Research on Tool Wear Factors for Milling Wood-plastic Composites Based on Response Surface Methodology

Weihua Wei,[a,]* Yingli Li,[a] Yuantong Li,[a] Yiqi Xu,[a] and Changyong Yang [b]

A high-speed milling experiment on wood-plastic composites was performed using cemented carbide tools, and the resulting wear pattern was studied. The influence of the cutting parameters, the cutting speed, feed speed, and axial cutting depth on the tool wear was studied *via* response surface methodology, and the influence of the interaction of the cutting parameters on tool wear was analyzed. Three-dimensional surface graphs and contour plots of the tool wear results were established. According to the experimental results, a mathematical model of the tool wear based on the second-order response surface methodology was established, and the model was utilized to verify its feasibility. The results show that the nose width (NW) increases with the increase of the cutting speed and axial cutting depth and decreases with the increase of feed speed. Among the factors affecting tool wear, the cutting speed had the greatest influence, followed by the feed rate, with the axial cutting depth affecting tool wear the least. According to the results of the interaction between the tool wear and the cutting parameters, a low feed speed and small axial cutting depth can be selected to ensure long tool life; for low-speed cutting, a high feed speed and large axial cutting depth can be adopted to ensure tool life while improving machining efficiency.

Keywords: Wood-plastic composites; High-speed milling; Tool wear; Mathematical model; Response surface methodology

Contact information: a: College of Mechanical and Electrical Engineering, Nanjing Forestry University, Nanjing, 210037 China; b: Jiangsu Key Laboratory of Precision and Micro-Manufacturing Technology, Nanjing University of Aeronautics and Astronautics, Nanjing, 210016 China;
** Corresponding author: whwei@njfu.edu.cn*

INTRODUCTION

Wood-plastic composites (WPCs) have the advantages that wood or plastic alone does not have, and they are widely used in automotive interiors, garden landscapes, interior design, as well as other industries. However, due to the anisotropy and non-uniformity of WPCs, during the WPCs milling process, the cutting tools are subjected to friction, vibration, impact, *etc.*; the tool is rapidly worn; and the tool failure evolution mechanism is complex. Therefore, the tool is required to have not only high hardness and wear resistance, but also sufficient strength and toughness (Wei *et al*. 2018, 2019). The use of high-performance tool materials can effectively reduce overall tool wear and extend the tool life (Darmawan *et al*. 2001), but the expensive tool price reduces the processing economy. As important parameters for the cutting conditions, the processing parameters have a major effect on tool wear. Selecting the appropriate machining parameters is one of the keys to improving tool life and reducing production costs (Wang *et al*. 2011). Ubeyli *et al*. (2008) investigated the effect of the feed rate on tool wearing when milling B_4C_p reinforced aluminum metal matrix composites produced *via* a liquid phase sintering method and used an optical microscope to measure the magnitude of flank wear on the tools. Experimental results indicated that a higher feed rate led to lower tool wear for the tools and that coated tools exhibited better performance than uncoated tools, with respect to the flank wear. Altan *et al*. (2018) used the Taguchi method and the analysis of variance (ANOVA) statistical method to study the effect of the cutting parameters on tool wear. The study indicated that the feed rate had the most significant effect on tool wear during the initial wear and rapid wear stages. In the stable wear stage, the feed rate and cutting speed had almost the same effect on tool wear, but the effect of the cutting speed was slightly greater. Szwajka and Trzepieciński (2016) investigated the effect of the cutting speed on tool life using a single factor method. The results showed that as the cutting speed increased, the tool life decreased. Zhu *et al*. (2017) pointed out that when milling high-density fiberboard (HDF) with a TiC-reinforced Al_2O_3 ceramic cutting tool, a high spindle rotation speed and feed rate during high-speed milling lead to a high materials removal rate and a high frequency of contact between the tool and workpiece in comparison to a low speed milling, which further induced serious tool wear. In addition, the main wear forms of a TiC-reinforced Al_2O_3 ceramic cutting tool were pull-out of grain, flaking, and chipping, and the wear mechanisms were primarily abrasive wear and adhesive wear. Guo *et al*. (2018) found that both the Si_3N_4 cutting tool and the Al_2O_3 cutting tool caused adhesive wear while cutting plywood, and the tool adhesive wear during high-speed cutting was more serious than during low-speed cutting. Yi *et al*. (2015) established a surface roughness model of a micro milling process *via* the response surface methodology (RSM); the model had high reliability and practicability under the experimental conditions. It could be used to select the appropriate cutting parameters and predict the surface roughness before machining. However, most of these studies were based on metal and wood materials and do not research tool wear during the high-speed milling of WPCs. In these studies, a single factor method is often used in the experimental design, no overall mathematical model is established, and the systematic analysis of interactions between the influential factors is lacking. The response surface methodology is an optimization method of comprehensive test designs and mathematical modeling, which can study the interaction between two or more factors (Chan *et al*. 2019). Compared with a single-factor test, RSM can comprehensively analyze the selected experiment parameters in a shorter time and in a more economical way and with fewer experiment iterations (Khuri and Mukhopadhyay 2010).

