Research on Milling Forces During High-speed Milling of Wood-plastic Composites

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To analyze the influence of the milling parameters, including the spindle speed, feed rate, axial cutting depth, and radial cutting depth, on the milling force during high-speed milling of wood-plastic composites, an orthogonal test was performed with carbide cutting tools. The results showed that the tangential (F_x) and radial forces (F_y) decreased with an increase in the spindle speed, increased with an increase in the feed rate, and increased with an increase in the axial milling depth. Also, both were influenced by a relatively small amount of change in the axial milling depth. Mathematical models of F_x and F_y during the high-speed milling of wood-plastic composites were established with a multiple linear regression method. The variance analysis showed that the two mathematical models of the milling forces were significant overall.

Keywords: Wood-plastic composites; High-speed milling; Milling force; Mathematical model

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INTRODUCTION

Presently, there are many methods to cut wood, wood composite boards, wood-plastic composites (WPCs), and other wood materials. These methods mainly include sawing, milling, drilling, grinding, turning, and others. Among them, milling is the most important shaping process for forming the surface and obtaining complex geometries, and it is widely used in the second forming process. High-speed milling technology is particularly important in industries where mass production models are used, such as in the automobile, furniture, and building material industries. High-speed milling technology has many advantages, such as increasing the production efficiency, reducing the cutting force, improving the machining precision and surface quality, reducing the costs, *etc.*, and it has been widely used in the aviation, aerospace, and automotive sectors, as well as other manufacturing sectors (Byrne *et al*. 2003; Wei *et al*. 2012, 2018). In these sectors, aluminum alloy, cast iron, alloy steel, titanium alloy, high temperature alloy, quenched steel, and other metal materials are widely used. Compared with these metal materials, WPCs are anisotropic and heterogeneous, which leads to a large amount of milling vibration and noise during high-speed milling, increased difficulty of chip removal, and the production of a large amount of chip dust at a high removal rate. It also leads to difficulty in guaranteeing the machining accuracy and surface quality, and deterioration of the processing environment (Kılıç *et al*. 2009). In the study of cutting forces, Đurković*, et al*. (2018) analyzed the influence of cutting regime elements and tool geometry on cutting force and established a cutting force prediction model. Darmawan and associates pointed out that the coated carbide tools are more advantageous in reducing the progression of tool wear and retaining lower normal force and noise level (Darmawan *et al*. 2001a,b; Darmawan and Tanaka 2004). However, these studies were based on wood and wood-based materials, and did not involve substantial research on WPCs.

A typical WPC was used as the test object and an orthogonal experiment design was applied as an experimental design in this study to study the effects of the cutting parameters, including the spindle speed, feed rate, axial cutting depth, and radial cutting depth, on the milling force. Additionally, a multiple linear regression analysis was used to establish mathematical models of the tangential (F_x) and radial forces (F_y). A variance analysis was used to analyze the overall significance level of the models. The results have important academic theoretical value and engineering application value that can enrich the processing technology of polymer materials and can also provide a scientific basis for the optimization of high-speed milling of WPCs.

EXPERIMENTAL

Test Material and Cutting Tools

In this research, several pieces of a WPC produced by Nanjing Dayuan Plastic Wood New Material Co. Ltd. (Nanjing, China) were used. The general properties of the material are shown in Table 1.

Table 1. Properties of the WPC

Size (mm)	Proportion (mass)	Density (g/cm^3)	Flexural Modulus (MPa)	Shore Hardness (HD)
322 × 75 × 40	Wood Flour: 50% Polyethylene: 25% Adhesive: 25%	1.19	28	58

Translatable carbide cutting tools manufactured by Zhuzhou Diamond Cutting Tool Co. Ltd. (Zhuzhou, China) were used to perform the test. The arbor model used was EMP01-020-G20-AP11-02. The blades used in the test were an ordinary carbide blade with a grade of YD201 and model APKT11T304-LH .The specifications of cutting tool is presented in Table 2.

