were carried out at last. In the test, four cutting tools with diameters of 5mm, 6mm, 7mm and 8mm were used in orbital drilling with the eccentric from 0.5mm to the tool radius in every 0.5mm. The tests were executed at a spindle speed of 2000rpm and a screw pitch of 1mm. The thrust force, exit machining quality and cutting temperature on side wall in each processing were measured.

3 Result And Discussion

3.1 Influence of cutting parameters on thrust force and cutting temperature

CFRP is a kind of laminated material formed by bonded prepreg at a certain angle with epoxy resin as adhesive. Due to the structural properties of the laminated materials and the physical properties of the epoxy resin, the strength of CFRP in the plane of prepreg is high and the strength perpendicular to the plane direction is low. In the vertical direction when the thrust force is greater than the interlaminar strength of the workpiece during processing, the insufficient strength leads to the separation and cracking between the prepregs and then delamination is formed, resulting in the rapid reduction of workpiece strength. Therefore, it is of great significance to study the thrust force in CFRP orbital drilling to improve the machining quality.

The experimental parameters and the results in the test of the influence of cutting parameters on thrust force and cutting temperature in CFRP orbital drilling are listed in Table 2. The results of the test of between-subjects effects and regression analysis of thrust force are listed in Table 3 and Table 4.

Table 2
Experimental parameters and result

No.	Spindle speed	Tangential feed rate	Axial feed rate	Thrust force(N)	Maximum temperature (°C)
1	1	1	1	116.5	95.9
2	1	2	2	135.2	84.6
3	1	3	3	140	68.9
4	2	1	2	107.7	114.1
5	2	2	3	120.8	88.2
6	2	3	1	99.48	72.2
7	3	1	3	111.1	100
8	3	2	1	90.2	79.2
9	3	3	2	106.9	64.6

Table 3
Test of Between-Subjects Effects of thrust force

Dependent Variable: Thrust force					
Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Correct Model	2041.731a	6	340.288	58.737	0.017
Intercept	117393.033	1	117393.033	20263.314	0.000
Spindle speed	1269.304	2	634.652	109.548	0.009
Tangential feed rate	26.845	2	13.423	2.317	0.301
Axial feed rate	745.581	2	372.791	64.348	0.015
Error	11.587	2	5.793		
Total	119446.350	9			
Corrected Total	2053.318	8			
a. R Squared=0.994 (Adjusted R Squared=0.997)					

Table 4
Regression analysis of thrust force

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	105.460	9.437		11.175	0.000
Spindle speed	-0.014	0.002	-0.752	-6.206	0.002
Tangential feed rate	29.622	35.879	0.100	0.826	0.447
Axial feed rate	2190.667	448.489	0.592	4.885	0.005
Dependent Variable: Thrust force					

It can be found that the F value of the model test is 58.737, Sig.<0.05, so the model is statistically significant. The significance of spindle speed and axial feed rate is less than 0.05, which shows that the change of the spindle speed and axial feed rate has a prominent effect on the thrust force, while the effect of tangential feed rate on the thrust force is inconspicuous. By observing the normalized coefficient of regression analysis results, it can be found that spindle speed is the most crucial factor affecting the thrust force in CFRP orbital drilling, which has a negative correlation, the axial feed rate is positive to the thrust force of machining. That is, the increasing of spindle speed can reduce the thrust force, and the decreasing of the axial feed rate also can reduce the thrust force generated in orbital drilling.

The strength of epoxy resin is sensitive to temperature. A large number of studies show that the increase of processing temperature will lead to the decrease of the CFRP matrix materials strength which is more prone to produce defect. In hole processing, the material that closer to the hole exit gets a higher cutting temperature. In test 1, the temperature of the marked point Sp2 which is 1.5mm away from the lower surface of the workpiece was compared. The result of the test of between-subjects effects and regression analysis of maximum temperature is listed in Table 5 and Table 6.

Table 5
Test of Between-Subjects Effects of maximum temperature

Dependent Variable: Maximum temperature					
Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Correct Model	2042.280a	6	340.380	22.117	0.044
Intercept	65484.810	1	65484.810	4255.023	0.000
Spindle speed	178.207	2	89.103	5.790	0.147
Tangential feed rate	1820.687	2	910.343	59.152	0.017
Axial feed rate	43.387	2	21.693	1.410	0.415
Error	30.780	2	15.390		
Total	67557.870	9			
Corrected Total	2073.060	8			
a. R Squared=0.985 (Adjusted R Squared=0.941)					

Table 6
Regression analysis of maximum temperature

Model	**Unstandardized Coefficients**		**Standardized Coefficients**	**t**	**Sig.**
	B	**Std. Error**	**Beta**		
(Constant)	117.228	11.846		9.896	0.000
Spindle speed	-0.001	0.003	-0.050	-0.332	0.754
Tangential feed rate	-278.211	45.037	-0.935	-6.177	0.002
Axial feed rate	326.667	562.967	0.088	0.580	0.587
Dependent Variable: Maximum temperature					

The result shows that the F value of the model test is 22.117, and Sig.<0.05, so the model used is statistically significant. Among the three factors, only the tangential feed has a significant effect on the maximum temperature of the side wall in the process of machining, which is less than 0.05. The result of regression analysis shows that the tangential feed rate has a negative correlation with maximum temperature.

