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Research article

Evaluation of the Milling Performance on Wood-Plastic Composite

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Abstract: This research aims to study the milling factors that affect the quality of milled surfaces, including surface roughness and burr formation. A composite material composed of recycled polypropylene plastic and rubber wood powder was selected. The side milling parameters evaluated comprise spindle speeds of 330, 610, and 850 rpm; feed rates of 43, 120, and 200 mm/min; and cutting depths of 1, 3, and 5 mm. Surface roughness decreased with increased spindle speeds, but reduced feed rates and depths of cut. Burr formation diminished with increased spindle speed and feed rate, but required a lower depth of cut. Regression models for surface roughness and burr development were established, demonstrating prediction errors of approximately 1.54% and 2.29%. The optimal milling parameters to minimize surface roughness were determined to be a spindle speed of 850 rpm, a feed rate of 43 mm/min, and a depth of cut of 1 mm, resulting in a surface roughness of 5.184 µm. The suggested conditions to reduce burr formation were a spindle speed of 610 rpm, a feed rate of 200 mm/min, and a depth of 1 mm, which resulted in a burr height of 0.251 mm. The optimal parameters for minimizing both burrs and roughness were a spindle speed of 610 rpm, a feed rate of 43 mm/min, and a depth of cut of 1 mm. This yielded 6.958 µm of roughness and 0.255 mm of burr creation. These conditions eliminate the necessity for post-milling finishing and correspond to ISO 21920 surface texture standards.

Keywords: Milling operation; wood-plastic composite; surface roughness; burr formation

1. Introduction

Rubber wood is a popular material for furniture production due to its high strength, beautiful texture, and corrosion resistance [1]. Currently, the average annual production of rubber wood furniture and construction materials is 2,700,000 cubic meters, valued at 34 billion baht per year [2]. The processing of rubber wood generates wood waste, which is then utilized to manufacture wood-plastic composites (WPCs), consequently enhancing the value of this waste [3]. WPCs serve as a substitute for natural wood, offering better properties, such as high strength, good impact resistance, ease of molding, resistance to mold growth, and environmental friendliness [4]. As a result, the value of WPCs is expected to increase to 13.244 billion USD by 2030 [5]. The production of WPCs involves mixing wood sawdust and plastics, such as polyethylene, in appropriate proportions and then extruding them to create composite materials. These materials can be formed using molds in various methods, such as hot compression, extrusion, or injection molding [6]. However, the formed materials still have limitations in terms of geometry and size due to mold constraints. Consequently, to manufacture products with specific dimensions and patterns, additional machining processes, such as milling, drilling, cutting, or turning, are necessary [7]. Milling is a popular technique in post-machining due to its high cutting rate and the ability to machine diverse geometries.

There are some studies related to milling for processing WPCs [8-12]. Thanate et al. [8] investigated the effects of milling parameters on the surface roughness of WPCs and found that the depth of cut had the most significant impact on surface roughness, followed by feed rate and spindle speed, respectively. A comparison of milling performance for different plastics used in WPCs, such as polyethylene (PE), polypropylene (PP), and polyvinyl chloride (PVC), showed that WPCs made from PP plastic had the lowest surface roughness due to its high density and high melting temperature [9]. Chainarong et al. [10] employed Response Surface Methodology (RSM) to determine the optimal milling conditions for WPCs, with a spindle speed of 1,000 rpm, a feed rate of 315 mm/min, and a cutting depth of 1 mm, resulting in a surface roughness of approximately 2.865 μm. They also studied the impact of milling parameters on the surface roughness of WPCs made from high-density polyethylene (HDPE) and rubberwood sawdust (RWS) [11], finding that surface roughness decreased as spindle speed increased, while both feed rate and cutting depth decreased. Wikanet et al. [12] investigated the milling factors affecting the qualities of WPCs and found that surface roughness decreased with increased spindle speed. The burr formation decreased with an increase in spindle speed and feed rate, but a decrease in cutting depth. In addition, up-milling resulted in higher burr formation than down-milling because the cutting-edge rotation was opposite to the direction of workpiece feeding.

The analysis of previous research revealed that while milling factors, including spindle speed, feed rate, and depth of cut, have been examined for their impact on the surface roughness of WPCs, the majority of studies have focused on surface milling. There has been little comprehensive research on side milling and slot milling, which influence burr formation as well as surface roughness. This research focuses on investigating the milling parameters and patterns that affect the surface quality of milled surfaces and burr formation in WPCs. The criteria evaluated comprise spindle speed, feed rate, and depth of cut in both shoulder milling and slot milling conditions. The determination of the suitable milling condition resulting in good machined quality was also considered. The results of this study will enhance WPC processing in the manufacturing of furniture and construction materials in many forms, thereby improving the market price of these products.

