Multi-objective Optimization of Milling Parameters for Carbon Fiber Reinforced Polymer Based on MOEA / D

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Abstract: In order to study the optimal milling parameters of carbon fiber reinforced polymer, this paper takes carbon fiber composite unidirectional plate as the research object, and the effects of cutting parameters on cutting forces and surfaces roughness were analyzed by high-speed cutting experiments. Experimental tests have validated the effectiveness of high speed cutting in reducing cutting forces, improving cutting efficiency, and improving machined surface quality. With the minimum surface roughness and maximum material removal rate as optimization goals, and the spindle speed, feed speed, and radial feed as design variables, the MOEA/D algorithm is used for multi objective optimization on, and to give the optimal solution set of carbon fiber composite milling.

Keywords: CFRP; High Speed Cutting; Cutting Force; Surface Roughness; Cutting Parameters; Multi-objective Optimization

1. Introduction

Carbon Fiber Reinforced Polymer has excellent mechanical properties, for instance, high specific intensity and modulus, high-temperature resistance, and anti-corrosion [1-2]. In aerospace, military equipment, transportation, and other fields, it is widely utilized [3]. Usually, the carbon fiber composite material is formed in one time, and its forming dimensional accuracy and shape often cannot meet the requirements, and the outer contour or local contour needs to be processed again [4]. Carbon fiber reinforced resin matrix composites are materials that are both heterogeneous and anisotropic in structure and consist of carbon fiber reinforcement and resin matrix. Due to the soft resin matrix, high hardness and high strength of carbon fiber reinforcement, serious tool wear, low machining efficiency and poor surface quality of parts are easy to occur in the secondary processing process [5-6].Selecting appropriate cutting parameters is necessary to enhance the quality and efficiency of carbon fiber composite machining. SAHRAIE et al. [7] through the experimental analysis of drilling composite materials under different cutting parameters, the method of delamination defects is studied. It is considered that the selection of reasonable tool parameters and process parameters can avoid the occurrence of delamination defects. SOEPANGKAT et al. [8] uses the response diagram to analyze the influence law of drill geometry, spindle of main shaft and feed velocity on the machining quality, optimizes the cutting parameters, and obtains the best combination of cutting parameters. VOSS R et al. [9] analyzed the effect of fiber direction and cutting process parameters on the surface quality of parts during in milling. NURHANIZA M [10] experimented with carbon fiber composites at high speeds and examined the variations in cutting force, cutting stress, workpiece surface quality, and surface morphology. High-speed cutting has been proven to effectively reduction of surface roughness and improvement of surface processing quality of the parts. MA Feng [11] aims at the optimization of drilling parameters of CFRP parts. The optimal parameter combination is obtained by establishing a multi-objective optimization model and the proposed optimization scheme. The optimization results significantly improve the processing quality and processing efficiency.

The multi-objective optimization of machining parameters of SiCp / Al composites was carried out by WANG Jinfeng [12]. The influence of machining parameters on the optimization objectives was analyzed, the optimal parameter combination was obtained by multi-objective optimization.

Based on the original research, aiming at the practical problem of optimizing the milling parameters of CFRP, the milling experiment of carbon fiber composites was carried out by means of high-speed milling. A multi-objective optimization model for surface roughness and material removal rate was developed after analyzing the impact of cutting parameters on cutting force and surface roughness. The MOEA / D algorithm is used for optimize the solution, and the optimal cutting parameters suitable for the processing of carbon fiber composite materials are found, which provides a theoretical reference for the parameter optimization of carbon fiber composite material cutting, the reliability of the optimization results is verified by experiments.

2. Experimentation Design

For the sake of study and analyze the impact of cutting parameters on the cutting performance of carbon fiber composite materials, and find the optimal combination of cutting parameters to meet the optimization objectives. Combined with engineering practice, this paper uses carbon fiber composite unidirectional plate T300 as the research object to carry out high-speed milling experiment. In the actual milling process, the greater the axial feed, the greater the axial cutting force, but the load on unit cutting edge has no obvious change. Considering that the milling of carbon fiber composite materials is generally finishing, the machining allowance is small. In this experiment, the influence of axial depth of cut on the cutting experiment is not considered. The experimental scheme is designed by flank milling, and the spindle speed (n), feed speed (v_f) and radial cutting depth (a_e) are used as the optimization parameters. According to the existing high-speed cutting experience, the experimental parameters and levels are determined as display in table 1.