Therefore, when the diameter of the tool and hole is determined in CFRP orbital drilling, the thrust force can be reduced by properly enhancing the spindle speed and reducing the axial feed rate. And the machining temperature can be reduced by increasing tangential feed rate appropriately.

3.2 Influence of tool diameter on cutting performance

Orbital drilling is a method with machining flexibility. Because of the tools' eccentric machining, the tools of the same size can be used to make holes of different sizes, and the holes of the same size can also be processed with tools of different sizes by adjusting the eccentricity. It can be seen that in orbital drilling, the influence of the selection of tool diameter on the machining performance has to be taken into account, except for cutting parameters influence. In the second experiment, the influence of tool size on machining performance was analyzed by comparing thrust force, tool wear, geometric accuracy and exit quality of the holes with the same diameter processed by the tool with different sizes.

The tool abrases during the removing of material, so both of the bottom edges and peripheral cutting edges wear during orbital drilling. The bottom edge drills the material in orbital drilling, which directly affects the magnitude of the thrust force. Fig. 2 shows the flank wear of bottom edges and the changes of thrust force.

Figure 2a records the flank wear of the bottom edges of the tool with different diameters when machining 100 holes with diameters of 10mm. It can be seen that with the increase of the number of holes processed in orbital drilling, the flank wear of bottom edges increases gradually, and the wear speed of bottom edges is related to the diameter of the tool. The bottom edges with a larger diameter get a more severe wear when the same number of holes are processed. The flank wear of bottom edge decreases as the tool size decreases. At the 100th hole, the bottom edge's flank wear of the tool with the diameter of 9mm is 0.298mm, while the wear of the bottom edge with the diameter of 5mm is only 0.168mm. Fig. 2b shows the influence of the quantity of holes processed on the thrust force by tool of different sizes during steady machining. As can be observed, with the same cutting condition and processing quantity, the thrust force generated by the tool is affected by tool diameter, the larger tool diameter is, the larger thrust force will be. With the increase of machining quantity, the thrust force produced by different sizes of cutting tools increases slightly, but the gradient of thrust force has no obvious difference. Therefore, the selection of cutter size has an essential effect on the machining thrust force in orbital drilling.

In orbital drilling, the wear of peripheral cutting edges affects the geometric accuracy of the hole. Fig. 3 records the flank wear of peripheral cutting edges and the geometric accuracy variation of the hole with the increase of the machining quantity.

Only a small part of the peripheral cutting edge near the bottom edges participates in processing in orbital drilling, the flank wear also occurs in this part at first. As can be observed in Fig. 3a, after 20 holes processed the peripheral cutting edge tool wear of the 5mm diameter tool reached the width of the blade on the peripheral cutting edge. The tool with diameter of 6mm reaches the maximum value after 30 holes are machined, while the tool of 7mm reaches width of the blade when 70 holes are machined. Hereafter, the flank wear of peripheral cutting edges remains unchanged and can not show the degree of wear. With the number of holes machined increases, the diameter of the peripheral cutting edge where close to the bottom edge decreases. Resulting in a small amount of material can not be removed completely. At this time, the cutting edge adjacent to the worn part of the peripheral cutting edge begins to participate in cutting, which is also the reason why the tool can still be used in orbital drilling after serious wear on the flank of the peripheral cutting edge.

From the flank wear of peripheral cutting edge of the front 20 holes, it can be seen that the wear speed of the peripheral cutting edge has a negative correlation with the tool diameter. That means machining holes with fixed size, the larger the tool used, the smaller the eccentricity in processing, and the slower the wear speed of peripheral cutting edges.

In orbital drilling, the material on the hole wall is mainly removed by the peripheral cutting edge, with the increase of the number of machined holes, the wear of peripheral cutting edge intensifies and the dimensional deviation of the holes increases gradually. Fig. 3b records the change of hole diameter caused by the increase of machining quantity of tools with different sizes. As can be seen that with the increase of the number of tools, the diameter of machined holes is also gradually decreased, but the diameter changing speed of tools with different sizes is also different. Compared with the first hole machined by the tool of 5mm, the hole diameter of the 100th reduces about 60 micrometers, in contrast after machining 100 holes, the diameter of the hole machined by the tool of 9mm decreases about 25 micrometers. According to the changes of hole diameter fitting results, there is a negative correlation between tool diameter and changing speed of hole diameter in machining. The underlying cause is that when machining holes with the same size in orbital drilling, tools with a smaller diameter need to be processed with a larger eccentricity, thus leading to a larger $R_{m\&d}$. Compared with the bottom edges, peripheral cutting edge removes majority of materials in orbital drilling, resulting in the rapid wear of peripheral cutting edge, brings about a decrease of tool diameter, which affects the diameter of machined hole.

3.3 Influence of $R_{m\&d}$ on cutting performance

The ratio between drilling and milling is the ratio of the material removed by the peripheral cutting edges to the material removed by the bottom edges in orbital drilling[24], as indicated in Eq. (1)

$$R_{m\&d} = \frac{V_m}{V_d} = \frac{R_h^{\ 2} - R_t^{\ 2}}{R_t^{\ 2}}$$

Where $R_{m\&d}$ is the ratio between drilling and milling, V_m is the volume of material removed by milling, V_d is the volume of material removed by drilling, R_h is the radius of the hole, R_t is the radius of the tool.