2. Materials and Methods

2.1 Material and Equipment

2.1.1 Wood-Plastic Composite

The WPC developed by Chainarong et al. [13] was employed in this research. The components and properties of this WPC are detailed in Table 1. The material size is 55 × 55 × 18 mm, as shown in Figure 1.

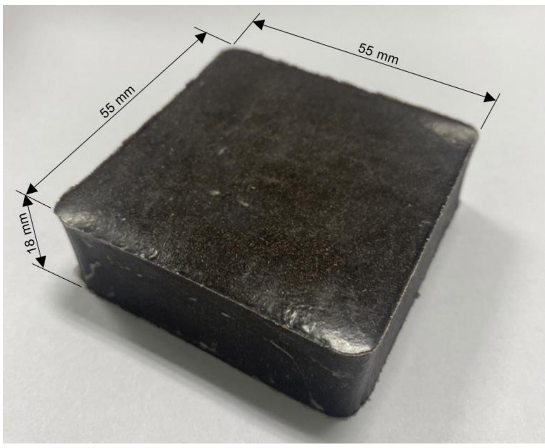


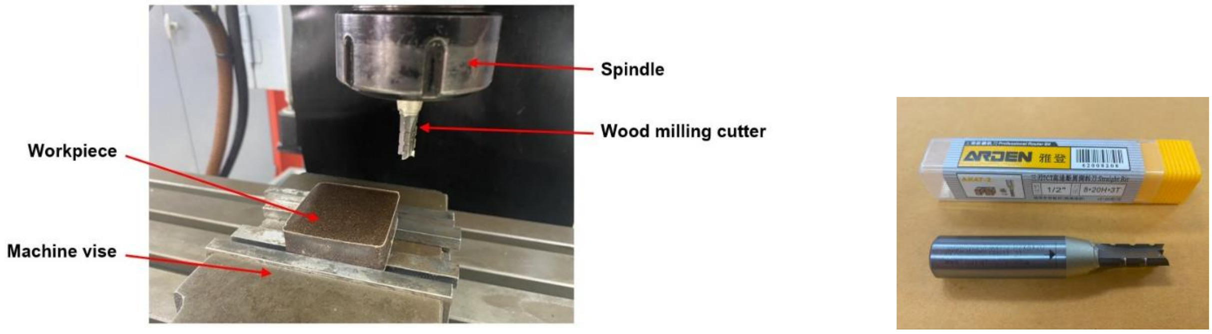
Figure 1. Wood-Plastic Composite

Table 1. Components and properties of WPC [13]

Components of WPC (weight percentage)	Properties of WPC
- Recycled Polypropylene: 51.8 % - Rubberwood Powder: 35.9 % - Calcium Carbonate: 7.2 % - Other: 5.1%	- Tensile strength and modulus: 24.82 MPa and 1.20 GPa - Compressive strength and modulus: 22.88 MPa and 1.32 GPa

2.1.2 Milling Machine and Equipment

The experiment utilized a Full Mark VBM-3V vertical milling machine (Figure 2(a), capable of achieving a maximum spindle speed of 1,250 rpm and a maximum feed rate of 875 mm/min. A 3-flute tungsten carbide cutter (ARDEN, model AK47-2) with an 8 mm diameter was employed. The cutting edges are sharpened and polished with optimal rake and relief angles to minimize cutting forces, reduce surface roughness, and prevent burr development. The tool design optimizes chip evacuation and heat dissipation, making it appropriate for both hardwood and composite wood materials, while maintaining a balance between material removal rate and surface quality, as shown in Figure 2(b).



(a) (b)

Figure 2. (a) Experimental setup and (b) Wood milling cutter

2.2 Experimental Design

A full factorial design was employed in this study to investigate the main effects and interaction effects of the milling parameters for all conditions. Three experimental factors were established, each with three levels, resulting in a total of 27 experimental conditions, as shown in Table 2. The experiments were conducted three times, resulting in a total of 81 trials. The milling operations of side milling and slot milling (Figure 3) entailed the cutting of the workpiece in the direction same as the workpiece feed direction over a distance of 55 mm. The side milling results will be compared with those of slot milling (Figure 3(b)), which was completed by Wikanet et al. [12].

