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Orthogonal design of experiment and analysis of abrasive water jet cutting on carbon fiber reinforced composites


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Abstract: The carbon fiber reinforced composite is a new type of composite material with an excellent property in strength and elastic modulus, and has found extensive applications in aerospace, energy, automotive industry and so on. However, this composite has a strict requirement on processing techniques, for example, brittle damage or delamination often exists in conventional processing techniques. Abrasive water jet machining technology is a new type of green machining technique with distinct advantages such as high-energy and thermal distortion free. The use of abrasive water jet technique to process carbon fiber composite materials has become a popular trend since it can significantly improve the processing accuracy and surface quality of carbon fiber composite materials. However, there are too many parameters that affect the quality of an abrasive water jet machining. At present, few studies are carried out on the parameter optimization of such a machining process, which leads to the unstable quality of surface processing. In this paper, orthogonal design of experiment and regression analysis were employed to establish the empirical model between cutting surface roughness and machining process parameters. Then a verified model was used to optimize the machining process parameters for abrasive water jet cutting carbon fiber reinforced composites.

Key words: abrasive water jet; carbon fiber reinforced composites; surface roughness; orthogonal experiment; regression analysis

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1 Introduction

Carbon fiber reinforced composite (CFRP) is one of the composite material, which composed of two parts including resin matrix, carbon fiber reinforced body[1]. It was first manufactured by the United States in the 1950s, and as a new type of structural materials, it shows a broad application prospects. CFRP whose specific strength is 5 times the steel has excellent mechanical properties, its fatigue limit reaches 70%-80% of the tensile strength, while the general metal is about 30%-40%[2]. At the same time, when the temperature is 400 ℃, the strength and elastic modulus of CFRP have almost no change, while the strength of aluminum alloy decreases significantly and the elastic modulus decrease to almost zero. Based on this, CFRP is widely used as a structural material in the aerospace, energy

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and automotive and other fields. However, CFRP has a high demand for processing technology, in the process of processing, it is prone to brittle damage or stratification, the wear of high-speed steel blade is also very serious, and the dimensional accuracy is difficult to control[3]. As a new type of non-traditional processing technology, high-pressure abrasive water jet technology provides a new idea for the processing of refractory materials such as CFRP with the advantages of high energy and point cutting[4].

Abrasive water jet machining technology (AWJ) is a relatively new and nature-friendly technology that uses high speed abrasive water to cut materials [5]. It belongs to special processing technologies with high-energy beam and is the frontier field of manufacturing technology. According to the different forms of mixing with water, abrasive water jet can be divided into two types: after mixing abrasive water jet and front mixed abrasive water jet. In addition, the former is more commonly used, so it will be mainly discuss as following. Abrasive water jet technology has the characteristics of high energy, cold cutting and point cutting, it is not easy to produce stratification and have no heat affected area [6]. This technology is less sensitive to material properties and exhibits better performance in the machining difficult machine materials such as ceramics, glass and rocks[7]. Therefore, it can be considered that the use of abrasive water jet to cut carbon fiber reinforced composites has great application prospect.

Orthogonal experiment was used to analyze the relationship between roughness and traverse rate, hydraulic pressure, standoff distance. The analysis of variance was carried out to determine the influence of each technological parameter on the roughness of cutting surface. Finally, multiple linear regression analysis was used in developing mathematical models in order to predict the cutting roughness.

2 Experimental work

The master-slave control is widely employed in the robot manipulation. In most cases, the joystick or the keyboard is the routine input device for the robot master-slave control system.

2.1 Material

In the present study, carbon fiber composite laminates produced in Japan Toray is used. Its specific performance is shown in Tab.1.

Tab.1 Parameters of material property

Parameters	Value
Model	T300
Thickness	2.98 mm
Density	1.75 g/cm^3
The diameter of carbon fiber	7 μm
Tensile strength	3 530 MPa
Tensile modulus	230 GPa
Elongation	1.5%

2.2 Equipment

The equipment used for machining the sample was an abrasive water jet machine. It is produced by Nanjing Dadi water jet company, and its model is DWJ1313-FC-X4-Ⅲ, the specific parameters are shown in Tab.2.

