Tool Wear During High-speed Milling of Wood-plastic Composites

Weihua Wei,[a,]* Yingli Li,[a] Tongming Xue,[a] Yuantong Li,[a] Peng Sun,[a] Bin Yang,[a] Zhen Yin,[b] and Changtong Mei [c]

A high-speed milling test was performed with a self-developed wood-plastic composite using uncoated and coated carbide cutting tools. The nose width was used to represent the tool wear. An advanced tool measurement system was adopted to measure the wear of each tool. The influence of some cutting parameters, including spindle speed, feed rate, axial cutting depth, and radial cutting depth, on the tool wear was analyzed using a single factor test method. Scanning electron microscopy was used to observe the wear morphology on the rake and clearance face of the tool before and after the tool was worn. The results showed that the tool nose width increased with increased axial cutting depths or spindle speeds, while the radial depth under the condition of the same cutting length decreased with an increase in the feed rate. Moreover, the main form of tool wear was abrasive wear and coating peel-off when the wood-plastic composites were machined with high-speed milling.

Keywords: Wood-plastic composites; High-speed milling; Cutting parameters; Tool wear

*Contact information: a: College of Mechanical and Electrical Engineering, Nanjing Forestry University, Nanjing, 210037, China; b: College of Mechanical Engineering, Suzhou University of Science and Technology, Suzhou 215009, China; c: College of Materials Science and Engineering, Nanjing Forestry University, Nanjing, 210037, China; *Corresponding author: whwei@njfu.edu.cn*

INTRODUCTION

Wood-plastic composites (WPCs) have attracted wide attention in the literature due to some obvious advantages that wood or plastic alone cannot have. Wood-plastic composites combine both the performance characteristics of wood and engineering plastics, and thus the resulting tool wear characteristics are similar for both materials (Kılıç *et al.* 2009; Wei *et al.* 2018). As a kind of advanced manufacturing technology with high efficiency, high quality, and low consumption, high-speed cutting technology has been widely used in the cutting of wood-based materials. Compared with low-speed cutting, high-speed cutting can achieve higher processing efficiency and surface quality, but tool wear was more serious (Guo *et al.* 2018a). Zhu *et al.* (2017) in cutting high-density fiberboard (HDF) further pointed out that the high cutting speed included high feed speed and spindle speed, which increased the processing capacity per unit time and brought more cutting heat and acting force to the tool surface. When the tool encountered hard particles, it was easy to leave scratches on the surface of tool, causing abrasive wear. Philbin and Gordon (2005) claim that mechanical abrasive wear is the main type of wear when a polycrystalline diamond tool (PCD) is used to cut a fiber laminate composite plate. Literature indicates that the coating treatment can provide better performance while preserving the advantages of the tool base itself, especially in terms of reducing the progression of wear rate and clearance wear (Faga and Settineri 2006; Gilewicz *et al.*

2010). Darmawan *et al*. (2001), in a study of the turning of wood-based materials, showed that delamination of the coating film and wear of the substrate of the coated carbide tools were primarily caused by mechanical abrasion wear. Guo *et al.* (2018b) stated that the cutting tool was subjected to more severe cyclical thermal loads and mechanical loads during high-speed milling, and these factors can overcome the adhesion between the coating and the cemented carbide substrate. This causes cracks and fractures in the coating, which in turn contributed to the coating peeled off and the tool failed prematurely. In addition, the wear of a cutting tool is significantly affected by cutting parameters during the machining process, including cutting speed, feed rate, and cutting depth. Szwajka and Trzepieciński (2016) found that the cutting speed had a significant effect on the tool life, and the tool life decreased as cutting speed increased. Xue (2018) pointed out that the wear of a tool increased with increasing cutting speed, axial cutting depth, and radial cutting depth, and it decreased with increasing feed rate. Overall, these results mainly focused on the tool wear mechanism or tool life evaluation in the processing of wood, composite board, and engineered plastics, and did not study the substantive problems of the wear and damage mechanism of cutting tools for WPCs.