Table 2. Milling parameters

Parameter	Unit	Level		
		Low	Medium	High
Speed (*S*)	rpm.	330	610	850
Feed Rate (*F*)	mm/min	43	120	200
Depth of Cut (*D*)	mm	1	3	5

(a) (b)

Figure 3. Milling processes: (a) side milling and (b) slot milling [12]

The average surface roughness (Ra) was evaluated using a Mitutoyo surface roughness tester (model SJ-210) equipped with a stylus tip radius of 2 μm, a resolution of 0.35 μm, and a measurement speed of 0.5 mm/s (Figure 4(a)). The burr width was subsequently evaluated using a CARL ZEISS AXIO IMAGER A1m microscope with magnifications ranging from 1.25x to 100x and 2 mm/revolution (Figure 4(b)). The burr formation (WB) was assessed by collecting samples over a measurement length from the mill edge to the large burr area. For both parameters, three repeated measurements were performed at different locations, with a measurement length of 17.5 mm, to ensure accuracy and reliability (Figure 3).

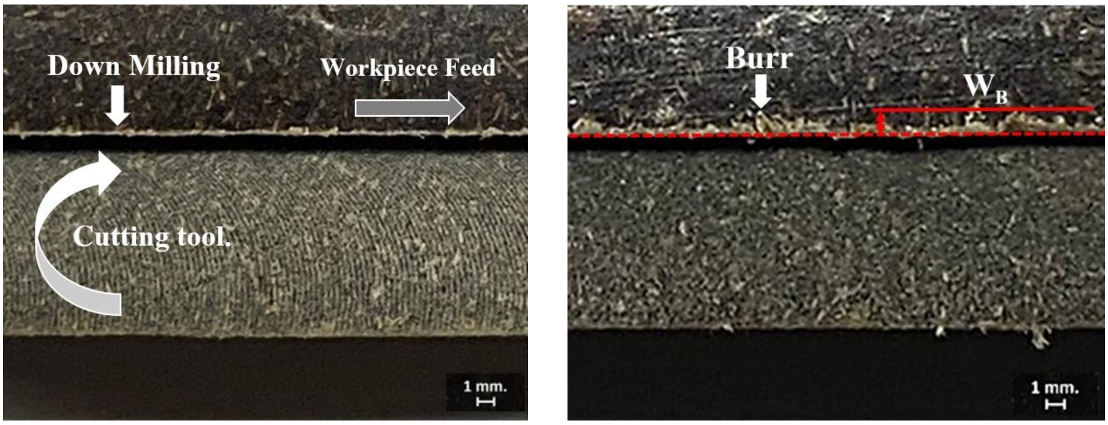
(a) (b)

Figure 4. (a) Mitutoyo SJ-210 surface roughness tester and (b) CARL ZEISS AXIO IMAGER A1m microscope.

3. Results and Discussion

3.1 Milling Performance on Wood-Plastic Composites

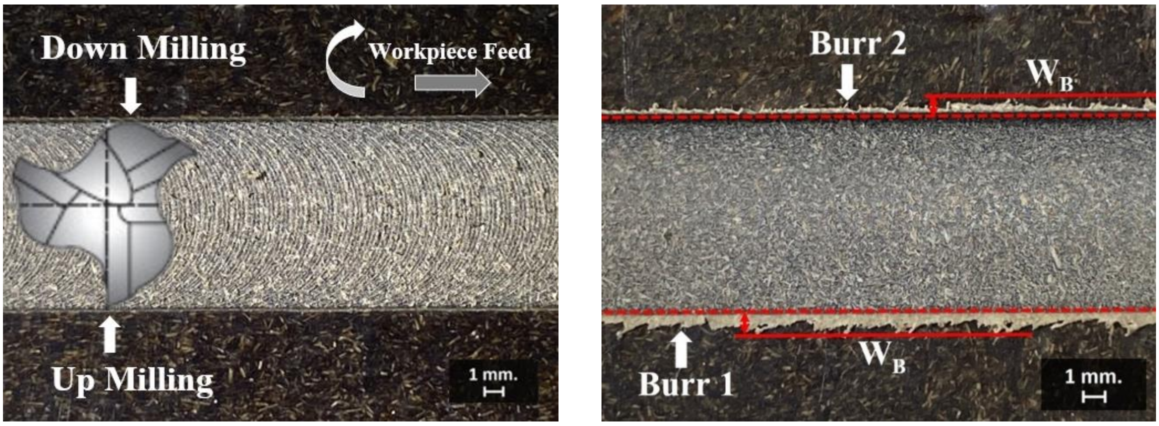
The experimental results for side milling showed that the average surface roughness was 9.803 μm with a standard deviation of 2.529 μm, while the average burr formation was 0.280 mm with a standard deviation of 0.020 mm. Negligible burr formation (0.245 mm) was observed at a spindle speed of 610 rpm, feed rate of 200 mm/min, and depth of cut of 1 mm, as illustrated in Figure 5(a). However, under these conditions, the milled surface was relatively rough, with an average roughness of 16.213 μm. In contrast, at a spindle speed of 850 rpm, a feed rate of 43 mm/min, and a depth of cut of 1 mm, a larger burr formation of 0.273 mm was observed, while the surface roughness decreased significantly to 5.184 μm (Figure 5(b)). The burr formation was significantly induced by high spindle speed, low feed rate, and feed depth as softening material.