In this paper, the self-developed WPCs were used as the test object, and the high-speed milling test of WPCs was performed with a cemented carbide tool. The influence of cutting parameters and their interaction on tool wear were studied *via* the RSM. A mathematical model of tool wear was established, and the relationship between the cutting parameters and tool wear was obtained. The feasibility of the model was verified *via* ANOVA, and the optimal combination of the cutting parameters for improving tool life was determined, which provides a theoretical basis for the subsequent selection of processing parameters.

EXPERIMENTAL

Materials

The sample used in the test is a composite material made up of wood flour, polyethylene and adhesive, which was produced by Nanjing Dayuan Plastic Wood New

Material Co. Ltd. (Nanjing, China). This wood plastic composite has good water resistance and resistance to degradation when wet. The sample size was 322 mm (L) × 80 mm (W) × 40 mm (H), and their properties are shown in Table 1.

Table 1. Properties of the WPCs

Proportion (mass)	Density (g/cm^3)	Flexural Modulus (MPa)	Shore Hardness (HD)
Wood flour: 65% Polyethylene: 25% Adhesive: 10%	1.19	28	58

The experiment was performed with up-milling using a UCP 800 Duro CNC machining center by Mikron (Agno, Switzerland). The cemented carbide blades produced by Zhuzhou Diamond Cutting Tool Co. Ltd. (Zhuzhou, China) were used to perform the test, and the blades specifications are shown in Table 2. Before the test, the blades were installed on the arbor (model EMP01-020-G20-AP11-02, Zhuzhou Diamond Cutting co. Ltd.), which had a diameter (*D*) of 20 mm, and only one blade was mounted on the arbor for each set of tests.

Table 2. Specification Parameters of the Blade

Model	Material	Size: L × I.W × S (mm)	Rake Angle γ_0 (°)	Clearance Angle α_0(°)	Corner Radius *R* (mm)
YD201	Cemented Carbide	12.24 × 6.5 × 3.6	19	11	0.4

Methods

In this test, the tool nose width (NW) was selected as the representative value of tool wear, as shown in Fig. 1. At the end of each test, the NW was measured with a Nikon DS-U3 DS digital microscopic imaging system (Tokyo, Japan).

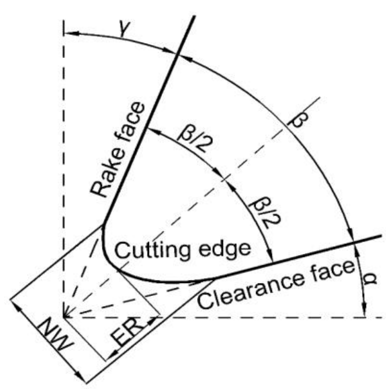

Fig. 1. Microscopic angle and geometric parameters of the cutting tool

A central composite design (CCD) for the RSM was adopted in this test. The cutting speed (*v*), feed rate (*f*), and axial cutting depth (a_p) were selected as the three factors, and three levels were selected as the number of levels. This design requires 20 sets of tests, including 1 set of factor designs, 6 sets of center point designs, and 1 set of axial point designs. During the machining test, the radial cutting depth remained unchanged (5 mm), and the milling length of each set was 21.12 m. The cutting parameters and their levels are shown in Table 3.

Table 3. Cutting Parameters and Levels

Cutting Parameters	Levels		
	-1	0	1
Cutting Speed *v* (m/min)	500	800	1100
Feed Rate *f* (mm/rev)	0.1	0.2	0.3
Axial Cutting Depth a_p (mm)	2	4	6

RESULTS AND DISCUSSION

According to the design matrix, the experimental values of the NW under different cutting conditions (v, f, and a_p) were obtained (as shown in Table 4).