To investigate the effects of the cutting parameters, including spindle speed, feed rate, axial cutting depth, and radial cutting depth, on tool wear and to explore the main mechanism of tool wear by observing the rake face and the clearance face of the tool before and after wear, the high-speed milling test of a self-developed WPC was performed in this study with uncoated carbide cutting tools. Moreover, the paper also considers the wear mechanism of the coated tool and compared it with the wear mechanism of the uncoated tool to better explore the evolution of the tool from wear to failure. The research results will help enrich the processing technology of wood polymer materials, and provide a scientific basis for optimizing the high-speed milling of WPCs.

EXPERIMENTAL

Materials

The WPC used in the experiment was produced by Nanjing Dayuan Plastic Wood New Material Co., Ltd. (Nanjing, China). 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

The experiment was performed with up-milling using a UCP 800 Duro Five-axis Machining Centre manufactured by Mikron (Agno, Switzerland). Translatable carbide cutting tools manufactured by Zhuzhou Diamond Cutting Tool Co., Ltd. (Zhuzhou, China) were used to perform the test. The arbor model (EMP01-020-G20-AP11-02) with a diameter (D) of 20 mm was used in the test. The blades used in the test were an ordinary carbide blade with a grade of YD201 and a coated carbide blade with a grade of YBG302, and only one blade was mounted on the arbor at the beginning of each set of tests. The specifications of cutting tools are presented in Table 2.

Table 2. Specifications of Cutting Tools

Grade	Coated Materials	Rake Angle (γ_0)	Sharpness Angle (β_0)	Clearance Angle (α_0)
YD201	-	19°	60°	11°
YBG302	TiAlN	19°	60°	11°

Test Parameters

The wear loss of the tool changed with the cutting parameters. To investigate the influence of four parameters (spindle speed n, feed rate v_f, axial milling depth a_p, and radial milling depth a_e), on tool wear, a single factor design was applied in this experiment. The selected milling amount is shown in Table 3.

Table 3. Cutting Parameters of Tool Wear Test

n (rpm)	v_f (mm/min)	a_p (mm)	a_e (mm)
8000	1000	2	5
12000	3000	3	7.5
16000	5000	4	10

Methods

There are many ways to represent the tool wear in woodworking machining. Nose width (NW) as an important parameter to evaluate tool wear can effectively reflect the tool wear state (Saloni *et al*. 2011; Guo *et al*. 2014). Therefore, the NW was adopted to represent the tool wear based on the existing measurement devices and conditions in this test. Figure 1 shows the measurement details of NW.

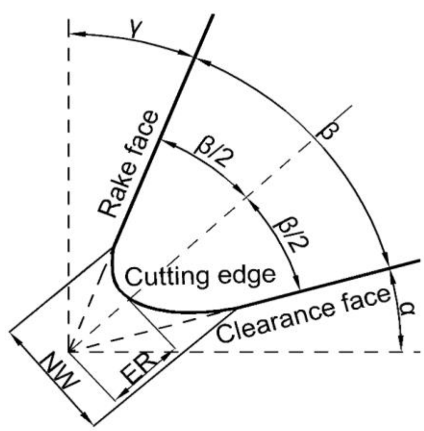

Fig. 1. Schematic diagram of NW measurement on the tool

The tool NW was measured with a Nikon DS-U3 DS digital microscopic imaging system (Tokyo, Japan) after the milling length of each test reached 10.24 m. It is important to note that the tool should be positioned so that the plane formed by the main cutting edge and the axis of the blade is maintained perpendicular to each other during actual measurements, which guarantees the nose width can be accurately measured.

After the high-speed milling test, the surface morphology of the rake and clearance face of the tool was observed using a JSM-7600F field emission scanning electron microscope (FE-SEM; Japan Electron Optics Laboratory Co., Ltd., Tokyo, Japan) and compared with the non-worn tool to analyze the tool specific wear mechanisms.

RESULTS AND DISCUSSION

Influence of Milling Parameters on Tool Wear

The tool was maneuvered carefully to ensure the accuracy of the results. Therefore, the average nose width was selected as the final measured value. Table 4 shows the final measurement of the nose width for nine groups of cuttings in the test. Where No. 1 test was taken as a reference test to investigate the effect of the variables on tool wear.