(a) (b)

Figure 5. Characteristics of side milled workpiece: (a) Negligible burr formation and (b) burr formation.

In comparison with slot milling (Figure 6) from the previous study [12], side milling at 610 rpm spindle speed, 200 mm/min feed rate, and 1 mm depth of cut produced a surface roughness of 6.575 μm, with burr formation of 0.770 mm for up-milling and 0.257 mm for down-milling (Figure 6a). Under the same depth of cut but with 850 rpm spindle speed and 43 mm/min feed rate, slot milling produced a similar surface roughness (6.575 μm), while burr formation increased to 0.806 mm for up-milling and 0.269 mm for down-milling (Figure 6b). These results indicate that side and slot milling show no significant difference in overall machining performance. However, slot milling tends to generate burrs on both sides of the cut edge, with up-milling producing larger burrs because the cutting edge rotates in the opposite direction to the feed direction [14].



(a) (b)

Figure 6. Characteristics of slot milled workpiece: (a) Negligible burr formation and (b) burr formation [12].

3.2 The Effects of Side Milling Factors on Surface Roughness

The Analysis of Variance (ANOVA) was employed to analyze the results of the side milling using Design-Expert. The data was initially examined for normality, and it was determined to be both normal and independently distributed. Thus, the data can be used to investigate the effect of milling factors on surface roughness (R_a). The main effects and interaction effects of spindle speed (*S*), feed rate (*F*), and feed depth (*D*) were analyzed at a 95% confidence level. The results in Table 3 show that all primary parameters had a substantial impact on surface roughness, with spindle speed having the most significant influence. The surface roughness was considerably influenced by the interaction between spindle speed and feed rate (*SF*), as well as between feed rate and feed depth (*FD*). However, the interaction between spindle speed and feed depth (*SD*), and the three-way interaction (*SFD*) were not significant (p-value > 0.05). The insignificance can result from the mixed positive and negative correlations of the cutting parameters.

Table 3. ANOVA analysis on surface roughness

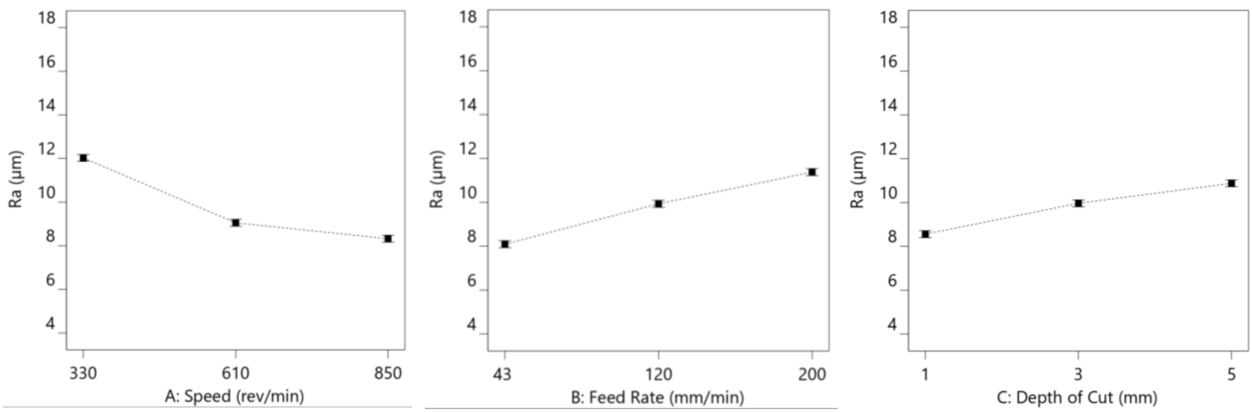
Source	Sum of Squares	df	Mean Square	F-Value	P-Value
Model	488.51	26	18.79	60.94	< 0.0001*
S-Speed	207.68	2	103.84	336.81	< 0.0001*
F-Feed Rate	146.50	2	73.25	237.59	< 0.0001*
D-Depth of Cut	73.77	2	36.88	119.64	< 0.0001*
SF	49.41	4	12.35	40.06	< 0.0001*
SD	1.57	4	0.3924	1.27	0.2920
FD	5.14	4	1.29	4.17	0.0051*
SFD	4.44	8	0.5554	1.80	0.0970
Pure Error	16.65	54	0.3083		
Total	505.16	80			
R^2	96.70				
Adjusted R^2	95.12				