Table 2. Specifications of Cutting Tool

Tool materials	Uncoated tungsten carbide
Grade in AISI system	K15 - K35
Dimensions of milling blade, mm	12.24 × 6.5 ×3.6
Rake angle γ_0	19°
Sharpness angle β_0	60°
Clearance angle α_0	11°

Test Instrument

As shown in Fig. 1, cutting forces were tested by up-milling with the UCP 800 Duro five-axis machining centre manufactured by Mikron (Agno, Switzerland). The machine was equipped with an ITNC530 CNC system (Heidenhain, Berlin, Germany), laser tool (9602, BLUM, Willich, Germany), and a TC52 workpiece probe (BLUM), which can achieve tool dynamic detection and greatly improve the detection accuracy. This kind of machine not only can process and measure a workpiece synchronously, but it can also improve the repositioning accuracy of the workpiece. The maximum spindle speed and feed rate of the machine were 20000 rpm and 20 m/min, respectively, and the longitudinal travel of the X, Y, and Z axes were 850 mm, 650 mm, and 500 mm, respectively.

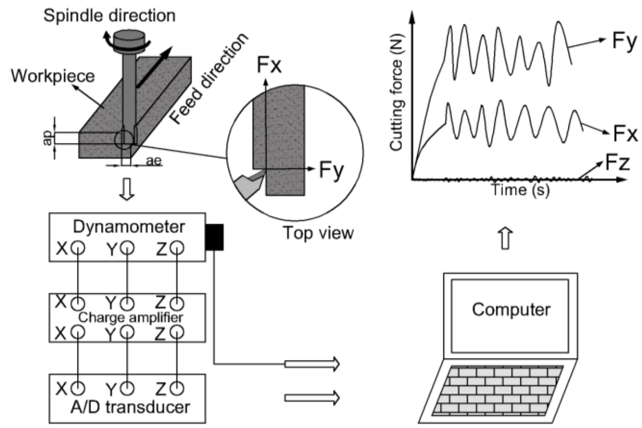

Fig. 1. The schematic diagram of cutting force measuring system

The Swiss Kistler 9257B three-way dynamometer (Winterthur, Switzerland) was used during testing, which is shown in Fig. 2. The collected electrical signal was converted to a force signal by a Kistler 5070 charge amplifier for simultaneous display in the software. The Kistler 9257B three-way dynamometer is convenient for recording the triaxial force and torque values, and automatically generates the Excel spreadsheets. The basic parameters of the Kistler 9257B three-way dynamometer are as follows: the F_x, F_y, and F_z all range from 5 kN, and the sensitivity of the F_x, F_y, and F_z was -7.5 pC/N, -7.5 pC/N, and -3.7 pC/N, respectively.

Fig. 2. Kistler 9257B three-way dynamometer installed on the machine

Testing of the Milling Force

The purpose of the milling force test was to determine the influence of the milling parameters on the milling force during high-speed milling of WPCs. If the single factor method was used for testing, then the workload would be complicated, the test operation would be difficult, there would be too much test data, and the data analysis and processing would be prone to error. To achieve the same effect with fewer problems, the orthogonal test method was used in this study. The L9 (3^4) was used as the three-level and four-factor table with the spindle speed (n), feed rate (v_f), axial milling depth (a_p), and radial milling depth (a_e), as is shown in Table 3. The L9 (3^4) orthogonal test table of the milling force is shown as Table 4.

Table 3. Orthogonal Test Factor Table of the Milling Force

Factor	Number 1	Number 2	Number 3
Spindle speed n (rpm)	8000	12000	16000
Feed rate v_f (mm/min)	1000	3000	5000
Axial depth a_p (mm)	2	3	4
Radial depth a_e (mm)	5	7.5	10

Table 4. L9 (3^4) Orthogonal Test Table of the Milling Force

Number	n (rpm)	v_f (mm/min)	a_p (mm)	a_e (mm)	F_x (N)	F_y (N)
1	8000	1000	2	5	6.47	11.78
2	8000	3000	3	7.5	9.67	23.47
3	8000	5000	4	10	14.94	30.98
4	12000	1000	3	10	4.93	16.2
5	12000	3000	4	5	10.7	28.53
6	12000	5000	2	7.5	7.31	19.52
7	16000	1000	4	7.5	4.62	17.43
8	16000	3000	2	10	5.84	14.65
9	16000	5000	3	5	6.09	28.85

Because milling is the process of edge cutting into and out of a workpiece, the tool has an intermittent reciprocating motion. The milling edge cuts into the workpiece and away from the workpiece in the opposite direction, so that the resulting milling force is reversed. The F_x is the tangential cutting force, which is parallel to the cutting direction, and F_y is the radial cutting force, which is perpendicular to the cutting direction. Both are in the cutting plane.