The milling experiment uses resin-based carbon fiber composite material. The part material material is T300 unidirectional plate. The ply angle of each layer is 0 °, and the size is. There are 20 layers of ply. The actual thickness of each layer is 0.15 mm, then the overall thickness is 3 mm. The CNC machine tool used in the experiment is Beijing Jingdiao JDVT600T_A13S high-speed machining center, as shown in Figure 1. The tool uses a cemented carbide 4-edge end mill with a tool diameter of 8 mm and a spiral angle of 45°, as shown in Figure 2. The Kistler force measurement system was used in the experiment, including piezoelectric dynamometer 9257B, data collector 5697A1, charge amplifier and signal receiver. The Hommel-etamic W5 portable surface roughness was used to measure the roughness of the machined surface of the sample. Figure 3 is the test platform built for this experiment.

Table 1. Parameters and levels

Factor / Level	Spindle Speed (r/min)	Feed Speed (mm/min)	Radial Cutting Depth (mm)
Level 1	6000	400	0.2
Level 2	8000	500	0.4
Level 3	10000	600	0.6

Figure 1. Beijing Jingdiao JDVT600T _ A13S High-speed Machining Center

Figure 2. Carbide Vertical Milling Cutter

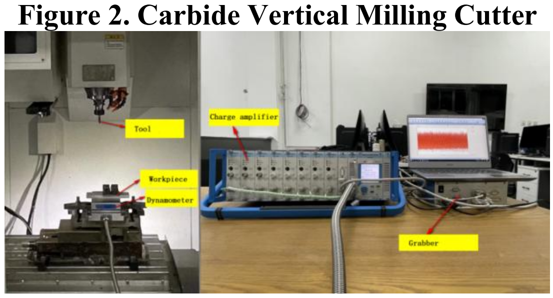

Figure 3. Milling Experimental Equipment

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3. Experimental Result and Date Analysis

3.1 Experimental Result

The orthogonal experiment was designed according to the orthogonal table, and the experimental results are display in Table 2. In the current value range, the orthogonal experiment is designed according to the orthogonal table L9, and the experimental parameters are 9 groups.

Table 2. Average Cutting Force and Surface Roughness of Each Group in Orthogonal Experiment

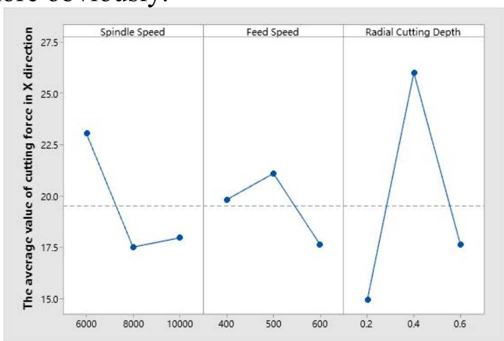
Order number	Axial cutting depth (mm)	Spindle speed(r/min)	Feed speed(mm/min)	Radial cutting depth (mm)	Cutting force F_x (N)	Cutting force F_y (N)	Surface roughness Ra(μm)
1	3	6000	400	0.2	17.08	11.85	1.77
2	3	6000	500	0.4	32.99	9.29	2
3	3	6000	600	0.6	19.1	8.374	2.35
4	3	8000	400	0.4	24.14	12.9	1.5
5	3	8000	500	0.6	15.53	7.922	1.45
6	3	8000	600	0.2	12.88	6.915	0.74
7	3	10000	400	0.6	18.24	6.476	1.80
8	3	10000	500	0.2	14.79	6.995	0.8
9	3	10000	600	0.4	20.88	6.134	1.2

3.2 Effect of Cutting Parameter on Cutting Force

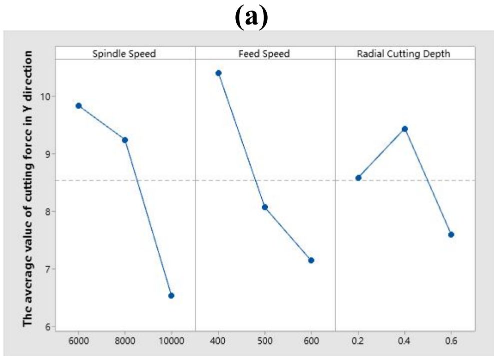
Table 3. Correlation Analysis between Cutting Force and Cutting Parameters

index	Spindle speed	Feed speed	Radial cutting depth	Cutting force F_y	Cutting force F_x
Spindle speed	1				
Feed speed	0	1			
Radial cutting depth	0	0	1		
Cutting force F_y	-0.596	-0.590	-0.180	1	
Cutting force F_x	-0.363	-0.257	0.193	0.362	1