Generally, the diameter of the tool used in orbital drilling is smaller than the diameter of the hole and larger than the radius of the hole, so the $R_{m\&d}$ in orbital drilling is a value between 0 and 3. Fig. 4 shows the influence of ratio on thrust force of tools with different diameters. As can be seen, changing the $R_{m\&d}$ by adjusting the eccentricity has no effects on the thrust force of steady machining in orbital drilling, while the tool diameter has a significant effect on the thrust force.

In CFRP orbital drilling, when the bottom of the tool passes through the bottom of workpiece, the bottom edge pushes a small amount of material out of the lower surface of the workpiece to form a cap suspended at the exit, which is connected to the workpiece by a crescent material. As shown in Fig. 5, the area is surrounded by a solid red line. After the bottom edge passes through the workpiece, the bottom edge no longer cuts the material, and the thrust force generated by the bottom edge rapidly declines to zero. The peripheral cutting edge of the tool continue to cut the material remained at the exit, affected by the spiral groove of the tool, the thrust force generated by the peripheral cutting edge is opposite to the axial feed direction.

When the $R_{m\&d}$ in orbital drilling is small, that means the tool diameter is close to the hole diameter, the volume of the material removed by the peripheral cutting edge at the exit is relatively small, the action time is short and the upward thrust force is not apparent. The diameter of the hole increases gradually with the increase of the $R_{m\&d}$. The volume of the material removed by the peripheral cutting edge at exit also increases. The cutting time of the peripheral cutting edge is gradually prolonged and the effect of upward thrust force becomes manifest. The experiment results show that the thrust force at exit has the same change tendency for all tools with different sizes. Fig. 6 records the thrust force at the $R_{m\&d}$ of 0.3, 1.5 and 3, when the tool with diameter of 7mm processes the material at exit. The curve depicts the rapid reduction of the thrust force when the tool breaks through the workpiece, and the thrust force of removing the material remaining at the exit by the peripheral cutting edge. It can be seen that with the increase of the $R_{m\&d}$, the magnitude and action time of upward thrust force at exit increase significantly.

Delamination often occurs on the workpiece surface where lacking of material supporting. The delamination factor[25] which can characterize the level of damage caused by machining at entrance and exit was used to evaluate the exit quality. The factor F_d is the ratio of D_{max} to D_{nom} (F_d is delamination factor, D_{max} is the maximum diameter of damage zone, D_{nom} is the hole diameter). As indicated in Eq. (2) and shown in Fig. 7.

$$F_d = \frac{D_{\max}}{D_{nom}} \quad (2)$$

The exit quality of tools with different sizes at different $R_{m\&d}$ between drilling and milling is shown in Fig. 8. As can be observed, from the result in Fig. 4 and Fig. 8, the tool of 5mm gets the worst exit which machined at the $R_{m\&d}$ of 0.44 and a low thrust force at 55N. However, at the $R_{m\&d}$ of 3, the tool with the diameter of 8mm gets an undamaged exit with delamination factor of 1 at a thrust force of 110N. Therefore, the $R_{m\&d}$ also has an important impact on the machining quality. The curves of different sizes of tools in Fig. 8 have the same trend, the delamination factor at the exit is larger when the diameter of the tool is close to the hole, with the increase of the $R_{m\&d}$, the delamination factors at exit decrease gradually, which means machining at a small $R_{m\&d}$ is not conducive to ensure exit quality. In consequence, using a smaller tool to obtain a larger $R_{m\&d}$ is helpful to improve the exit quality when machining holes of the same size in orbital drilling.

In addition to the influence of cutting parameters on cutting temperature in CFRP orbital drilling, the influence of the $R_{m\&d}$ of tools with different sizes on cutting temperature is also studied in this paper, the results are shown in Fig. 9.

As the results show, at the same $R_{m\&d}$ the temperature of the marked point is affected by the tool diameter, and the cutting temperature of the tool with a large diameter is higher. The cutting temperature is affected by the $R_{m\&d}$, and forms a “spoon” shape curve, machining with a small or large $R_{m\&d}$ will produce a higher cutting temperature, and a lower cutting temperature can be obtained at the $R_{m\&d}$ near 1. In orbital drilling, the tool produces a cutting area which is larger than the tool diameter in the form of eccentric machining. The eccentricity is small when the $R_{m\&d}$ is close to zero, resulting in a small chip space. The friction between high temperature chips, the tool and machined surface increases the sidewall temperature of the workpiece. When the $R_{m\&d}$ is close to one, the chip space is enlarged with the increase of the eccentricity, which leads to a reduction of the friction and the decrease temperature of sidewall. When the $R_{m\&d}$ continues to increase, the volume of the material removed by drilling remains unchanged, the material removed by milling increases gradually and generates more heat, causing the temperature raise of peripheral cutting edge. Therefore, in CFRP orbital drilling, the$R_{m\&d}$ should be a value between 0.7 and 1.5.