Table 4. Experiment Results of the NW

No.	Levels			Cutting Parameters			NW (mm)
	v	*f*	a_p	*v* (m/min)	*f* (mm/rev)	a_p (mm)	
1	-1	-1	-1	500	0.1	2	0.10950
2	1	-1	-1	1100	0.1	2	0.18800
3	-1	1	-1	500	0.3	2	0.09628
4	1	1	-1	1100	0.3	2	0.12753
5	-1	-1	1	500	0.1	6	0.13673
6	1	-1	1	1100	0.1	6	0.22840
7	-1	1	1	500	0.3	6	0.09436
8	1	1	1	1100	0.3	6	0.15011
9	-1	0	0	500	0.2	4	0.10345
10	1	0	0	1100	0.2	4	0.17861
11	0	-1	0	800	0.1	4	0.15861
12	0	1	0	800	0.3	4	0.10656
13	0	0	-1	800	0.2	2	0.12166
14	0	0	1	800	0.2	6	0.14367
15	0	0	0	800	0.2	4	0.13217
16	0	0	0	800	0.2	4	0.11069
17	0	0	0	800	0.2	4	0.11783
18	0	0	0	800	0.2	4	0.12765
19	0	0	0	800	0.2	4	0.14127
20	0	0	0	800	0.2	4	0.12048

Mathematical Regression Model and Verification

Mathematical regression model of tool wear

For the RSM, the response function used to represent tool wear can be expressed as Eq. 1,

$$NW = F\{v, f, a_p\} \quad (1)$$

where NW (mm) is the response value, F is the response function, v (m/min) is the cutting speed, f (mm/rev) is the feed rate, and a_p (mm) is the axial cutting depth (Prasad *et al.* 2010).

The second order response surface regression equation used to represent the response surface for the NW factors is shown in Eq. 2,

$$Y = A_0 + \sum_{i=1}^{n} A_i X_i + \sum_{i,j=1}^{n} A_{ij} X_i X_j + \sum_{i=1}^{n} A_{ii} X_i^2 \quad (2)$$

where Y is the response value, A_0 is the free term of the equation, the terms with coefficients A_1, A_2, …, A_n are linear terms, the terms with A_{12}, A_{13}, …, $A_{(n-1)n}$ are the interaction terms, and the terms with A_{11}, A_{22}, …, A_{nn} are quadratic terms.

For three factors, the selected second order response surface regression equation of tool wear can be expressed as Eq. 3,

$$NW = A_0 + A_1 v + A_2 f + A_3 a_p + A_{12} vf + A_{13} v a_p + A_{23} f a_p + A_{11} v^2 A_{22} f^2 + A_{33} a_p^2 \quad (3)$$

where the variables were the same as Eq. 2.

The values of the coefficients in Eq. 3 could be calculated *via* the regression method. According to the test data values in Table 4, the value of the coefficients in Eq. 3 were analyzed and calculated using the Design-Expert experimental design software (Version 10, Stat-Ease, Minneapolis, MN), and the mathematical model of tool wear was obtained, as shown in Eq. 4,

$$NW = 0.12718 + 0.03323v - 0.02464f + 0.01103a_p - 0.0106vf + 0.00471va_p - 0.00587fa_p + 0.0106v^2 + 0.00216f^2 + 0.00224a_p^2 \quad (4)$$

where the variables were the same as Eq. 1.

Model feasibility analysis

Feasibility analysis of the established regression model was performed using the analysis of variance (ANOVA) method (Xiao *et al*. 2018). Table 5 shows the ANOVA table for the regression model of tool wear. The "Prob>F" value of the model was less than 0.0001 (as shown in Table 5), which implied the established regression model is feasible. The R^2 and adjusted R^2 of the model were 0.9642 and 0.9319, respectively, which indicated that the independent variables selected by the model fit the dependent variables very well.