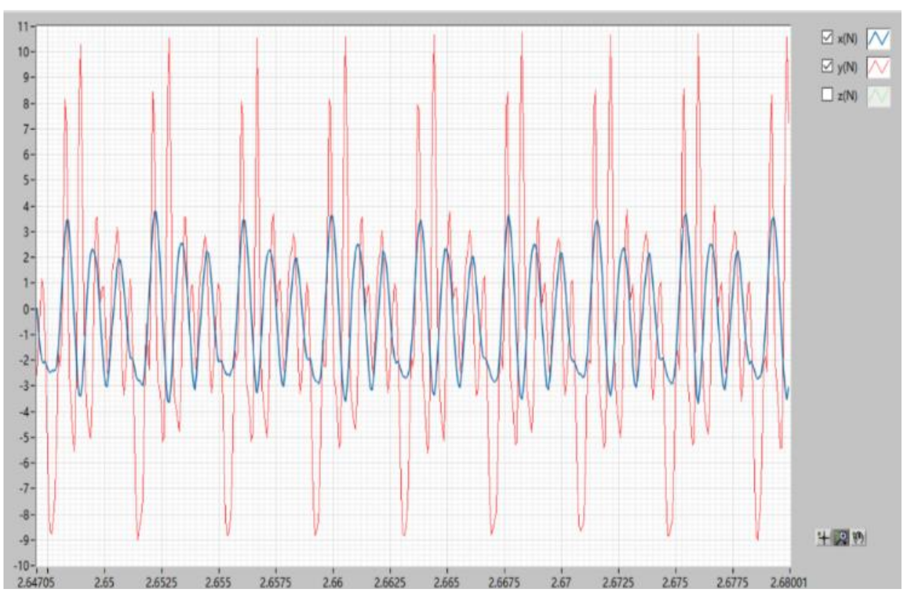

Fig. 3. Periodic variation in the milling force

In theory, their absolute values in the positive and negative directions are equal, but it was found from the measured results that their absolute value in the positive and negative directions had a certain difference and the impact was small, which may have been caused by machine vibration and other objective factors. The cyclical trends of the F_x and F_y are shown in Fig. 3. A uniform waveform was formed by median filtering. The results of this test were the final maximum values of the F_x and F_y after being filtered. Additionally, the F_z is the force parallel to the direction of the arbor. Because the tool used in this test was an indexable carbide tool, the milling edge was parallel to the axis after the blade was mounted. Therefore, there is theoretically not a cutting force in this direction, except for a weak signal caused by vibration, and thus a more in-depth study was not performed on this force.

RESULTS AND DISCUSSION

Influence of the Milling Parameters on the Milling Forces

Influence of the spindle speed on the milling forces

The results of the orthogonal test were analyzed. The average values of the F_x and F_y at different spindle speeds were calculated and the results are shown in Fig. 4.