4 Conclusion

The present work investigates the relationships between machinability and cutting parameters, tool diameter and $R_{m\&d}$ in CFRP orbital drilling. Based on the experimental result, conclusions can be drawn as follows:

1) In CFRP orbital drilling, the spindle speed and axial feed rate have the most obvious influence on thrust force, while the tangential feed rate has no significant effect on the thrust force. The tangential feed rate has the most obvious effect on cutting temperature of hole wall, while the spindle speed and axial feed rate does not show the evident impact on the temperature.

2) The selection of the diameter of cutting tools affect the thrust force in addition to the influence of cutting parameters. When machining the holes of the same size, the diameter of tool has an obvious impact on the thrust force. The larger the tool is, the greater the thrust force is.

3)The diameter of the tool is positively correlated with tool wear on bottom edge, and has a negatively correlation with the tool wear on peripheral cutting edge. Affected by the wear velocity of the peripheral cutting edge, when machining the same number of holes with the same size, the geometric accuracy of the tool with a larger diameter is better.

4) The $R_{m\&d}$ has no obvious effect on the thrust force when processing holes of different sizes with the tool of the same size. While the $R_{m\&d}$ obviously affects the machined quality at the exit. The larger the

$R_{m\&d}$ is, the more obvious the upward thrust force of the tool effect at the exit, and the better the exit quality is.

5) In orbital drilling the cutting temperature of the tool will be affected by the $R_{m\&d}$. The $R_{m\&d}$ to cutting temperature curve presents a shape of “spoon”, that is, the cutting temperature will be high when machining at a lower or a higher $R_{m\&d}$. While the lower cutting temperature can be obtained when the $R_{m\&d}$ is between 0.7 and 1.5.

Declarations

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Figures

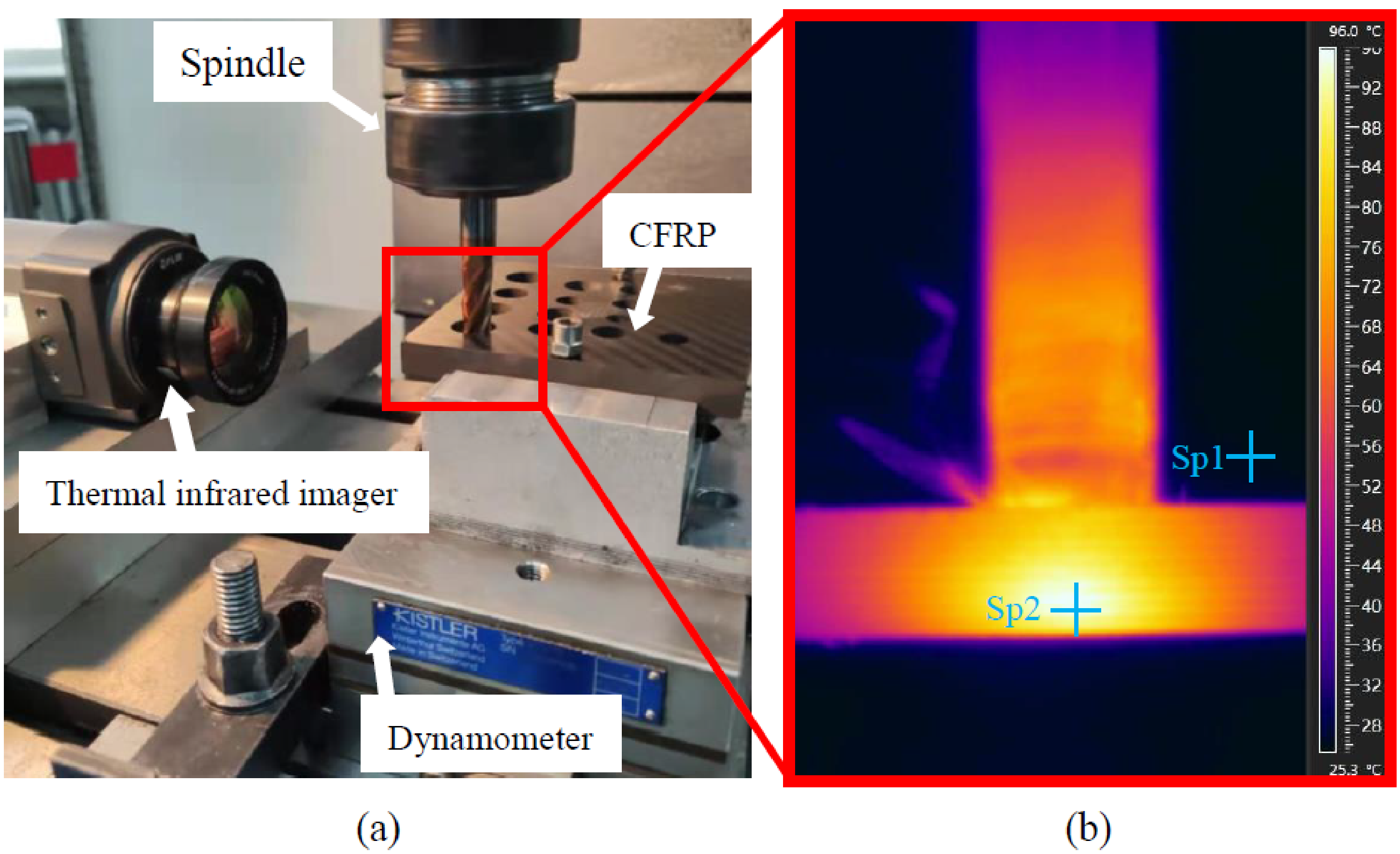

Figure 1

The experimental setup in this research. (a) Experiment setup; (b) Infrared image of the workpiece.