Analysis of Table 3 shows that within the selected cutting parameter range, there is a negative correlation between spindle speed and cutting force in the milling of carbon fiber composite materials. As the spindle speed increase, the cutting force shows a decreasing tread. This is because when the spindle speed increases, the shear angle of the material in the cutting zone increases, the shear surface decreases, and the cutting resistance decreases. There is a negative correlation between feed rate and cutting force, that is, when the feed speed increases, the cutting deformation coefficient decreases, the material is not able to deform in the high-speed cutting state, and the friction coefficient between the tool and the chip is reduced. The actual cutting force generated during the cutting process will be smaller, while the radial force will be reduced more obviously.



(a)



(b)

Figure 4. The Main Effect Plots of Cutting Force on Cutting Parameters: (a) Main Effects of Control Factors on X-direction; (b) Main Effects of Control Factors on Y-direction

Figure 4 analyzes the main effect diagram of each factor level on the cutting force component. Within the range of experimental parameters, with the rise of spindle speed, the cutting force F_x component decreases and then increases slowly, and the cutting force F_y component decreases. Comprehensive analysis of the cutting force in both directions shows a decreasing trend as a whole.

Table 4. Normality Test Output Results

	Kolmogorov-Smirnov(V)a			Shapiro-Wilk		
	Statistics	Degree of freedom	Significance	Statistics	Degree of freedom	Significance
F_x	0.194	9	0.200*	0.882	9	0.164
F_y	0.194	9	0.200*	0.870	9	0.123

Table 4 Shapiro-Wilk test was performed on the sample data of this experiment. The test results indicate that the X direction of the cutting force component statistics $W = 0.882$, significant level $Sig. = 0.164 > 0.05$; the cutting component statistics $W = 0.870$, and significance level $Sig. = 0.123 > 0.05$ in the Y direction, so the original hypothesis is, the dependent variable F_x and F_y assumption of normal distribution are retained, and regression analysis can be performed.

According to previous research experience, there is an exponential relationship between cutting force and cutting parameters, and the expression of cutting force can be established by the power exponential function of cutting parameters. Through the experimental data, the empirical formula between cutting force and cutting parameters is established. The standard form is:

$$F_x = C_F n^{b_1} a_e^{b_2} v_f^{b_3} \quad (1)$$

Where, F_x —The component of milling force in x direction;

C_F —Comprehensive influence factors; it is related to the workpiece material and the cutting conditions of the tool;

n —Spindle speed,r/min;

a_e —Radial cutting depth,mm;

v_f —Feed speed,mm/min;

b_1 、 b_2 and b_3 were exponential constant.

Formula (1) is a nonlinear function. In order to facilitate the linear processing of the above formula, the logarithm of both sides of the formula is taken to obtain the linear equation.

$$\ln F_x = \ln C_F + b_1 \ln n + b_2 \ln a_e + b_3 \ln v_f \quad (2)$$

The regress function in MATLAB is used to perform multivariate linear fitting of the least square method to obtain the coefficient matrix of the equation. The logarithm of the two sides of the equation can obtain the prediction model of the milling force in the x direction:

$$F_x = 9.030 n^{-0.446} a_e^{-0.302} v_f^{0.222} \quad (3)$$

Similarly, prediction model of milling force in y direction is:

$$F_y = 14.120 n^{-0.741} a_e^{-0.873} v_f^{-0.0569} \quad (4)$$

3.3 Effect of Cutting Parameter on Surface Roughness

Table 5. Correlation Analysis between Cutting Force and Surface Roughness

Index	Spindle speed	Feed speed	Radial cutting depth	Surface roughness
Spindle speed	1			
Feed speed	0	1		
Radial cutting depth	0	0	1	
Surface roughness	-0.625	-0.210	0.617	1

It can be seen from Table 5 that in the selected range of cutting parameters, the spindle speed is negatively correlated with the surface roughness. As the increase of the spindle speed, the heat generated in the machining will be quickly taken away with the chips, which is less on the workpiece and the tool, and can effectively improve the machining quality of the workpiece. There is a positive correlation between feed speed and surface roughness. With the increase of feed speed, the amount of cutting per tooth increases, and the surface roughness increases.