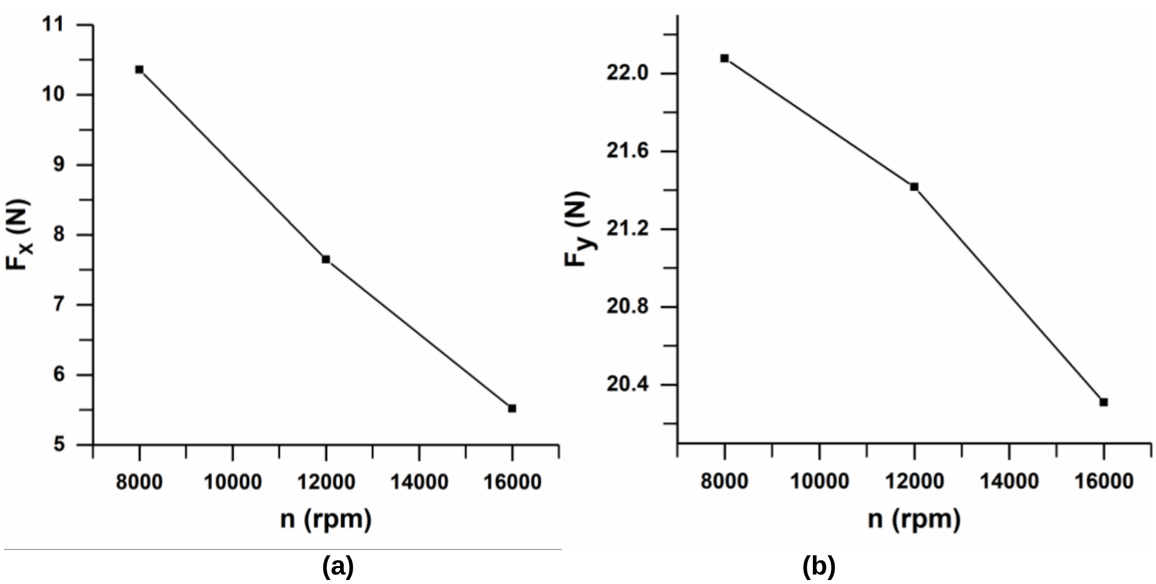

Fig. 4. Influence of the spindle speed on the (a) F_x and (b) F_y

When the spindle speed was 8000 rpm, the F_x and F_y were both the highest, and when the spindle speed increased to 16,000 rpm, the F_x and F_y both achieved minimum values. The results showed that the F_x and F_y gradually decreased with an increase in the spindle speed and the changing trend was close to a straight line, which indicated a slight relationship between the milling force and spindle speed. The increase in the spindle speed resulted in a decrease in the feed per revolution under the same conditions, which caused a decrease in the average milling thickness per unit time. The cutting deformation caused by the workpiece material and the power required in the single cutting time were reduced; therefore, the total milling force was reduced. It was also found from Fig. 4 that the F_x was smaller than the F_y, but the change trend of the F_x was more obvious than that of the F_y.

Influence of feed rate on milling forces

The average values of the tangential force F_x and the radial force F_y at different feed rates were also calculated. The results are shown in Fig. 5. It was found that when the feed rate was increased from 1000 mm/min to 3000 mm/min and to 5000 mm/min, both F_x and F_y were gradually increased. This shows that the impact of feed rate on the milling forces was relatively large, and the changing trends of F_x and F_y increased rapidly and then increased slowly, but the trend for F_x was more obvious. This is mainly because when feed rate increases from 1000 mm/min to 5000mm/min, feed peer revolution increases from 0.09 mm/rev to 0.45 mm/rev, which means more materials being cut per unit time. In other words, the required load that the material produces plastic and elastic deformation was larger when the average thickness of the milling was higher, which results in the need for more energy to disengage the chips from the workpiece.