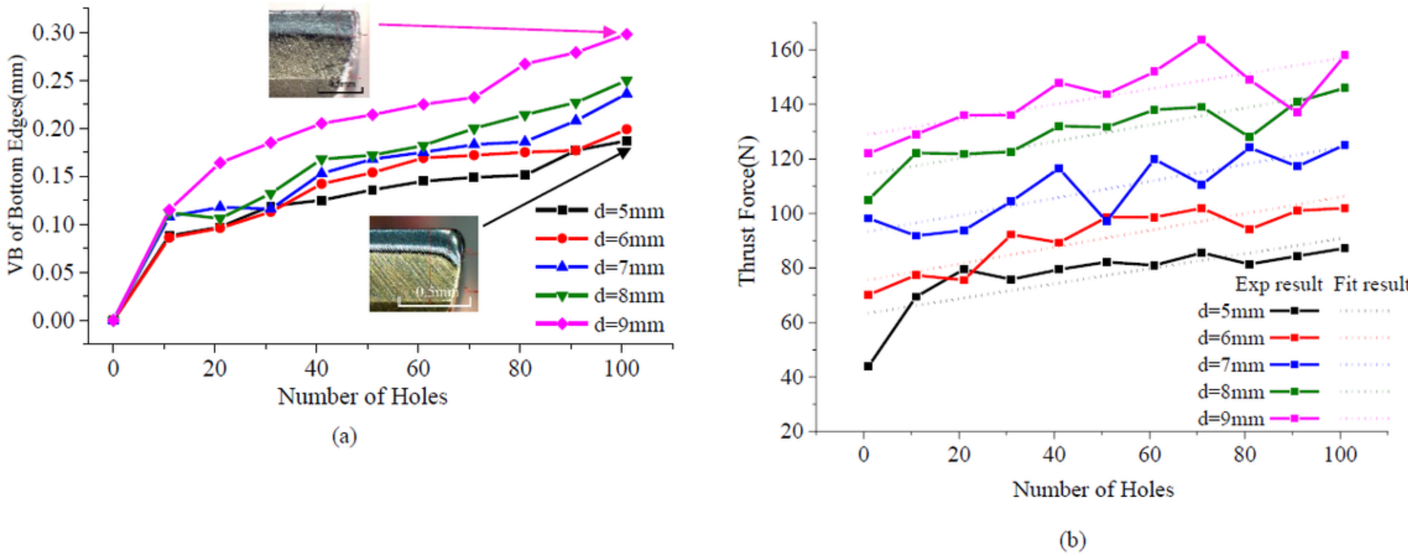

Figure 2

The wear of bottom edge and the changes of thrust force. (a) Effect of hole machining quantity on flank wear of bottom edges; (b) Effect of hole machining quantity on thrust force

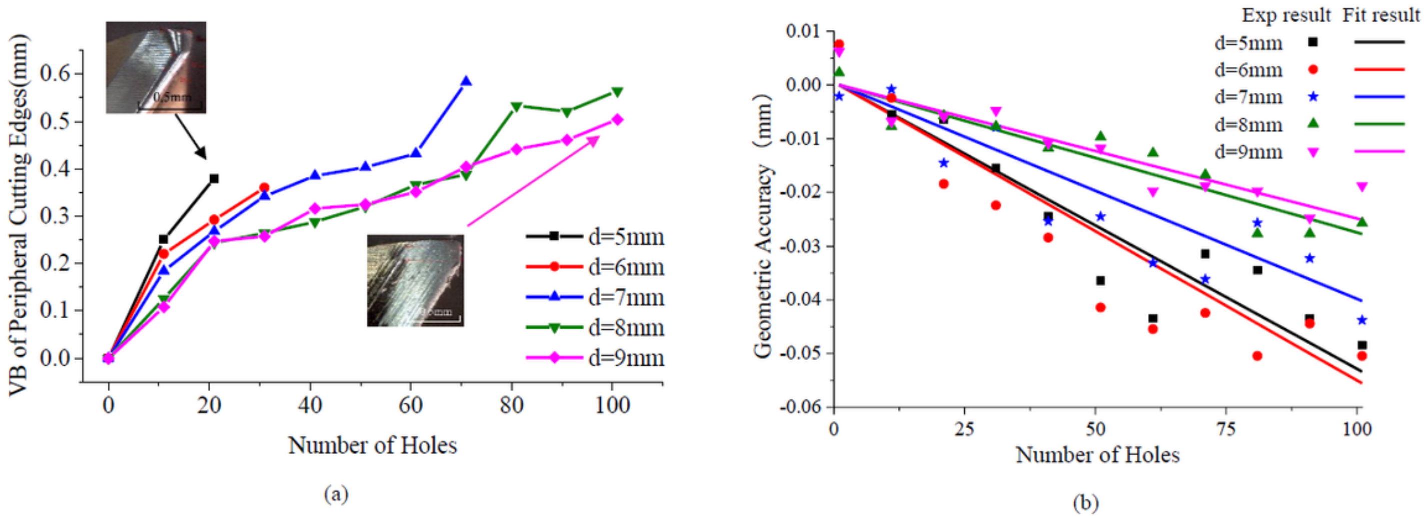

Figure 3

The wear of peripheral cutting edge and the changes of geometric accuracy. (a) Flank wear of peripheral cutting edge; (b) Effect of hole machining quantity on geometric accuracy