Table 5. ANOVA Table of the Model

Source	Sum of Squares	Degree of Freedom	Mean Square	F value	Prob>F	
Model	0.021	9	2.285E-003	29.89	< 0.0001	Significant
Residual	7.645E-004	10	7.645E-005	-	-	-
Lack of Fit	1.648E-004	5	3.296E-005	0.27	0.9087	Not Significant
Pure Error	5.998E-004	5	1.200E-004	-	-	-
Total	0.021	19	-	-	-	-
	R^2=0.9642, adjusted R^2=0.9319					

Model regression coefficient significance test and optimization

The significance of the model population does not fully explain the fact that the independent variable is important for the dependent variable, since there might be some scenarios where the independent variable does not work or should be replaced by other, more important, dependent variables (Mandal *et al*. 2011; Ni *et al*. 2019). Therefore, the significance of the established model regression coefficients was tested, and the results are shown in Table 6. For the linear terms, the cutting speed (*A*), feed rate (*B*), and axial cutting depth (*C*) had a significant effect on tool wear (the "Prob>F" value was less than 0.01). For the interaction terms, the interaction between *v* and *f* (*AB*) had a significant effect on tool wear (the "Prob>F" value was less than 0.01), while the interactions were not significant (the "Prob>F" value was greater than 0.05). For the second order terms, all terms did not exhibit a significant influence on tool wear (the "Prob>F" value was greater than 0.05).

Table 6. Significance Test of the Model Regression Coefficient

Source	Sum of Squares	Degree of Freedom	Mean Square	F value	Prob>F
A - cutting speed	0.011	1	0.011	144.46	<0.0001
B - feed rate	6.071E-003	1	6.071E-003	79.41	<0.0001
C - axial cutting	1.217E-006	1	1.217E-003	15.91	0.0026
AB	8.647E-004	1	8.647E-004	11.31	0.0072
AC	1.774E-004	1	1.774E-004	2.32	0.1587
BC	2.758E-004	1	2.758E-004	3.61	0.0867
A^2	3.091E-004	1	3.091E-004	4.04	0.0721
B^2	1.279E-005	1	1.279E-005	0.17	0.6911
C^2	1.376E-005	1	1.376E-005	0.18	0.6804

In order to obtain the best model, the stepwise regression analysis method (alpha = 0.05) was combined to eliminate the insignificant terms in the model. The optimized mathematical model of tool wear was shown in Eq. 5,

$$NW = 0.12806 + 0.03323v - 0.02464f + 0.01103a_p - 0.0104vf + 0.01324v^2 \quad (5)$$

where the variables were the same as Eq. 1. Table 7 shows the ANOVA for the optimized model after removing the insignificant terms. It can be seen from Table 7 that the significance and fitting degree of the optimized model were still good (adjusted R^2 = 0.9198), and all terms (*v*, *f*, a_p, *vf*, and v^2) had a strong significant effect on tool wear (the "Prob>F" value was less than 0.01).

Table 7. ANOVA Table of the Optimized Model

Source	Sum of Squares	Degree of Freedom	Mean Square	F value	Prob>F	
Model	0.020	5	4.015E-003	44.60	<0.0001	Significant
A - cutting speed	0.011	1	0.011	122.70	<0.0001	-
B - feed rate	6.071E-003	1	6.071E-003	67.45	<0.0001	-
C - axial cutting	1.217E-003	1	1.217E-003	13.52	0.0025	-
AB	8.647E-004	1	8.647E-004	9.61	0.0078	-
A^2	8.762E-004	1	8.762E-004	9.73	0.0075	-
Residual	1.260E-003	14	9.001E-005	-	-	-
Lack of fit	6.604E-004	9	7.338E-005	0.61	0.7543	Not Significant
Pure Error	5.998E-004	5	1.200E-004	-	-	-
Total	0.021	19	-	-	-	-
	R^2 = 0.9409, adjusted R^2 = 0.9198					

In order to determine whether the test data was normally distributed, the normal plot of the residuals was drawn (as shown in Fig. 2). Figure 2 shows that the residual distribution was close to the best fit line, so it conforms to the normal distribution. In addition, the predicted value and the actual value almost coincided with each other (as shown in Fig. 3), which further confirms the feasibility of the model.