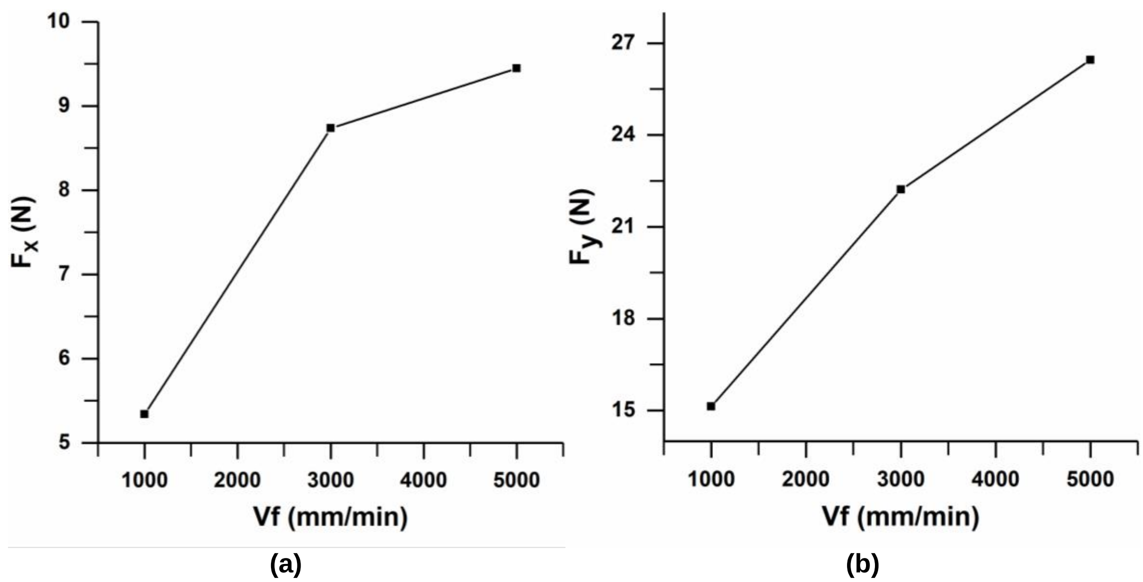

Fig. 5. Influence of the feed rate on the (a) F_x and (b) F_y

Influence of the axial depth on the milling forces

It was mentioned above that the change in the spindle speed and feed speed had a certain effect on the F_x and F_y. The reason was that the change in the spindle speed and feed rate resulted in a change in the average cutting thickness during milling. The axial cutting depth represents the cutting thickness. Figure 6 shows that the F_x and F_y tended to increase gradually when the axial depth increased from 2 mm to 3 mm and then to 4 mm. The F_x first slowly increased and then rapidly increased, while the F_y behaved in the opposite manner and rapidly increased at first and then slowly increased. This showed that the axial depth had a major impact on the milling force. The main reason was that the cutting zone area increased with an increase in the cutting thickness, which increased the deformation resistance of the workpiece material. Because of the increase in the deformation resistance of the workpiece material, a greater deformation force was needed when the chip is away from the material matrix. Additionally, the internal friction between the cutting edge and workpiece surface to be machined increased, which increased the total milling force.