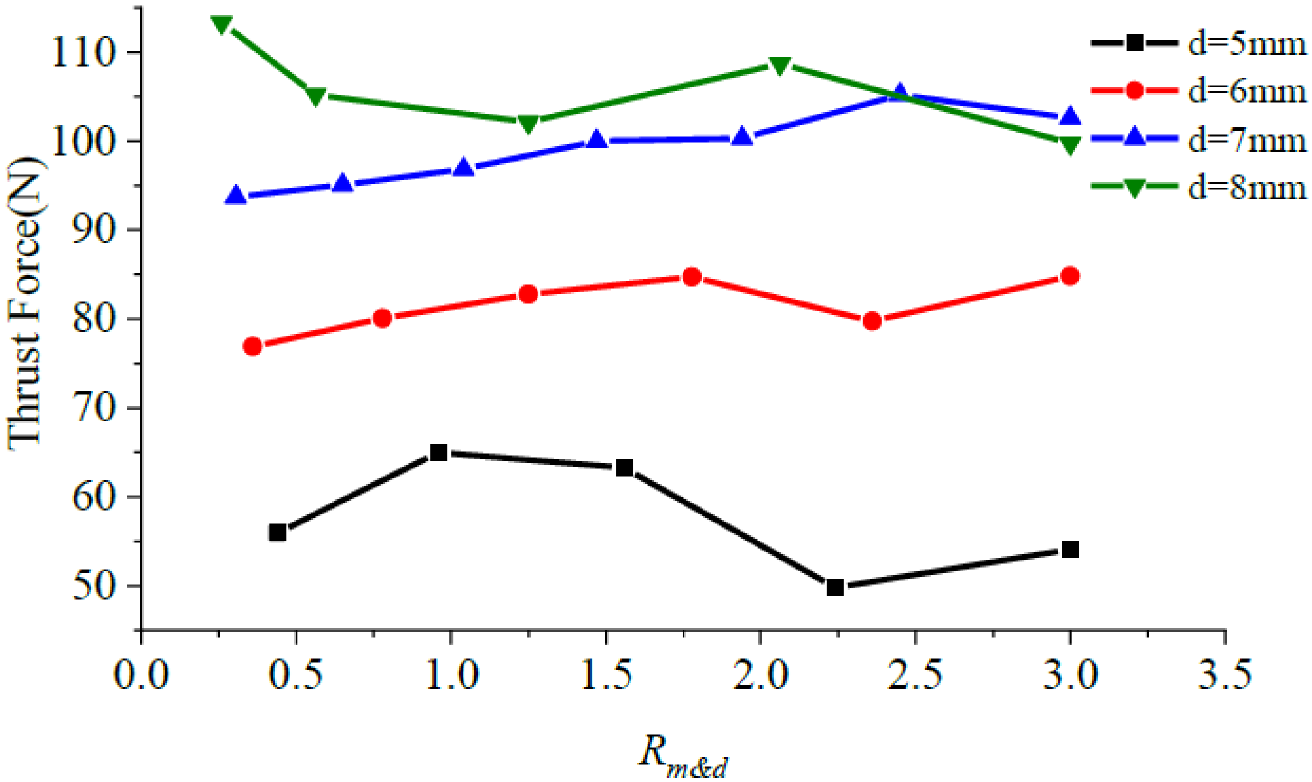

Figure 4

Influence of R(m&d) on thrust force

Figure 5

Material removed at exit

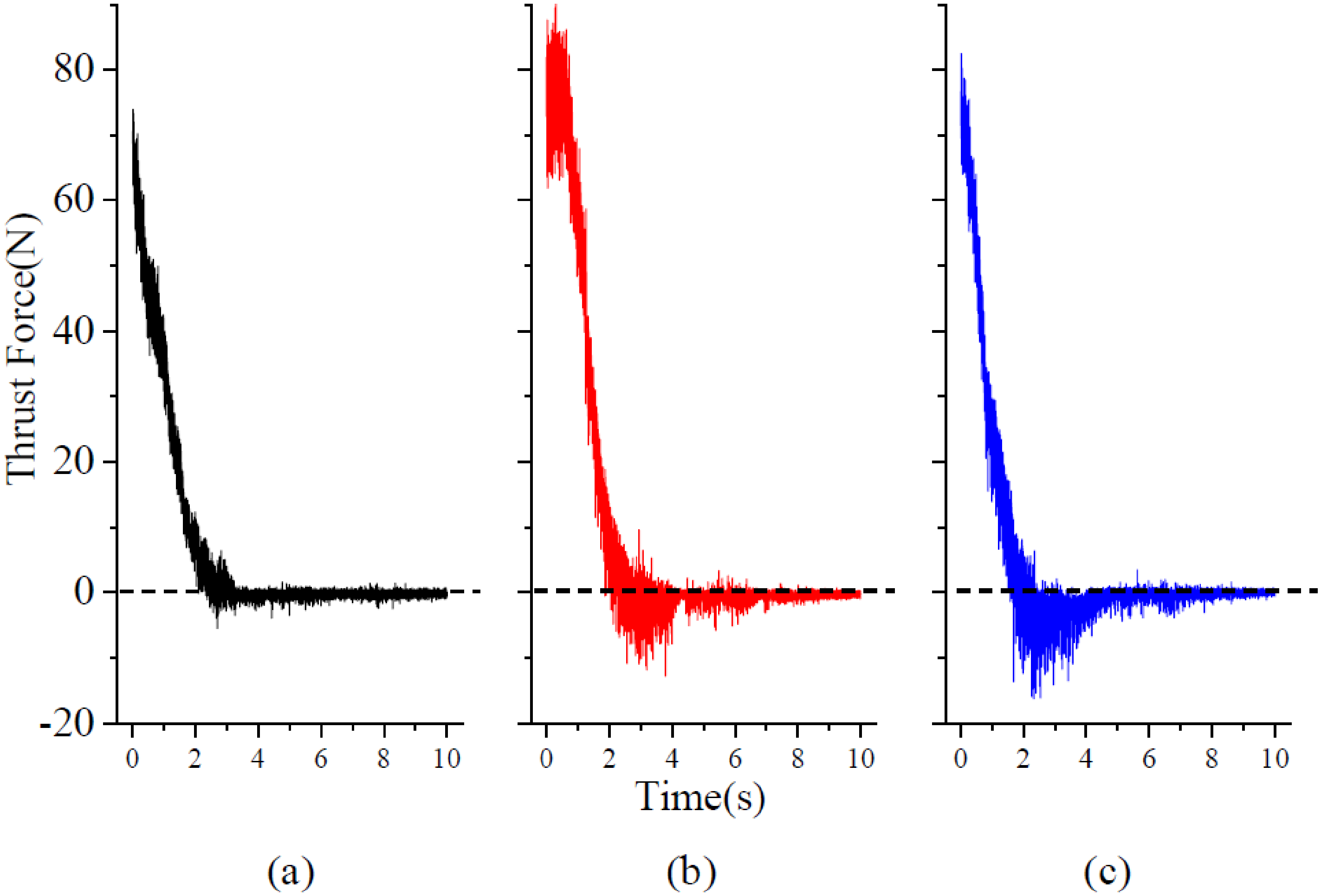

Figure 6

Influence of R(m&d) on upward thrust force at exit. (a) R(m&d)=0.3; (b) R(m&d)=1.5 ;(c) R(m&d)=3