Tab.2 Operational parameters of abrasive water jet machine

Parameters	Value
Cutting accuracy	± 0.1 mm
Repeat positioning accuracy	± 0.5 mm
Adjustment range of cutting pressure	0-340 MPa
Maximum water flow	4.7 L/min
Water nozzle diameter	0.33 mm
Diameter of water nozzle	Ruby
Abrasive	Garnet
Maximum operating speed	20 m/min

The equipment used to measure the roughness is a μ scanf custom 3D measurement system and it is produced by Nanofocus Company in Germany. It use non-contact measurement principle and the wavelength of the light source is "505 nm", The workbench is made of marble and its dimensions are "1 550 mm×800 mm×750 mm". The movement range of platform in *X/Y* direction is "300 mm×300 mm" , its resolution in *X/Y* direction is "0.3 μm" . The measurement range in *Z* direction is "1 mm" and its resolution in *Z* direction is less than "1 nm" .

2.3 Experimental design

Compared to other multivariate routine experiments, even if the number of experiments is greatly reduced, the orthogonal experiment can also clearly reflect the effect of each factor on the outcome and evaluate the magnitude of its impact, so it can effectively help us to find the best combination of technological parameters. Therefore, the influence of the parameters of abrasive water jet on the roughness of the working surface of carbon fiber composite laminates is studied by orthogonal experiment, and the ANOVA is carried out to analyze the significant effect of each parameter on the roughness of working surface. There are many factors that affect the roughness such as material properties, hydraulic pressure, standoff distance, traverse rate, abrasive flow rate, abrasive type and so on. In this experiment, traverse rate (V), hydraulic pressure (p), standoff distance (H) were chosen as factors, and three levels were used for each factor. So orthogonal experiment of $L_9(3^4)$ was used and there is an error column. Machining parameters and their respective levels are shown in Tab.3.

Tab.3 Machining parameters and their values

Levels	$V/(\mathrm{mm}\cdot\mathrm{min}^{-1})$	p/MPa	H/mm
1	100	220	6
2	300	260	10
3	500	300	14

3 Results and discussion

3.1 Results

Experiment design using $L_9(3^4)$ orthogonal array and experimental results are shown in Tab.4.

Tab.4 Orthogonal design of experiment with $L_9(3^4)$ array and experimental results

Experiment no.	$V/(\mathrm{mm}\cdot\mathrm{min}^{-1})$	p/MPa	H/mm	Ra/μm
1	100	200	5	2.352
2	100	250	7	2.627
3	100	300	9	2.761
4	500	200	7	3.581
5	500	250	9	3.265
6	500	300	5	3.045
7	900	200	9	3.993
8	900	250	5	3.352
9	900	300	7	3.104
K_{1j}	7.740	9.926	8.749	T=28.080
K_{2j}	9.891	9.244	9.312	
K_{3j}	10.449	8.910	10.019	Y=3.120
R_j	2.709	1.016	0.973	
S_j	1.364	0.179	0.270	2.017

The manner of cutting the carbon fiber composite laminates with a width of 13 mm is used in the experiment, and the cutting length is 100 mm. The roughness is measured by the μ scanf custom 3D measurement system, and the total measurement area is "2.5 mm×0.8 mm", it is "2.5 mm" from the top and bottom surfaces, "0.8 mm" for the measurement length, and 2.5 mm×0.8 mm for the total measurement area. The roughness is measured at the midpoint of the measurement area, and the cutting surface is measured five times, taking the average as the final result.

3.2 Effect of machining parameters on *Ra*

The test results of each level of technological parameters are compared as shown in Fig.1, where the influence of each technological parameter on the roughness of cutting surface are exhibited.