Note: * Parameters have a significant effect at the 0.05 significance level.

The regression model to predict surface roughness (*Ra*) was developed by excluding these variables and reconsidering them, as illustrated in Equation (1). The coefficient of determination (R^2) was 96.70%, and the adjusted R^2 was 95.12%, indicating that the equation can be used to predict results accurately. From Equation (1), the subscripts 1 and 2 represent the levels of each machining parameter, corresponding to the low and high levels, respectively. For example, S_1 represents the low-speed level of 330 rpm, while S_2 represents the high-speed level of 850 rpm.

$$Ra = 9.80 + 2.22S_1 - 0.7472S_2 - 1.71F_1 + 0.1308F_2 - 1.24D_1 + 0.1648D_2 - 0.6321S_1F_1 + 0.8549S_2F_1 - 0.7965S_1F_2 + 0.9881S_2F_2 + 0.0337F_1D_1 - 0.1056F_2D_1 \quad (1)$$

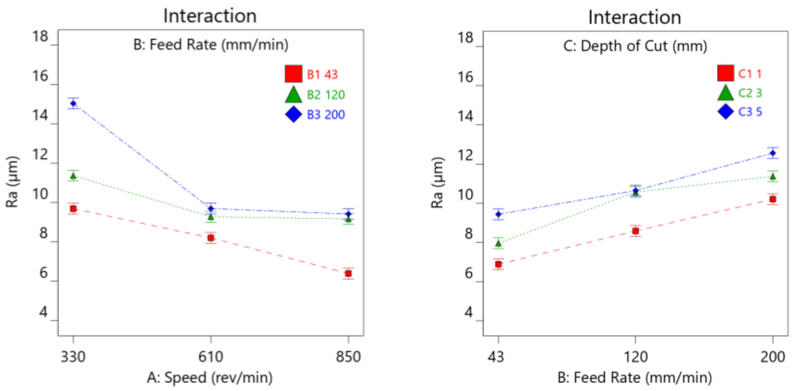
The relationship between the main milling factors that influence surface roughness is illustrated in Figure 7. The roughness of the surface decreases as the spindle speed increases (Figure 7(a)). Nevertheless, the surface roughness increases as the feed rate and depth of cut are increased (Figures 7(b) and (c)). According to Merchant's orthogonal cutting model [15], the cutting force is directly proportional to the feed rate and depth of cut, while being inversely proportional to the cutting speed, which is influenced by the spindle speed. Increased spindle speeds enhance surface smoothness by diminishing shear friction during milling, whereas higher feed rates and larger cuts intensify these forces. An increase in cutting force raises the cutting temperature, resulting in greater surface roughness and burr formation, which is particularly relevant to the ductile properties of WPCs. This conclusion coincides with the research presented in [10,16]



(a) (b) (c)

Figure 7. The effects of main milling parameters on surface roughness: (a) spindle speed, (b) feed rate, and (c) feed depth

The effects of combined milling parameters on surface roughness are shown in Figure 8, where B1–B3 correspond to feed rates of 43, 120, and 200 mm/min, and C1–C3 correspond to depths of cut of 1, 3, and 5 mm, respectively. Analysis of interaction effects indicates that a high spindle speed is essential for achieving a low surface roughness value; concurrently, a low feed rate must be maintained (Figure 8(a)). The feed rate and depth of cut exhibit a comparable pattern, as lower feed rates and depths of cut lead to reduced surface roughness (Figure 8(b)).