Figure 5 analyzes the main effect plots of each cutting parameter on surface roughness. Within the range of experimental parameters, with the increase of spindle speed, the surface roughness decreases first and then increases slowly, and the overall trend is decreasing. It is consistent with the change rule of surface roughness of workpiece in high speed cutting, which shows that high speed cutting is suitable for the processing of carbon fiber composite materials.

Table 6 Shapiro-Wilk test was performed on

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the sample data of this experiment. The test results indicate that the surface roughness statistics $W = 0.930$, significant level $P = 0.482 > 0.05$, revealed that the dependent variable surface roughness is consistent with the assumption of normal distribution and can be used for regression analysis.

Table 6. Normality Test Output Results

	Kolmogorov-Smirnov(V)a			Shapiro-Wilk		
	Statistics	Degree of freedom	significance	Statistics	Degree freedom	significance
Ra	0.130	9	0.200*	0.963	9	0.827

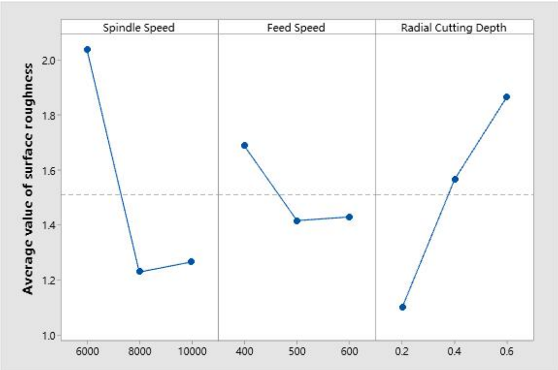

Figure 5. The Main Effect Plots of Surface Roughness on Cutting Parameters

According to the theory of metal cutting, there is a certain exponential relationship between the surface roughness of the workpiece and the cutting parameters. Through the above orthogonal test data, the empirical formula between the surface roughness and the cutting parameters is established. The standard form is:

$$Ra = C_{\mathrm{Ra}} n^{a_1} a_{\mathrm{e}}^{a_2} v_{\mathrm{f}}^{a_3} \quad (5)$$

Where, Ra —surface roughness;

C_{Ra} —Comprehensive influence factors;It is related to the workpiece material and the cutting conditions of the tool;

n —Spindle speed,r/min;

a_{e} —Radial cutting depth,mm;

v_{f} —Feed speed,mm/min;

a_1 、 a_2 and a_3 were exponential constant.

Eq. (5) is a nonlinear function. In order to facilitate the linear processing of the above formula, the logarithm of both sides of the formula can be used to obtain a linear equation.

$$\ln Ra = \ln C_{\mathrm{Ra}} + a_1 \ln n + a_2 \ln a_{\mathrm{e}} + a_3 \ln v_{\mathrm{f}} \quad (6)$$

The regress function in MATLAB is used to fit the multiple linear regression of the least square method, and the coefficient matrix of the equation is obtained. The prediction model of surface roughness can be obtained by logarithm on both sides of the equation:

$$Ra = 14.7787 n^{-1.0669} a_{\mathrm{e}}^{-0.6959} v_{\mathrm{f}}^{0.5423} \quad (7)$$

4. Milling Process Parameters Optimization and Analysis

4.1 Construction of Multi-objective Optimization Model of Cutting Parameters

The above results show that the impact of cutting parameters on surface roughness, cutting material removal rate and cutting force in all directions is different. If the overall optimization of the three objectives is considered comprehensively, the optimization results of cutting parameters are often contradictory. According to the needs of engineering practice, it is necessary to solve the goal of high-quality and efficient processing of carbon fiber composites. High-quality processing is reflected by the surface roughness of the parts, and efficient processing is reflected by the material removal rate.

Through the S-W test of the empirical model of milling surface roughness of carbon fiber composites, it is proved that the regression model of surface roughness and milling parameters has good significance, and the optimal objective function is obtained as follows:

$$Ra = C_{\mathrm{Ra}} n^{a_1} a_{\mathrm{e}}^{a_2} v_{\mathrm{f}}^{a_3} \quad (8)$$

Where, C_{Ra} Depends on the processing material, a_1 、 a_2 and a_3 are undetermined coefficients.