Figure 7

Delamination factor

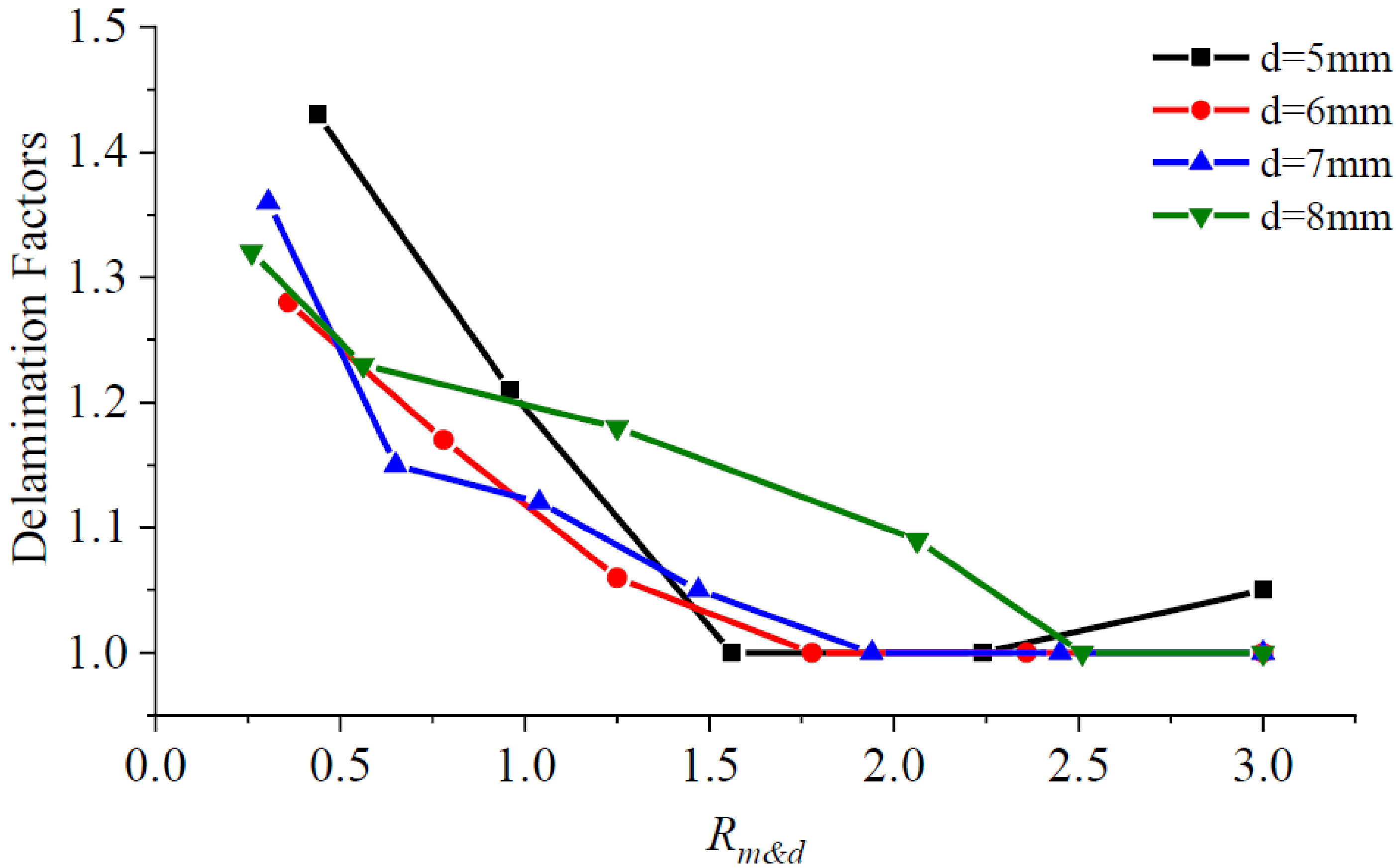

Figure 8

Exit quality of different R_(m&d)