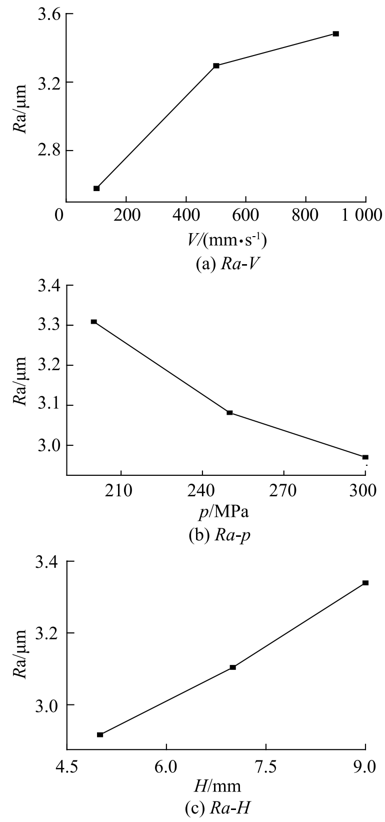

Fig.1 Effect of machining parameters on *Ra*

Fig.1a shows the effect of traverse rate on roughness; It can be seen that the roughness increases with increasing traverse rate. The reason is that during the cutting process, the CFRP is subjected to grinding. In addition, when the traverse rate is low, each section of the CFRP is subjected to a stronger grinding effect, resulting in a lower roughness; when the traverse rate is high, the roughness will increase because the grinding effect of each section of CFRP is relatively weak.

Fig.1b shows the effect of hydraulic pressure on roughness. Hydraulic pressure as one of the parameters of abrasive water jet processing can affect many technological parameters. The roughness is reduced with the increase of hydraulic pressure. When the other technological parameters are fixed, the increase in hydraulic pressure causes the abrasive in the abrasive water jet to have greater kinetic energy when it arrives at the material. They are better grinding the material and reducing the roughness of the overall cutting surface.

Fig.1c shows the effect of standoff distance on roughness, the standoff distance is also an important technological parameter in water jet cutting. The standoff distance affects the roughness of the cutting surface, the width and shape of the slit. The influence of the standoff distance on the roughness has two aspects. Increasing the target distance will increase the acceleration distance of the abrasive, so that the abrasive have higher kinetic energy and better cutting ability. On the other hand, when the hydraulic pressure and the abrasive flow rate are fixed, the abrasive are not at a higher speed than the water medium, and then when the abrasive water jet is ejected from the nozzle, there will be momentum transfer and turbulent diffusion. Therefore, the long standoff distance will decrease the kinetic energy of the abrasive and reduce the cutting ability of the abrasive. It can be seen from the figure that the influence of the standoff distance on the roughness is mainly in the second aspect. With the increase of the standoff distance, the roughness gradually increases and the surface quality decreases.

3.3 Analysis of variance

Analysis of variance is an effective method, which is based on the experimental results of the analysis to determine whether the influence of each factor is significant. Here, the impact of the technological parameters on the roughness of the cutting surface is analyzed by this method. The results of the analysis are as shown in Tab.5. In the Tab.5, *MP* is machining parameter; *DOF* is degree of freedom; *SS* is sum of squares; *V* is variance; *F* is F-ratio; *P* is percentage of contribution.

Tab.5　ANOVA of *Ra*

MP	*DOF*	*SS*	*V*	*F*	*P*
V	2	1.364	0.682	7.104	67.62
P	2	0.179	—	Pooled	8.88
H	2	0.270	0.135	1.406	13.39
e	2	0.204	0.102	—	10.11
$e^{\triangle}$	4	0.383	0.096	—	—
Total	8	2.017	0.252	—	100.00

As shown in the Tab.5, the value of variance is 0.089, which is less than 0.096 of the error column. Therefore, it can be concluded that the effect of hydraulic pressure on the roughness of cutting surface is not significant. According to the basic principle of ANOVA, when the sum of squares of a factor is smaller than that of error column, it can be classified into the error column. Correspondingly, the calculation of F-ratio will be changed from Eq.(1) to Eq.(2).

$$F_j = (S_j/f_i)/(S_e/f_e) , \tag{1}$$

$$F_j^{\Delta} = (S_j/f_i)/(S_e^{\Delta}/f_e^{\Delta}) . \tag{2}$$

It can be seen from the Tab.5 that the traverse rate is the most significant factor with F-ratio being 7.12. Based on Eq.(3) and Eq.(4) from the distribution quantile table of F-ratio and 7.104 is greater than 6.94 but less than 10.65, so it can beassumed that the traverse rate has a significant effect on the results for a 95% confidence level. The factor that being inferior to the traverse rate is standoff distance. However, it is found that standoff distance fails the test of significance at 95% confidence level and is considered insignificant.