(a) (b)

Figure 8. The effects of combined milling parameters on surface roughness: (a) spindle speed vs. feed rate and (b) feed rate vs. feed depth

The optimal side milling condition for minimizing surface roughness was achieved at a spindle speed of 850 rpm, a feed rate of 43 mm/min, and a depth of cut of 1 mm, yielding a predicted surface roughness of approximately 5.184 µm (Table 4). This value meets the roughness requirements specified in ISO 21920:2021 surface texture [17] without the necessity of post-machining surface finishing. The predictive equation was validated by conducting a total of 10 milling conditions (Table 4), and the results showed that the average difference between the predicted surface roughness values and the actual surface roughness was 1.544%, which is small and acceptable for implementation.

Table 4. Evaluation of the side-milled surface roughness regression model

No.	Speed (rpm)	Feed Rate (mm/min)	Depth of Cut (mm)	Cal. R_a (F_t)	Actual R_a (d_t)	Error $e_t = d_t - F_t$	$\frac{\|e_t\|}{d_t} \times 100$
1	850	43	1	5.184	5.256	0.072	1.370
2	610	120	1	7.925	8.332	0.407	4.885
3	610	43	3	8.068	8.058	-0.010	0.124
4	850	43	3	6.260	6.253	-0.007	0.112
5	610	43	5	9.541	9.568	0.027	0.282
6	330	120	5	12.073	12.110	0.037	0.306
7	850	120	1	7.815	8.062	0.247	3.064
8	330	43	1	8.477	8.612	0.135	1.568
9	610	200	5	10.869	11.111	0.242	2.178
10	610	200	1	8.519	8.653	0.134	1.549
						MAPE	1.544

3.3 The Effects of Side Milling Factors on Burr Formation

ANOVA was utilized to examine the impact of milling conditions on burr development. Table 5 indicates that all primary and interaction milling parameters strongly influence burr development, with feed depth exerting the most significant effect. Similar to surface roughness analysis, the combined parameters of the three-way interaction (*SFD*) do not significantly affect burr formation. This result can also be attributed to the different correlations among cutting parameters.

Table 5. ANOVA analysis on burr formation

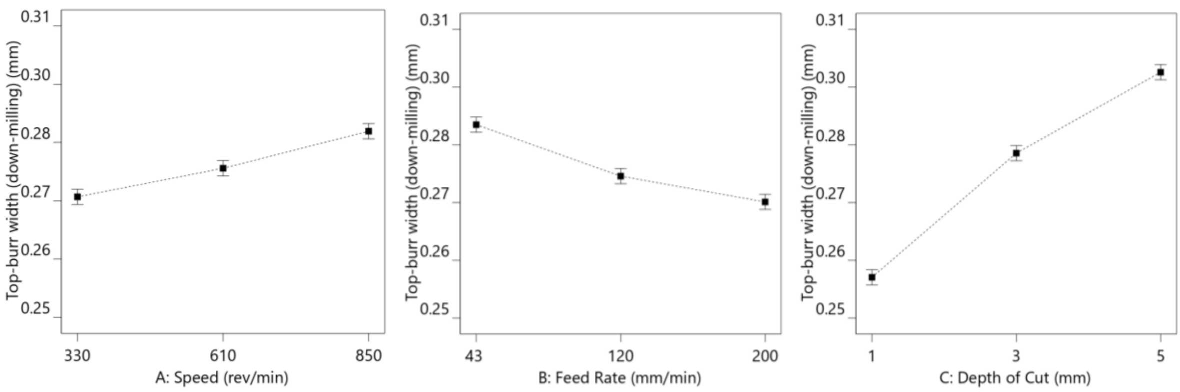
Source	Sum of Squares	df	Mean Square	F-Value	P-Value
Model	0.0312	18	0.0017	59.60	< 0.0001*
S-Speed	0.0022	2	0.0011	37.02	< 0.0001*
F-Feed Rate	0.0031	2	0.0016	53.88	< 0.0001*
D-Depth of Cut	0.0216	2	0.0108	371.38	< 0.0001*
SF	0.0013	4	0.0003	11.41	< 0.0001*
SD	0.0010	4	0.0002	8.49	< 0.0001*
FD	0.0020	4	0.0005	17.14	< 0.0001*
SFD	0.0003	8	0.0000	1.49	0.1812
Pure Error	0.0015	54	0.0000		
Total	0.0330	80			
R^2	95.53				
Adjusted R^2	93.37				

Note: * Parameters have a significant effect at the 0.05 significance level.