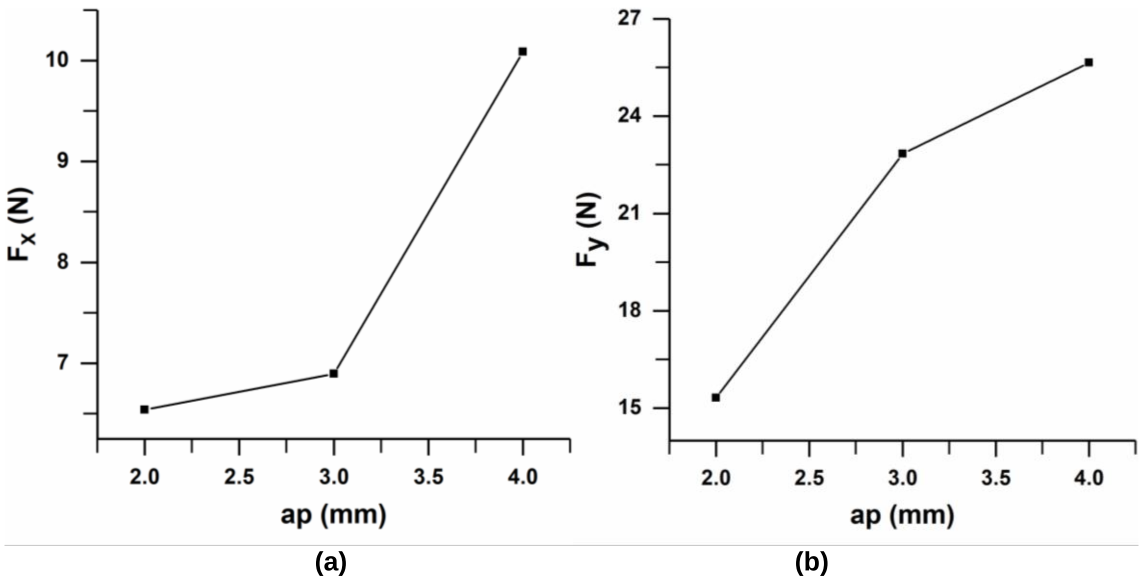

Fig. 6. Influence of the axial depth on the (a) F_x and (b) F_y

Influence of the radial cutting depth on the milling forces

Figure 7 shows that the F_x and F_y first decreased and then increased when the radial milling depth increased from 5 mm to 7.5 mm and then further increased to 10 mm, but the magnitude of the change was relatively small. The maximum and minimum values differed by only 2 N to 3 N for both the F_x and F_y. The influence of the radial milling depth on the milling forces was not obvious compared with the other factors (spindle speed, feed rate, and axial cutting depth). Thus, it was concluded that the radial milling depth had little effect on the milling forces.

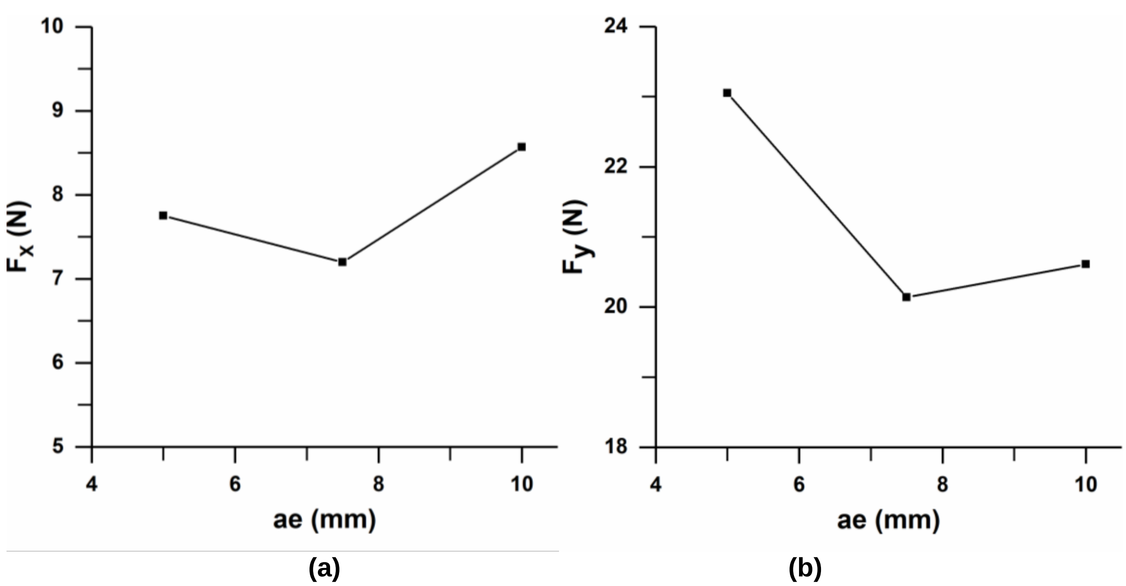

Fig. 7. Influence of the radial cutting depth on the milling forces: (a) F_x and (b) F_y

Analysis of the Milling Forces and Mathematical Models

One-dimensional linear regression has one major influencing factor as an independent variable to explain the variation in the dependent variable. One factor is changed to study the changes in the results, while keeping the other factors unchanged. This is a single factor test method and it studies the basic principles of practical problems (Kakosyan 1979; de Carvalho *et al*. 2004). However, for practical problems, a change in the dependent variable will be affected by more than one important factor. Multiple regression allows for more influential factors to be independent variables to explain the variation in the dependent variable (Lorenzo-Seva and Ferrando 2011; Schinazi 2011). The purpose of this test was to use the orthogonal test method to study the influence of the four important parameters (n, v_f, a_p, and a_e) on the milling forces (F_x and F_y). The analysis of the previous test results showed that three of the four factors (n, v_f, and a_p) had a remarkable effect on the F_x and F_y, and the results showed that the dependent variables F_x and F_y were substantially and linearly related to them. Multiple linear regression analysis was required to study the relationship between the variables. This analysis obtained a mathematical model function between the dependent variable and independent variables. The SPSS Statistics software was used to perform the regression analysis in this research (23th version , IBM, Northampton, United States).