In this experiment, the influence of cutting parameters on side milling is mainly studied, so the influence of axial cutting depth is not considered. Therefore, the material removal rate (M_{RR}) can be expressed as:

$$M_{\mathrm{RR}} = n f_{\mathrm{z}} z a_{\mathrm{e}} = v_{\mathrm{f}} a_{\mathrm{e}} \quad (9)$$

In the formula, n is expressed as the spindle speed, z is the number of tool teeth; f_{z} is the feed per tooth, v_{f} is the feed rate, and a_{e} is the radial depth of cutting.

In order to achieve the maximum material removal rate and the highest processing quality, the objective function of the optimization problem is expressed as:

$$y = \min[Ra(X),\ -M_{\mathrm{RR}}(X)] \tag{10}$$

In this optimization problem, taking the variables of the orthogonal experiment of carbon fiber composite materials as the reference, the spindle speed n, feed speed v_{f} and radial depth of cut a_{e} are selected to form the design vector X together.

$$X = (n, v_{\mathrm{f}}, a_{\mathrm{e}})^T \tag{11}$$

Thus, the complete form of the milling parameter optimization model can be expressed as:

$$\begin{cases} \min y = [Ra(X) - M_{\mathrm{RR}}(X)] \\ X = (n, v_{\mathrm{f}}, a_{\mathrm{e}})^T \end{cases} \tag{12}$$

For the setting of the optimization interval, with reference to the influence of cutting parameters on the dependent variables in this experiment, the optimal solution will be obtained within the range of orthogonal experimental parameters. Therefore, the orthogonal experiment of carbon fiber composite materials is used as a reference. The range of design variables is shown in Table 7:

Table 7. The Value Range of Decision Variables

Decision variable	Spindle speed (r/min)	Feed speed (mm/min)	Radial cutting depth (mm)
Upper limit of value	10000	600	0.6
Lower limit of value	6000	400	0.2

4.2 The Optimization Model is Solved Based on MOEA / D

According to the established multi-objective milling parameter optimization model, the multi-objective evolutionary algorithms based on decomposition (MOEA / D) is used to figure out the question. The initial population of the algorithm is set to 50, and the number of iterations is set to 100. Through the iterative optimization of MOEA / D algorithm, the results of multi-objective optimization are given in figure 6. The hollow circle represents the optimized front point, which is evenly distributed on the curve, and the different positions reflect the conflict and compromise between the two optimization objectives. In this paper, the optimization objectives are the minimum surface roughness and the maximum material removal rate, so the optimization front is concentrated in the lower left corner of the picture, and the conflict of the objectives makes the optimization front present a graphical shape.

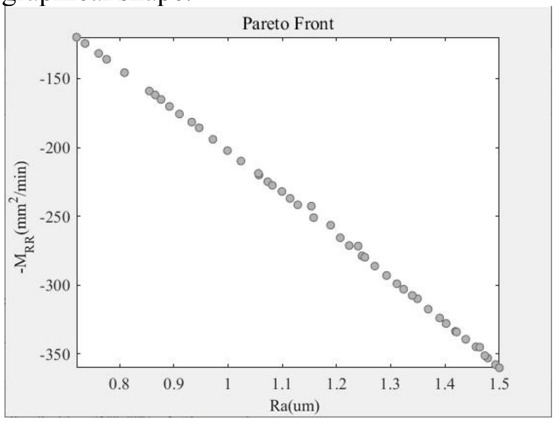

Figure 6. Multi-objective Optimization Results

Figure 7 is the value of the decision variable in the Pareto front, the X_1-axis represents the spindle speed, the X_2-axis represents the feed speed, and the X_3- axis represents the radial feed. The figure shows that the value range of the spindle speed is between 9400 ~ 9600 r/min, indicating that the high spindle speed can effectively reduce the surface roughness of the parts. The value range of feed rate is 596 ~ 600 mm/min. When the surface is in high speed cutting state, the cutting feed rate can be appropriately increased to achieve efficient machining.