A regression equation for predicting burr formation (W_B) was established in Equation (2). The coefficient of determination (R^2) is 95.53%, while the adjusted R^2 is 93.37%, indicating that the equation is suitable for predicting results. Similarly, as in Eq. (1), subscripts 1 and 2 denote the low and high settings of each machining parameter, respectively. For instance, S_1 corresponds to the low-speed level of 330 rpm, whereas S_2 corresponds to the high-speed level of 850 rpm.

$$W_B = 0.2802 - 0.0060S_1 - 0.0005S_2 - 0.0083F_1 - 0.0017F_2 - 0.0212D_1 + 0.0028D_2 - 0.0027S_1F_1 - 0.0049S_2F_1 - 0.0004S_1F_2 + 0.0044S_2F_2 + 0.0017S_1D_1 - 0.0017S_2D_1 - 0.0066S_1D_2 + 0.0032S_2D_2 - 0.0047F_1D_1 + 0.0044F_2D_1 + 0.0096F_1D_2 - 0.0054F_2D_2 \quad (2)$$

It was demonstrated that increasing spindle speed results in enhanced burr formation (Figure 9(a)). Nonetheless, increasing the feed rate and decreasing the depth of cut leads to a reduction in burr formation (Figures 9(b) and (c)). A greater depth of cut implies increased material removal, hence increasing burr development.



(a) (b) (c)

Figure 9. The effects of main milling parameters on burr formation: (a) spindle speed, (b) feed rate, and (c) feed depth

Figure 10 illustrates the impact of various milling parameters on burr development, with B1–B3 representing feed rates of 43, 120, and 200 mm/min, and C1–C3 denoting depths of cut of 1, 3, and 5 mm, respectively. Figure 10 illustrates that reducing burr formation requires a combination of a lower spindle speed and a small depth of cut, along with a relatively high feed rate. According to Merchant's orthogonal cutting model, this parameter setting reduces the overall cutting force and heat generation in the workpiece, thereby minimizing burr formation on the machined surface [15]. This result agrees with the findings of [18]. The optimal milling condition for the lowest burr formation was determined through an analysis. The optimal cutting conditions for minimizing burr formation were a spindle speed of 610 rpm, a feed rate of 200 mm/min, and a depth of cut of 1 mm, resulting in a predicted burr formation of 0.251 mm (Table 6), and eliminating the need for post-machining.

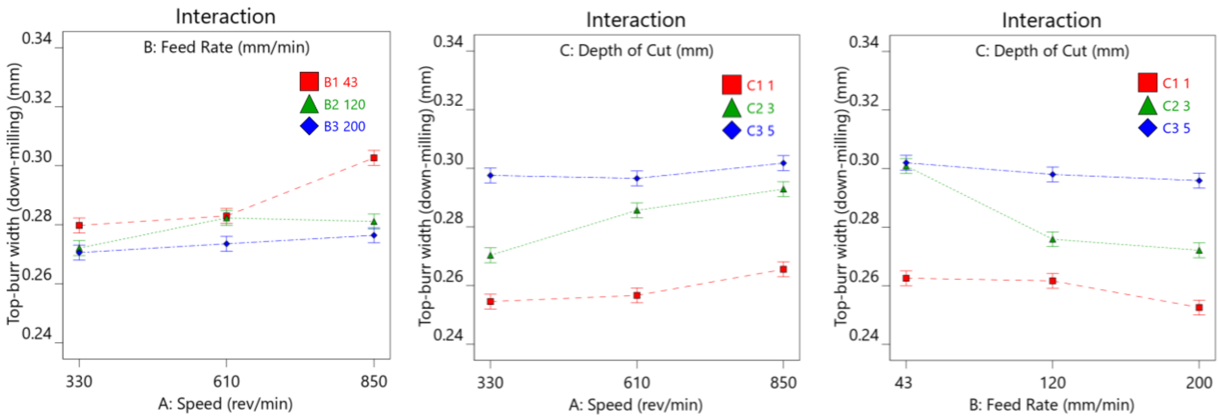


Figure 10. The effects of combined milling parameters on burr formation: (a) spindle speed vs. feed rate, (b) spindle speed vs. feed depth, and (c) feed rate vs. feed depth