Table 4. Measurement Results of NW

Factors / Number	n (rpm)	v_f (mm/min)	a_p (mm)	a_e (mm)	NW (µm)
1	16000	3000	4	10	170.70
2	12000	3000	4	10	126.89
3	8000	3000	4	10	79.17
4	16000	5000	4	10	129.22
5	16000	1000	4	10	220.57
6	16000	3000	3	10	165.99
7	16000	3000	2	10	149.55
8	16000	3000	4	7.5	163.22
9	16000	3000	4	5	152.95

Influence of spindle speed on tool wear

Table 4 shows the results of test numbers 1, 2, and 3, which reflected the influence of the spindle speed on nose width. The feed rate v_f, axial milling depth a_p, and radial milling depth a_e were kept at 3000 mm/min, 4 mm, and 10 mm, respectively, but the spindle speed n was changed to 8000, 12000, and 16000 rpm. The trend of the nose width is shown in Fig. 2.

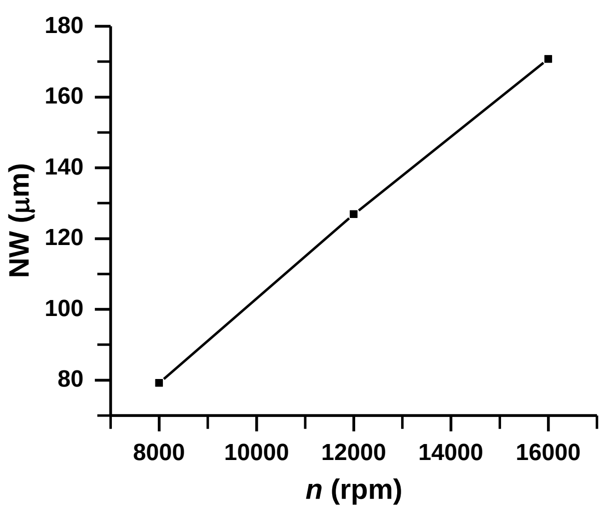

Fig. 2. The influence of spindle speed on NW

When the spindle speed n was increased from 8000 to 12000 rpm and 16000 rpm, the nose width of the tool gradually increased. The nose width of the tool at 16000 rpm spindle speed was approximately double the value at the 8000 rpm spindle speed. The spindle speed and milling speed were proportional, which meant that at a greater spindle speed, there was a greater milling speed and higher friction frequency between the tool and the workpiece materials. The tool and the workpiece were both subjected to a higher frequency of mechanical and thermal shocks at high spindle speeds, and then generated a large amount of milling heat and further increased the temperature of the tool, which increased the wear of the tool.

Influence of feed rate on tool wear

As shown in Table 4, test numbers 1, 4, and 5 reflected the influence of feed rate on nose width. The spindle speed n, the axial milling depth a_p, and the radial milling depth a_e were kept at 16000 rpm, 4 mm, and 10 mm, respectively, but the feed rate v_f was changed to 1000, 3000, and 5000 mm/min. The trend of the nose width is shown in Fig. 3.

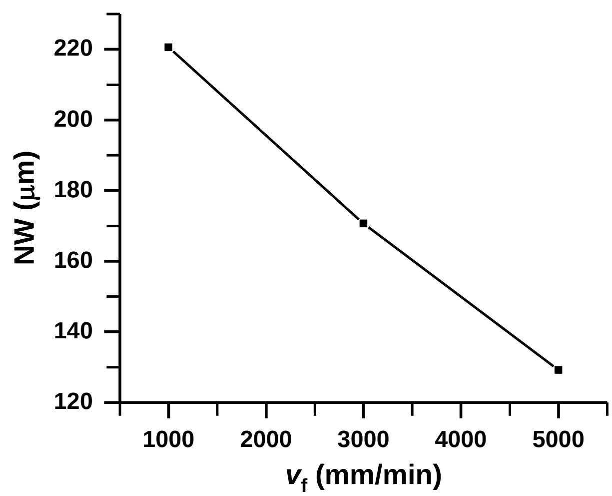

Fig. 3. The influence of feed rate on NW

The nose width was negatively correlated with the feed rate when analyzed with the results of the three sets of tests. The nose width was smaller if the feed rate was greater. The tool wear was the highest when the feed rate was at the minimum value. As the feed rate increased, the tool wear decreased. It took a longer time to mill the same length of material when the feed rate was smaller. In other words, the contact area was subjected to longer periods of friction action because of the longer contact time between the tool and the workpiece. Thus, a large amount of heat was produced and was hard to exude out in time, which accelerated the wear of the cutting tool.