$$F_{0.95}(2,4) = 6.94, F_{0.975}(2,4) = 10.65Ra , \tag{3}$$

$$Y(x) = \beta_0 + \sum \beta_i x_i + \sum \beta_{ii} x_i^2 + \sum \sum \beta_{ii} x_i x_j . \tag{4}$$

3.4 Mathematical models

The mathematical model can be used to predict the roughness of cutting surface, and to better guide the production, so that the application of abrasive water jet is more extensive. At present, people mainly use artificial neural networks (ANN) and regression analysis to establish the mathematical model, and the regression model showed a slightly better performance compared to the ANN model[8]. Therefore, in this paper, multiple linear regression analysis whose expression is Eq.(4) was used in developing mathematical models, it is the most widely used statistical technical in almost every field[9]. In this Equation, β_0 is a constant, β_i is the first order or liner effect coefficients, β_{ij} is the interaction effect coefficients and β_{ii} is the second order or quadratic effect coefficients. According to the analysis of variance in the previous section, it can be seen that the effect of hydraulic pressure on the result is small, so its quadratic effect coefficients are canceled.

Use Matlab to get the appropriate multiple regression model by least squares as shown in Eq. (5), in this equation, x_1 is traverse rate, x_2 is hydraulic pressure and x_3 is standoff distance.

$$Ra = 0.451\,688 + 0.007\,827x_1 - 0.000\,015x_2 + 0.295\,666x_3 - 0.000\,002x_1^{\,2} - 0.049\,042x_3^{\,2} - 0.000\,022x_1x_2 + 0.000\,145x_1x_3 + 0.001\,257x_2x_3. \quad (5)$$

This model is also applicable to other types of machine tools. But this prediction of surface roughness is not accurate when the parameters are beyond the scope of this article due to the complexity of the mechanism of abrasive water jet.

4 Conclusions

On the basic of experiment results, effect of machining parameters and analysis of variance, the condusions can be draw as follows:

1) In the process parameters, the traverse rate has the greatest influence on the cutting surface quality, and the standoff distance is the second important factor.

2) With the traverse rate and the standoff distance increases, the roughness of cutting surface increases. While the greater the hydraulic pressure, the smaller the roughness of cutting surface.

3) The greater the kinetic energy of the abrasive water jet , the better the quality of the cut surface.

4) A multiple regression model is obtained as shown in Eq.(5).

References

[1] LI Wei, GUO Quanfeng. Application of carbon fiber composites to cosmonautic fields [J]. China optics, 2011,4(3):201-212.(in Chinese)

[2] LIU S, CHEN T, WU C. Rotary ultrasonic face grinding of carbon fiber reinforced plastic (CFRP): a study on cutting force model [J]. International journal of advanced manufacturing technology, 2017, 89(12/3/4): 847-856.

[3] ZENIA S , BEN AYED L , NOUARI M , et al. Numerical analysis of the interaction between the cutting forces, induced cutting damage, and machining parameters of CFRP composites[J]. International journal of advanced manufacturing technology, 2015, 78(1/2/3/4):465-480.

[4] SELVAM R, KARUNAMOORTHY L, ARUNKUMAR N. Investigation on performance of abrasive water jet in machining hybrid composites[J]. Materials and manufacturing processes, 2017, 32(6): 700-706.

[5] DONG Yazhou, LIU Weiwei, ZHANG Heng, et al. Online recycling of abrasives in abrasive water jet cleaning [J].Procedia CIRP, 2014, 15: 278-282.

[6] ARMAĞAN M, ARICI A A. Cutting performance of glass-vinyl ester composite by abrasive water jet[J]. Materials and manufacturing processes, 2017, 32(15): 1715-1722.

[7] JOSHI S S, SHALIGRAM C. A review of analysis of surface roughness in abrasive water jet cutting[J].International journal of engineering development and research, 2017,5(3):97-102.

[8] ÇAYDAŞ U, HASÇALLK A. A study on surface roughness in abrasive waterjet machining process using artificial neural networks and regression analysis method [J]. Journal of materials processing technology, 2008, 202(1/2/3): 574-582.

[9] AZMIR M A, AHSAN A K, RAHMAH A. Effect of abrasive water jet machining parameters on aramid fibre reinforced plastics composite[J]. International journal of material forming, 2009, 2(1): 37-44.

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