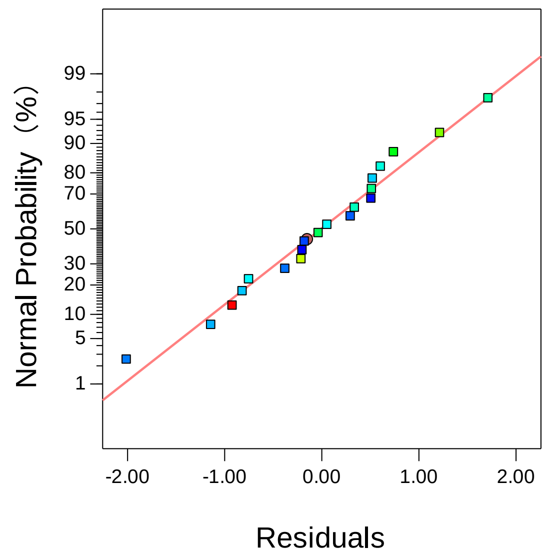

Fig. 2. Normal plot of residuals

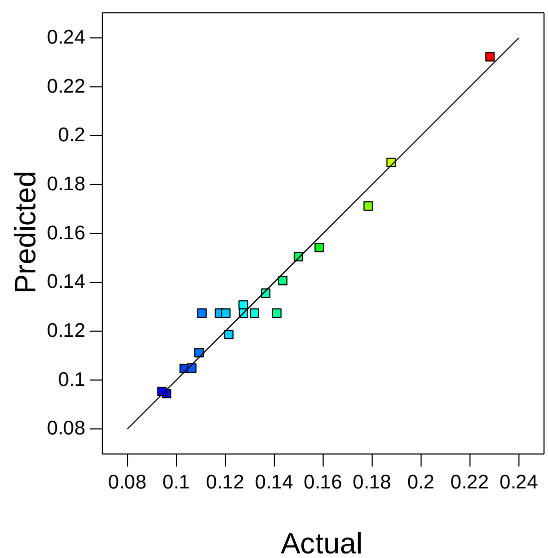

Fig. 3. Predicted *vs* Actual

Direct Effects of Variables

When studying tool wear, the *v* is one of the most important factors affecting tool wear (Szwajka and Trzepiecińsk 2016). Based on the test data obtained above, the influence of *v* on tool wear was studied for a range of 500 m/min to 1100 m/min. As shown in Table 7, it was found that *v* was statistically significant (the "Prob >F" value was less than 0.0001), and the positive coefficient (+ 0.03323) indicated that *v* had a positive influence on the amount of tool wear, which meant that the greater the *v* value, the larger the amount of tool wear. Figure 4 shows the effect of v on tool wear when f and a_p are at a medium level (f = 0.2 mm/rev and a_p = 4 mm). It is evident from Fig. 4 that the NW increased as v increased. When v was increased from 500 m/min to 1100 m/min, the NW increased from 0.10345 mm to 0.17861 mm, or a 72.65% increase. The reason for this was that when v increases, the contact frequency between the tool and workpiece increases, as well as the friction frequency, which leads to a temperature increase in the cutting edge area, the tool material softening, and the tool wearing more easily.