Significance analysis and mathematical model of the F_x

According to the principle of multiple linear regression analysis used in this test, formulas for the F_x and F_y were obtained and are expressed by Eqs. 1 and 2, respectively.

$$F_x = C_x + a_1 n + a_2 v_f + a_3 a_p \tag{1}$$

$$F_y = C_y + b_1 n + b_2 v_f + b_3 a_p \tag{2}$$

where F_x is the tangential milling force (N), F_y is the radial milling force (N), C_x and C_y are the correction coefficients of the tangential and radial forces, respectively, n is the spindle speed (rpm), v_f is the feed rate (mm/min), and a_p is the axial milling depth (mm).

By using the SPSS Statistics software to conduct a multiple linear regression analysis on the orthogonal test results of the milling forces, valuable results were obtained. As shown in Table 5, Adjusted R^2 of F_x model was 0.811, which indicated that the independent variables of the model can explain the dependent variable well and the fitting degree is very good.

Table 5. Model Summary of the F_x Model

Model	R	R^2	Adjusted R^2	Standard Estimation Error
1	0.939	0.882	0.811	1.45898

Table 6 shows the variance analysis of the F_x model. It was found that the sum of squares of the regression accounted for most of the total and the residual square sum was only a small portion. The significance was 0.009, which showed that the F_x model is significant and credible.

Table 6. ANOVA Analysis of the F_x Model

Model 1	Sum of Squares	Degrees of Freedom	Mean Square	F	Significance
Regress	79.352	3	26.451	12.426	0.009
Residual	10.643	5	2.129	-	-
Total	89.995	8	-	-	-

Table 7 gives the regression coefficients for the F_x model. The constant was 6.706, the spindle speed coefficient was -0.001, the feed rate coefficient was 0.001, and the coefficient of the axial cutting depth was 1.773. The multiple linear regression equation of the F_x is shown as Eq. 3

$$F_x = 6.706 - 0.001n + 0.001v_f + 1.773a_p \quad (3)$$

Table 7. Regression Coefficients for the F_x Model

Model 1	Nonstandard Coefficient		Quasi Coefficient	Statistics *t*	Significance
	Regression Coefficient	Standard Error			
Constant	6.706	2.724	-	2.462	0.057
Spindle speed *n*	-0.001	0	-0.625	-4.066	0.010
Feed rate v_f	0.001	0	0.530	3.447	0.018
Axial depth a_p	1.773	0.596	0.458	2.977	0.031

Significance analysis and mathematical model of the F_y

Adjusted R^2 of F_y model was 0.876 (Table 8), which indicated that the independent variables of the model can explain the dependent variable well and the fitting degree is very good.

Table 8. Model Summary of the F_y Model

Model	R	R^2	Adjusted R^2	Standard Estimation Error
2	0.960	0.923	0.876	2.44758

Table 9 shows the variance analysis of the F_y model. The sum of squares of the regression accounted for most of the total and the residual square sum was only a small portion. The significance was 0.003, which indicated that the F_y model is also significant and credible.

Table 9. ANOVA Analysis of the F_y Model

Model 2	Sum of Squares	Degrees of Freedom	Mean Square	F	Significance
Regress	356.732	3	118.911	19.849	0.003
Residual	29.953	5	5.991	-	-
Total	386.686	8	-	-	-

Table 10. Regression Coefficients for the F_y Model

Model 2	Nonstandard Coefficient		Quasi Coefficient	Statistics *t*	Significance
	Regression Coefficient	Standard Error			
Constant	-0.062	4.570	-	-0.014	0.990
Spindle speed *n*	0.00001	0	-1.10	-0.884	0.417
Feed rate v_f	0.003	0	0.705	5.661	0.002
Axial depth a_p	5.165	0.999	0.643	5.169	0.004

Table 10 gives the regression coefficients of the F_y model. The constant was -0.062, the spindle speed coefficient was 0.00001, the feed rate coefficient was 0.003, and the coefficient of the axial cutting depth was 5.165. The multiple linear regression equation of the F_y is shown as Eq. 4.