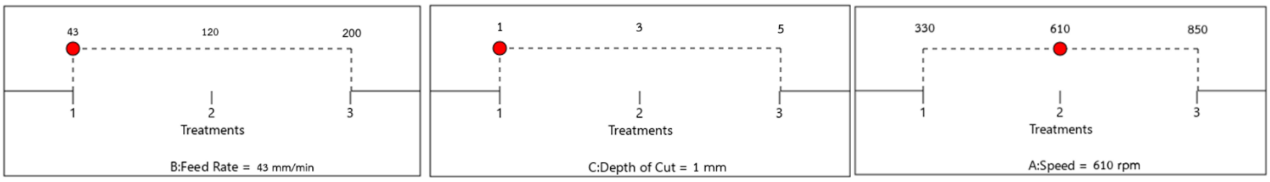
The regression model was validated by conducting 10 milling conditions as given in Table 6. The result was similar to those used for surface roughness analysis. The average difference between the predicted burr formation value and the actual burr formation was 2.294%, which is considered acceptable in comparison.

Table 6. Evaluation of the burr formation regression model

No.	Speed (rpm)	Feed Rate (mm/min)	Depth of Cut (mm)	Cal. Burr (F_t)	Actual Burr (d_t)	Error $e_t = d_t - F_t$	$\frac{\lvert e_t \rvert}{d_t} \times 100$
1	850	43	1	0.277	0.272	-0.005	1.838
2	610	120	1	0.264	0.262	-0.002	0.763
3	610	43	3	0.299	0.288	-0.011	3.819
4	850	43	3	0.318	0.301	-0.017	5.648
5	610	43	5	0.295	0.291	-0.004	1.375
6	330	120	5	0.296	0.302	0.006	1.987
7	850	120	1	0.264	0.260	-0.004	1.538
8	330	43	1	0.256	0.264	0.008	3.030
9	610	200	5	0.294	0.289	-0.005	1.730
10	610	200	1	0.251	0.248	-0.003	1.210
						MAPE	2.294

3.4 Optimal Milling Parameters for Minimizing Surface Roughness and Burr Formation

An analysis of optimal side milling parameters was conducted to minimize surface roughness and burr formation. An I-optimal design algorithm was employed to identify the best parameter combinations, providing practical guidance for wood machining manufacturers (Figure 11). The results revealed that the optimal conditions consisted of a low feed rate of 43 mm/min, a low depth of cut of 1 mm, and a moderate spindle speed of 610 rpm, resulting in a surface roughness of 6.958 µm and a burr formation of 0.255 mm, with a desirability assessment of 84.8%. These milling conditions result in low surface roughness and minimal burr formation, in compliance with ISO 21920 requirements. It is recommended that manufacturers eliminate the need for post-finishing processes in WPC milling, especially for furniture applications that require proper assembly.



(a) (b) (c)

Figure 11. Optimal side milling parameters for minimizing both surface roughness and burr formation: (a) feed rate, (b) depth of cut, and (c) spindle speed

4. Conclusions

The evaluation of the side milling performance of WPCs revealed that the cutting parameters, including spindle speed, feed rate, and feed depth, have a significant effect on surface roughness and the formation of burrs. The most significant factors influencing surface roughness were spindle speed, feed rate, and depth of cut. On the other hand, feed rate, spindle speed, and depth of cut had the most significant effects on burr formation. The results of regression models for surface roughness and burr formation revealed that the predicted and experimental values varied by about 1.54% and 2.29%, respectively. The optimal milling parameters for minimizing roughness include a spindle speed of 850 rpm, a feed rate of 43 mm/min, and a cutting depth of 1 mm, resulting in a surface roughness of 5.184 μm. The optimal milling parameters for minimizing burr formation included a spindle speed of 610 rpm, a feed rate of 200 mm/min, and a cutting depth of 1 mm, resulting in a burr formation of 0.251 mm. To minimize both surface roughness and burr, the recommended milling parameters were 610 rpm spindle speed, 43 mm/min feed rate, and 1 mm cutting depth. This resulted in a surface roughness of 6.958 μm and a burr formation of 0.255 mm, respectively. This corresponds to ISO 21920's surface texture specification and does not require any post-milling finishing. This demonstrates that the predicted regression models can be employed to estimate the quality of milling. The result is advantageous for industries involved in the machining of composite plastics and wood products. To further enhance milling performance, such as increasing speed while maintaining cut quality, considerations may include the type and dimensions of the cutter, as well as the utilization of various composite plastic and wood materials.

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Conflicts of Interest: The authors declare no conflict of interest.

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