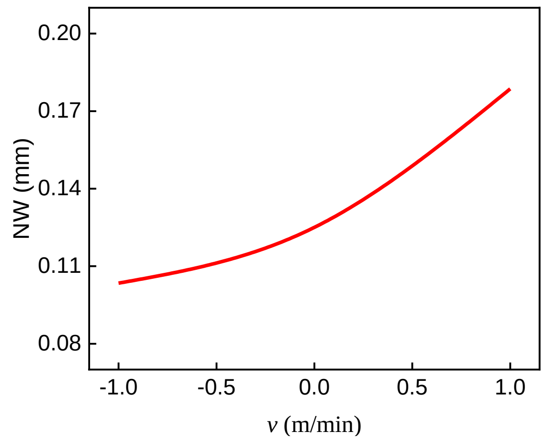

Fig. 4. The effect of the *v* on the NW

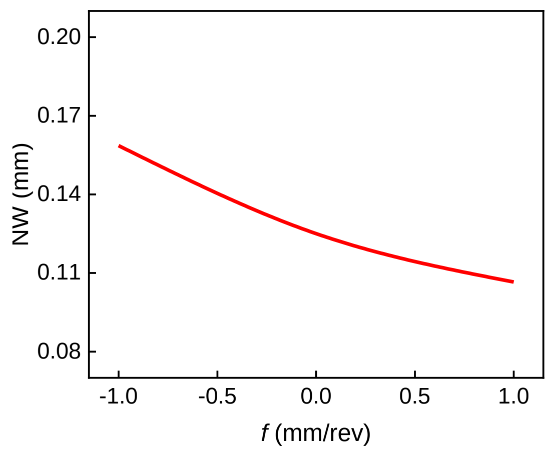

Fig. 5. The effect of the *f* on the NW

The feed rate (f) is another important parameter affecting the tool wear. When f ranges from 0.1 mm /rev to 0.3 mm /rev, it was found that f had a statistical significance (the "Prob >F" value was less than 0.0001), and a negative coefficient (- 0.02464) indicated that f had a negative influence on the tool wear, which meant that the greater the f value, the less the amount of tool wear (Table 7). Figure 5 shows the effect of f on tool wear when v and a_p are at a medium level (v = 800 m/min and a_p = 4 mm). As can be seen in Fig. 5, as the f increases the NW decreases, and when the f increases from 0.1 mm/rev to 0.3 mm/rev, the NW decreases from 0.15861 mm to 0.10656 mm, with a reduction rate of 32.82%. According to the analysis, when milling a workpiece of the same length, the larger the f, the shorter contact time between the tool and workpiece, and the lower the amount of tool wear.

In addition, when the a_p varies within 2 mm to 6 mm, it was found in that a_p had statistical significance (the "Prob >F" value was equal to 0.0026, which is less than 0.05), and the positive coefficient (+ 0.01103) indicated that the a_p had a positive impact on tool wear, which meant that the greater the a_p value, the greater the amount of tool wear (as shown in Table 7). Figure 6 shows the effect of a_p on the NW when v and f were maintained at a medium level (v = 800 m/min and f = 0.2 mm/rev), in which the NW increases as the a_p increases. When the a_p was increased from 2 mm to 4 mm, the NW increased from 0.12166 mm to 0.14367 mm, or a 18.09% increase. This could be due to the increase in the machining capacity per unit time caused by an increase in a_p, therefore applying a greater cutting force and acting force on the cutting edge of the tool (Wei *et al*. 2019), which speeds up the tool wear rate.

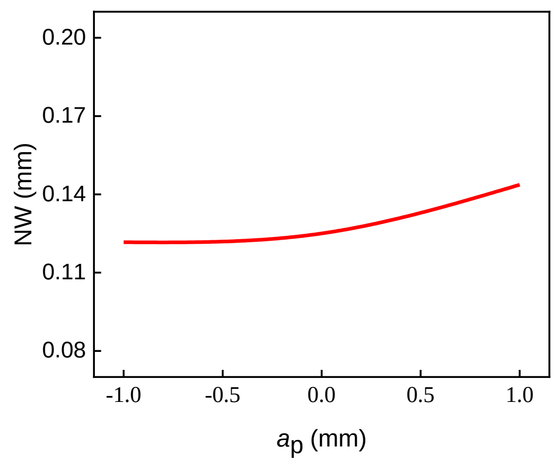

Fig. 6. The effect of the a_p on the NW

Interaction Effects of the Variables

In order to better study the variation of tool wear in terms of the cutting parameters, 3D surface graphs and contour plots were drawn, and the interaction effect of the cutting parameters on the NW were described (Fig. 7). As can be seen in Fig. 7, the effect of the v on the NW was the most significant, followed by the f, while the a_p had the least effect on the NW.

Figures 7a and 7b show the interaction effect of the v and the f on the NW at a constant a_p (a_p = 4 mm). Compared with a low v, it was evident (Fig. 7), that at a high v, the f had a more obvious effect on the NW. The NW had its lowest value (0.09436 mm) at a cutting speed of 500 m/min and a feed rate of 0.3 mm/rev. When the v was 1100 m/min and the f was 0.1 mm/rev, the NW reached its maximum value (0.2284 mm).

Figures 7c and 7d show the effect of the interaction between the v and a_p on the NW when the f was maintained a medium level (f = 0.2 mm/rev). When the v was low, the overall change in the NW was small as the a_p increased. When the v was large, the NW clearly increased as the a_p increased.

Figures 7e and 7f show the interaction effect of the f and the a_p on the NW when v was maintained a medium level (v = 800 mm/min). It is obvious from the figure that the a_p had a small effect on the NW when machining with a high f.

Therefore, for a high-speed cutting process, a low f and small a_p should be selected to ensure a relatively long tool life. For a low-speed cutting process, a large f and a_p should be adopted to ensure a relatively long tool life while improving machining efficiency.