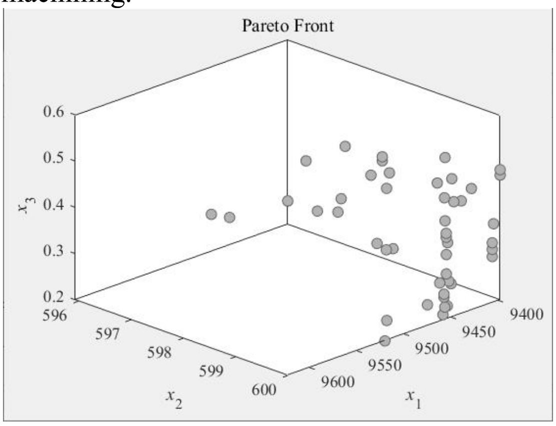

Figure 7. Pareto Front Decision Variables

Table 8 shows the optimized Perato optimal solution set. In actual production, appropriate cutting parameters can be selected according to machine tool performance and process requirements, so as to avoid blind selection of cutting parameters in milling of CFRP.

Table 8. Multi-objective Optimization Results

Number	Spindle speed (r/min)	Feed speed (mm/min)	Retinal cutting depth (mm)	Surface roughness(μm)	Material removal rate (mm^2/min)
1	9485.22	600	0.5748	1.4545	344.9081
2	9440.45	600	0.2554	0.8354	153.2490
3	9529.43	600	0.4906	1.2999	294.3583
4	9527.01	600	0.2082	0.7381	124.9363
5	9462.84	600	0.2437	0.8111	146.1827
6	9471.43	600	0.2785	0.8816	167.1069
7	9461.29	600	0.4449	1.2097	266.9616
8	9497.34	600	0.5462	1.4014	327.7098
9	9529.60	600	0.2857	0.8984	171.4063
10	9452.93	600	0.3754	1.0744	225.2345
11	9456.07	600	0.2298	0.7831	137.8664
12	9385.57	600	0.5033	1.3238	301.8388
13	9446.64	600	0.3270	0.9788	196.2253
14	9529.76	600	0.5942	1.4899	356.5064
15	9489.75	600	0.5003	1.3158	300.1774
16	9457.16	600	0.2700	0.8645	162.0067
17	9483.46	600	0.4714	1.2610	282.8180
18	9452.93	600	0.3754	1.0744	225.2345
19	9455.03	600	0.2614	0.8472	156.8660
20	9412.70	598	0.4494	1.2212	268.7674
21	9523.18	600	0.6000	1.5005	360.0000
22	9412.70	600	0.4070	1.1363	244.1839
23	9429.56	600	0.3110	0.9470	186.5646
24	9608.47	600	0.4117	1.1627	247.0169
25	9457.49	600	0.5387	1.3875	323.2218
26	9518.09	600	0.4810	1.2810	288.5839
27	9487.79	600	0.5113	1.3363	306.7944
28	9483.46	600	0.4579	1.2352	274.7164
29	9366.92	600	0.4375	1.1979	262.5287
30	9440.45	600	0.3418	1.0081	205.0742
31	9441.12	600	0.3541	1.0324	212.4451
32	9446.64	600	0.3019	0.9286	181.1401
33	9384.12	600	0.2930	0.9133	175.7832
34	9533.72	600	0.2167	0.7558	129.9916
35	9485.59	600	0.5847	1.4727	350.7983
36	9522.53	600	0.2000	0.7210	120.0000
37	9545.66	600	0.2507	0.8273	150.4296
38	9412.70	598	0.4753	1.2711	284.2878
39	9486.39	600	0.3888	1.1020	233.2911
40	9484.78	598	0.3356	0.9990	200.8238
41	9523.18	600	0.6000	1.5005	360.0000
42	9522.74	600	0.4221	1.1696	253.2739
43	9503.17	600	0.5259	1.3640	315.5423
44	9457.48	600	0.5614	1.4302	336.8482
45	9506.97	600	0.5262	1.3646	315.6949
46	9428.52	600	0.3868	1.0966	232.0566
47	9457.49	600	0.2174	0.7580	130.4667
48	9380.81	600	0.2762	0.8803	165.7319
49	9440.45	600	0.2259	0.7760	135.5640
50	9517.15	591	0.2355	0.8075	139.0826

4.3 Cutting Experiment and Analysis of CFRP

In order to verify the universal applicability of the optimization results in practical applications, 10 sets of experimental data were randomly selected from the optimization solution set obtained in this paper for processing verification. Since the material removal rate can be calculated by the formula, only the surface roughness of the cutting part needs to be verified in the experiment. Table 9 is the milling experiment and verification results of 10 sets of cutting parameters randomly selected from 50 sets of optimal solutions. The results shown that the prediction accuracy of the model is up to 98.52 %, and the average prediction accuracy is 95.44 %. It shows that the optimization results of cutting parameters in this paper are reliable and have reference significance for the milling of carbon fiber composite materials.