Influence of axial milling depth on tool wear

Table 4 shows that test numbers 1, 6, and 7 reflected the influence of axial milling depth on nose width. The spindle speed n, feed rate v_f, and the radial milling depth a_e were unchanged and were 16000 rpm, 3000 mm/min, and 10 mm, respectively, but the axial milling depth a_p was changed to 2, 3, and 4 mm. The trend of the nose width is shown in Fig. 4.

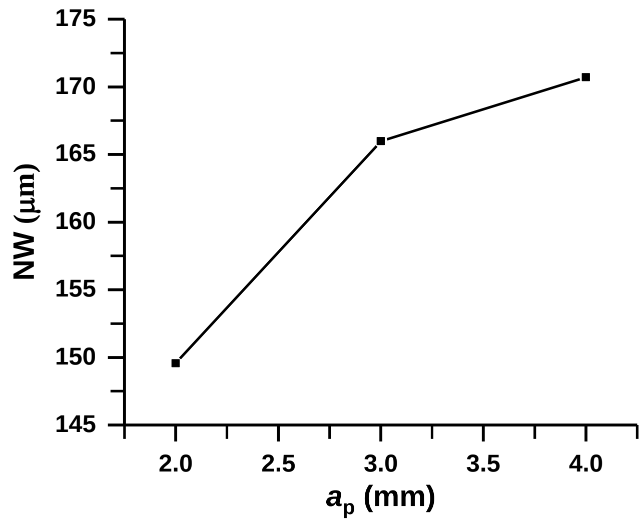

Fig. 4. The influence of axial milling depth on NW

Figure 4 shows that the nose width was larger if the axial milling depth was greater. The increase in axial milling depth will give the cutting-edge greater cutting forces (Wei *et al*. 2019), resulting in increasing the tool bearing capacity and accelerating the wear rate of the tool. In addition, the increase of the axial milling depth caused increasing friction between the chip and the rake face of the tool, workpiece, and the clearance face of the tool. The increased friction can directly increase the milling temperature, which reduces tool chemical stability and intensifies wear on the milling edge of tool.

Influence of radial milling depth on tool wear

As shown in Table 4, test numbers 1, 8, and 9 reflected the influence of radial depth on nose width. The spindle speed n, feed rate v_f, and the axial milling depth a_p were kept at 16000 rpm, 3000 mm/min, and 4 mm, respectively, but the radial milling depth a_e was changed to 5, 7.5, and 10 mm. The trend of the nose width is shown in Fig. 5.