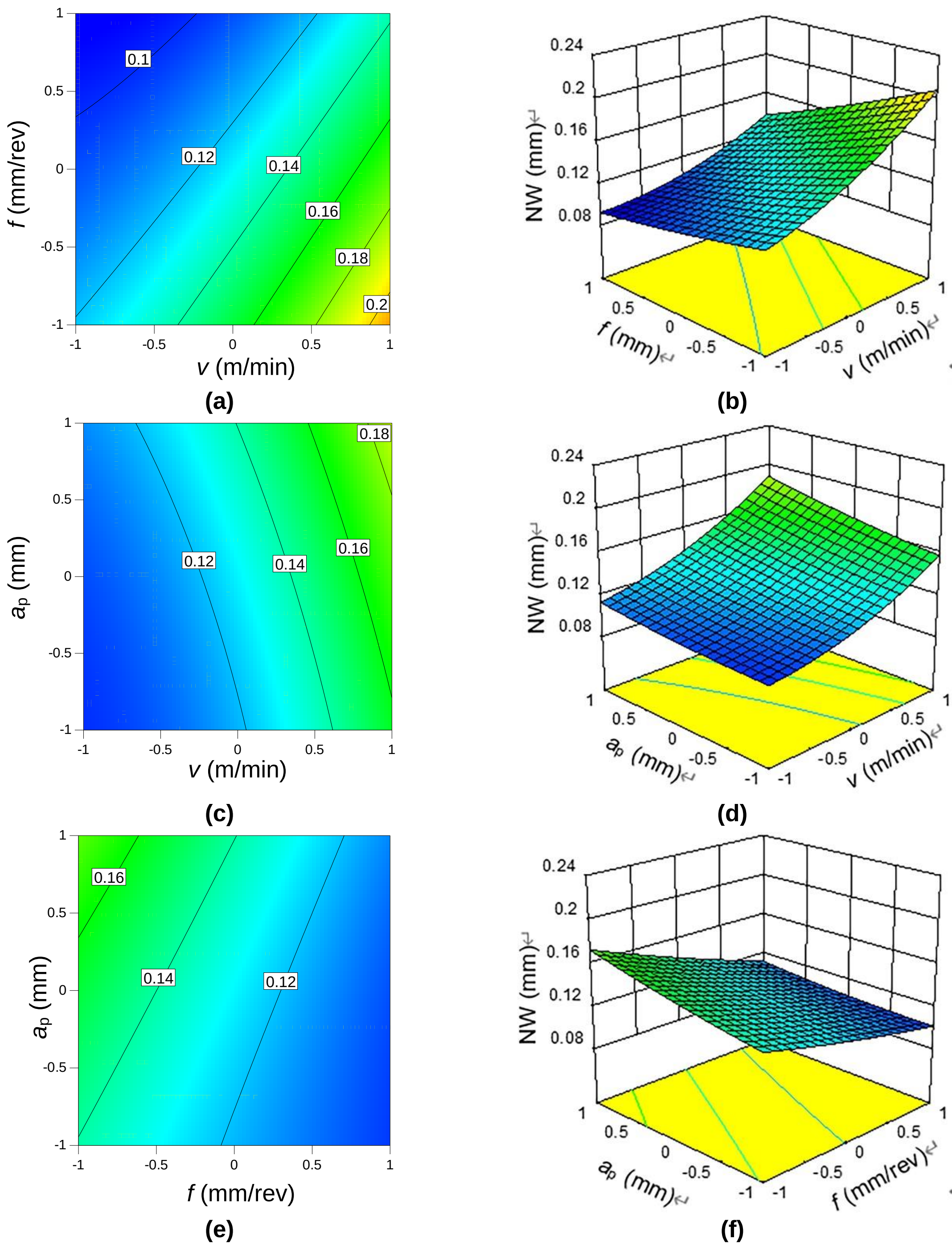

Fig. 7. The interaction effect of cutting parameters on NW

CONCLUSIONS

1. The tool wear test showed that among the tested cutting parameters that affected the nose width (NW), the cutting speed (*v*) had the greatest influence, the feed speed (*f*) had the second greatest, and the axial cutting depth (a_p) had the least. The interaction results showed that when the *v* was high, the influence of the *f* and the a_p on the NW was obvious, while when the *v* was low, the *f* and the a_p had little effect on the NW. For a high-speed cutting process, a low *f* and small a_p should be selected to ensure the tool life. For a low-speed cutting process, a large *f* and a_p should be adopted to ensure the tool life while improving machining efficiency.
2. The mathematical model of tool wear during the high-speed milling of WPCs was established *via* RSM and combined with a stepwise regression analysis to eliminate the insignificant terms in the model (as shown in Eq. 5). The ANOVA indicated that the established model was feasible, and that all terms in the model played a significant role in predicting tool wear (the "Prob>F" value was less than 0.01).

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