Table 9. The Partial Optimal Solution Verification Results Intercepted from the Pareto Front Solution Set

Number	Spindle speed(r/min)	Feed speed (mm/min)	Radial cutting depth (mm)	Optimized value of surface roughness(μm)	Experimental value of surface roughness(μm)	Prediction accuracy
1	9485.22	600	0.5748	1.4545	1.40	96.03%
2	9527.01	600	0.2082	0.7381	0.79	92.36%
3	9461.29	600	0.4449	1.2097	1.15	95.45%
4	9456.07	600	0.2298	0.7831	0.80	97.46%
5	9529.76	600	0.5942	1.4899	1.59	93.01%
6	9429.56	600	0.3110	0.9470	0.93	98.52%
7	9440.45	600	0.3418	1.0081	0.97	96.32%
8	9441.12	600	0.3541	1.0324	1.10	93.21%
9	9503.17	600	0.5259	1.3640	1.41	96.54%
10	9457.49	600	0.2174	0.7580	0.74	97.45%

5. Conclusions

1) As a difficult-to-machine material, high-speed cutting can be used to improve the machining quality, reduce the surface roughness and cutting force of carbon fiber composites.

2) A multi-objective optimization model based on exponential function is established. The regression analysis and test of the model show that the prediction model has a good fitting degree.

3) The multi-objective optimization of cutting parameters is carried out based on the decomposition-based over-objective evolutionary algorithm, and the optimal solution set of the optimization problem is obtained. The feasibility of cutting parameters is verified by cutting experiments, which provides a reference for the selection of cutting parameters in the milling of carbon fiber composites.

Reference

[1] Joo S J, Yu M H, Kim W S, et al. Design and manufacture of automotive composite front bumper assemble component considering interfacial bond characteristics between over-molded chopped glass fiber polypropylene and continuous glass fiber polypropylene composite. Composite structures, 2020, 236(111849):1-10.

[2] Ashby M F. Materials selection in mechanical design. 4th ed. Oxford: Elsevier, 2011.

[3] Hanlon M. Global UAV gets bigger and more capable [2005-11-11].

[4] Chen X K, Xie H Q, Chen H, et al. Optimization for CFRP pultrusion process based on genetic algorithm-neural network ,International journal of material forming, 2010, 3(2):1391-1399

[5] Bleicher F, Wiesinger G, Kumpf C, et al. Vibration assisted drilling of CFRP/metal stacks at low frequencies and high amplitudes .Production engineering, 2018,12(2):289-296.

[6] Jia Zhenyuan, Bi Guangjian, WANG Fuji, et al. Research on cutting mechanism of carbon fiber reinforced resin matrix composites. Journal of Mechanical Engineering, 2018, 53(23):199-208.

[7] Sahraie Jahromi A, Bahr B. An analytical method for predicting cutting forces in orthogonal machining of unidirectional

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composites .composites science and technology, 2010, 70:2290-2297.

[8] Soepangkat B O P, Norcahyo R, Effendi M K, et al. Multi-response optimization of carbon fiber reinforced polymer (CFRP) drilling using back propagation neural network-particle swarm optimization (BPNN-PSO). Engineering Science and Technology, an International Journal, 2020, 23(3):700-713.

[9] Voss R, Seeholzer L, Kuster F, et al. Influence of fiber orientation tool geometry and process parameters on surface quality in milling of CFRP. CIRP Journal of Manufacturing Science and Technology, 2017, 18: 75-91.

[10] Nurhaniza M, Ariffin M, Mustapha F, et al. Analyzing the effect of machining parameters setting to the surface roughness during end milling of CFRP-aluminium composite laminates. International Journal of Manufacturing Engineering, 2016, 2016.

[11] Ma Feng, Huang Shunhu, Liu Peiji, et al. Multi-obiective optimization method of CFRP drilling process parameters for power and drilling quality . Journal of Mechanical Engineering, 2023, 59(11): 290-299.

[12] Wang Jinfeng, Pan Lijuan, Xing Dixiong, et al. Multi-objective optimization of cutting parameters for SiCp / Al composites based on energy efficiency. Journal of Central South University, 2020, 51(6): 1565-1574.