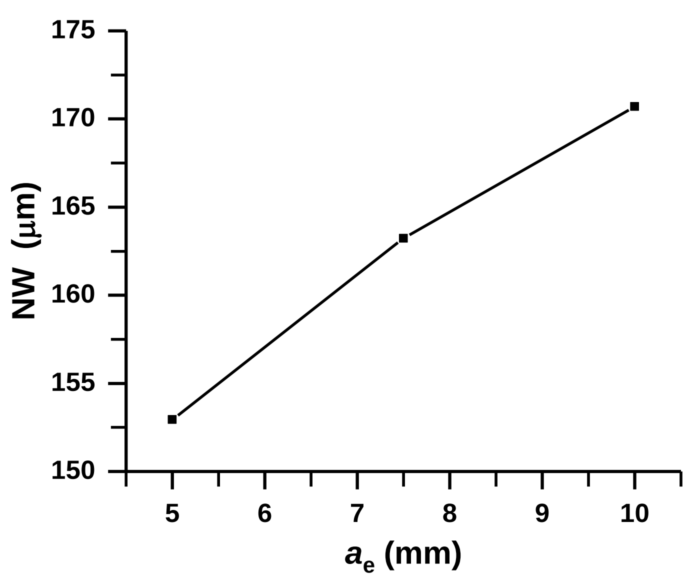

Fig. 5. The influence of radial milling on NW

The nose width was proportionally correlated with the radial depth when the results of the three sets of tests were analyzed. A greater radial depth led to a greater nose width. The increase of radial milling depth resulted in an increase in the area of the material being cut per unit time. In other words, a greater contact area between the tool and the workpiece during each revolution resulted in more heat generated between the tool and the workpieces. Therefore, the temperature in the cutting zone was remarkably increased, which increased the wear of the tool.

Tool Wear Mechanism Analysis

A scanning electron microscope was used to observe and measure the wear of the rake and clearance face before and after tool wear. Moreover, the specific mechanisms for tool wear were analyzed.

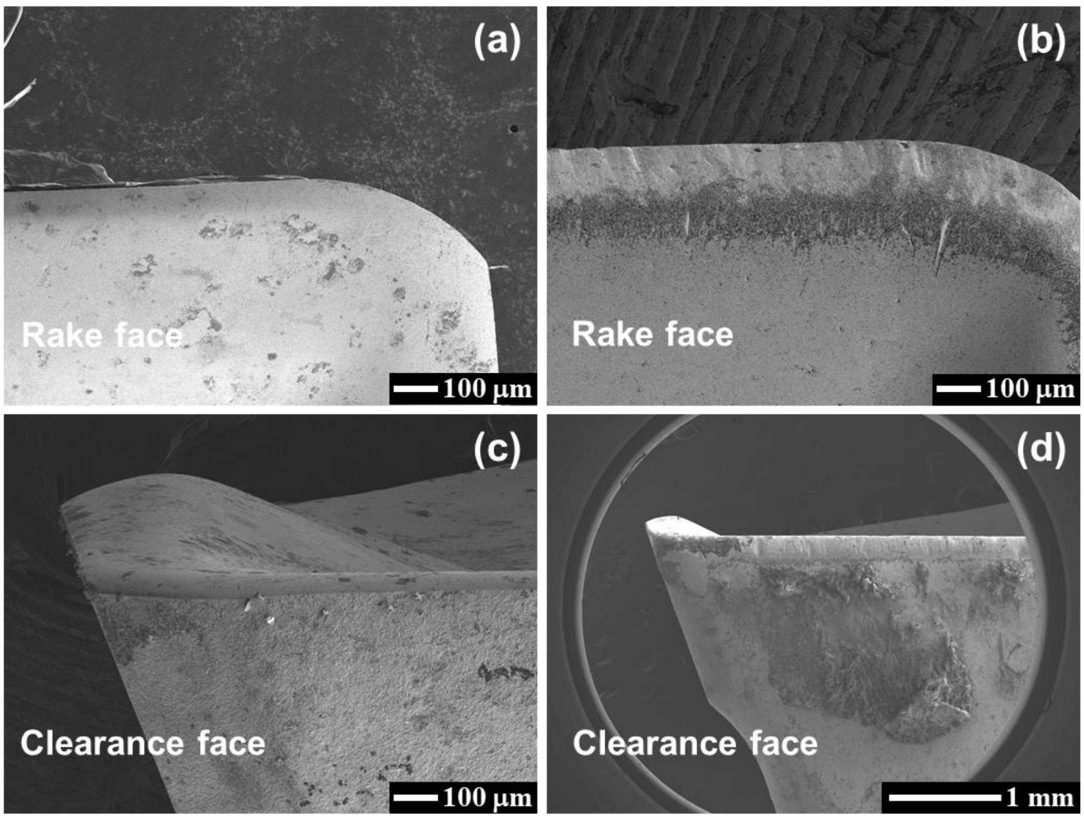

Fig. 6. The shape of the rake and clearance face before and after wear: (a) the rake face of the non-worn tool, (b) the rake face of the worn tool, (c) the clearance face of the non-worn tool, and (d) the clearance face of the worn tool