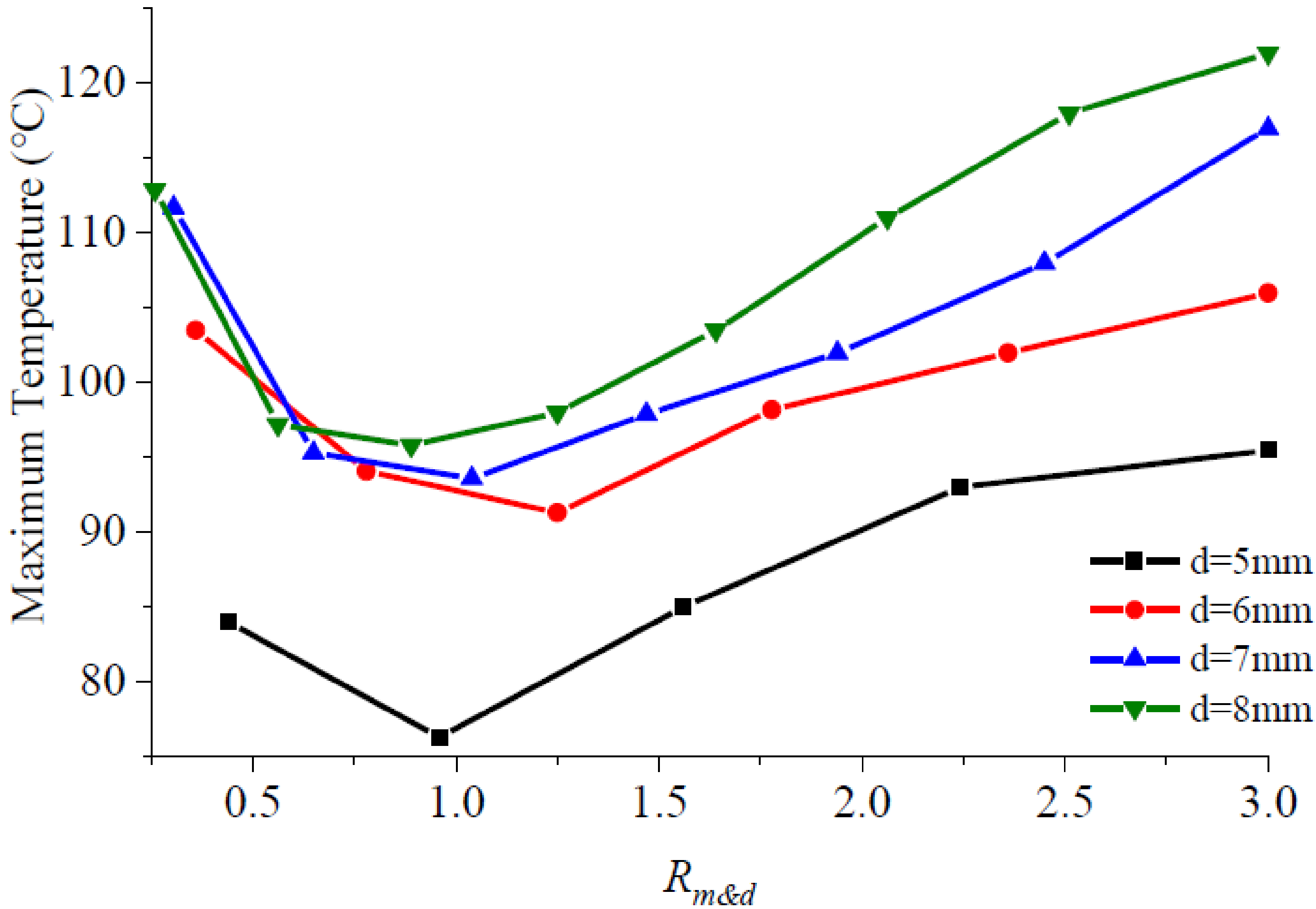

Figure 9

Effect of R(m&d) on cutting temperature