$$F_y = -0.062 + 0.00001n + 0.003v_f + 5.165a_p \quad (4)$$

CONCLUSIONS

1. When a wood-plastic composite (WPC) is milled at high speeds, the forces F_x and F_y are affected by the milling parameters, but the F_z is mostly unaffected.
2. In high-speed milling, high speed and low feed can be selected to reduce the feed per revolution to reduce the cutting force. In addition, the small axial milling depth and the large radial milling depth reduce the milling force while maintaining the same average milling area.
3. Based on the multivariate linear regression analysis of the orthogonal test results, multivariate linear regression equations of the F_x and F_y in the high-speed milling of WPCs were established (Eqs. 3 and 4).
4. The variance analysis results showed that the two models were significant. The two equations can be used to accurately predict the F_x and F_y under different milling parameters, which can provide a reliable theoretical basis for actual milling.

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REFERENCES CITED

Byrne, G., Dornfeld, D., and Denkena, B. (2003). "Advancing cutting technology," *CIRP Ann.-Manuf. Techn.* 52(2), 483-507. DOI: 10.1016/S0007-8506(07)60200-5

Darmawan, W., Tanaka, C., Usuki, H., and Ohtani, T. (2001a). "Performance of coated carbide tools when grooving wood-based materials: effect of work materials and coating materials on the wear resistance of coated carbide tools," *Journal of Wood Science* 47(2), 94-101. DOI: 10.1007/BF00780556

Darmawan, W., Tanaka, C., Usuki, H., and Ohtani, T. (2001b). "Performance of coated carbide tools in turning wood-based materials: Effect of cutting speeds and coating materials on the wear characteristics of coated carbide tools in turning wood-chip cement board," *Journal of Wood Science* 47(5), 342-349. DOI: 10.1007/BF00766783

Darmawan, W., and Tanaka, C. (2004). "Discrimination of coated carbide tools wear by the features extracted from parallel force and noise level," *Annals of Forest Science* 61(7), 731-736. DOI: 10.1051/forest:2004070

de Carvalho, F. d. A. T., Neto, E. d. A. L., and Tenorio, C. P. (2004). "A new method to fit a linear regression model for interval-valued data," in: *KI 2004: Advances in Artificial Intelligence*, S. Biundo, T. Frühwirth, and G. Palm (eds.), Springer Berlin Heidelberg, Berlin, Germany, pp. 295-306.

Đurković, M., Mladenović, G., Tanović, L., and Danon, G. (2018). "Impact of feed rate, milling depth and tool rake angle in peripheral milling of oak wood on the cutting force (AOP Paper)," *Maderas. Ciencia y Tecnologia* 20(1), 25-34. DOI: 10.4067/S0718-221X2018005000003

Kakosyan, A. V. (1979). "Theory of estimation of parameters in a linear regression scheme," *Journal of Soviet Mathematics* 12(2), 227-237. DOI: 10.1007/BF01262721

Kılıç, M., Burdurlu E., Aslan S., Altun S., and Tümerdem, Ö. (2009). "The effect of surface roughness on tensile strength of the medium density fiberboard (MDF) overlaid with polyvinyl chloride (PVC)," *Materials and Design* 30, 4580-4583. DOI: 10.1016/j.matdes.2009.03.029

Lorenzo-Seva, U., and Ferrando, P. J. (2011). " FIRE: An SPSS program for variable selection in multiple linear regression analysis *via* the relative importance of predictors," *Behaior Research Methods* 43(1), 1-7. DOI: 10.3758/s13428-010-0043-y

Schinazi, R. B. (2011). *Probability with Statistical Applications*, Birkhäuser, Boston, MA.

Wei, W., Xu, J., Fu, Y., and Yang, S. (2012). "Tool wear in turning of titanium alloy after thermohydrogen treatment," *Chinese Journal of Mechanical Engineering* 25(4), 776-780. DOI: 10.3901/CJME.2012.04.776

Wei, W., Li, Y., Xue, T., Tao, S., Mei, C., Zhou, W., Wang, J., and Wang, T. (2018). "The research progress of machining mechanisms in milling wood-based materials," *BioResources* 13(1), 2139-2149. DOI: 10.15376/biores.13.1.2139-2149

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