Figure 6 shows the microscopic images of the rake and clearance face before and after tool wear, where panel (a) is the rake face of the non-worn tool and (b) is the rake face morphology after milling under the condition in Table 4 with parameters of the No. 7 test (n = 16000 rpm, v_f = 3000 mm/min, a_p = 2 mm, and a_e = 10 mm). The non-worn rake face was smooth. The surface crystal forms were consistent, and the worn and the non-worn area of the worn rake face had a clear dividing line. On the surface, there were a few clear scratches and some pothole-like areas observed at 100× magnification. Image (c) is the case where the non-worn rake face was enlarged by 100, and the clearance face was smooth, the milling edge was sharp, and the grains were small. Image (d) is the clearance face morphology after milling under the conditions in Table 4 with parameters of the No. 5 test (n = 16000 rpm, v_f = 3000 mm/min, a_p = 4 mm, and a_e = 10 mm). There were grains peeling off on the nose of the tool, and there were many vertical scratches in the wear area. Because the blade was ultrasonically cleaned and dried before microscopy, most of the chips attached to the blade surface were washed off. However, some of the more tightly attached chips remained on the worn blade, and some adhered to the tool body grain.

Abrasive wear

Because the test was conducted at a high speed and high feed rate, the high spindle speed made the temperature in the milling area increase remarkably and then caused a drop in surface hardness of the blade when there were hard spots in the workpiece materials. This made it easily produce a stripe wear band (or scratch) that was perpendicular to the milling edge, the so-called abrasive wear. Some scratches were long and thick and can be seen by the ordinary microscope; others were very small and only could be seen by the SEM. The length of the scratches was related to the diameter of the hard particles in the material. The depth of the scratches was related to the hardness of the hard spots.

Figure 7 presents two partially enlarged figures of the clearance face under different milling parameters, where the obvious scratches caused by the abrasive wear of the blade in the WPCs can be seen. Because in the milling process, the workpiece material was in circulation and friction, abrasive wear continued to exist until tool failure.

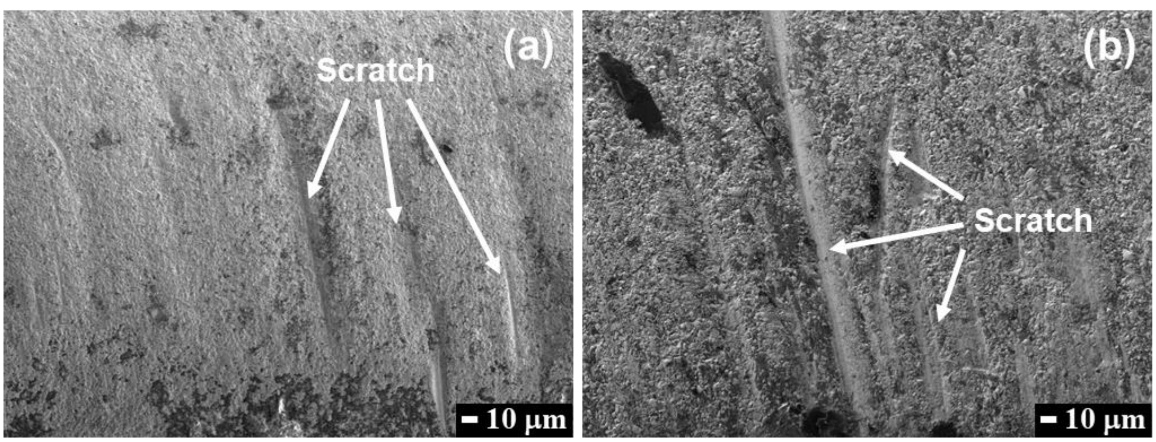

Fig. 7. The shape of the abrasive wear of the tool: (a) the scratches during test number 6 and (b) the scratches during test number 7

Coating peel-off

The coated carbide tool was coated with a layer of composite material on its base, which was superior to the ordinary carbide tool. Both materials increase the surface hardness of the tool and have good heat resistance, which reduces the milling tool wear and protects the tool base.

The wear of the coated carbide tool was much smaller than the ordinary carbide tool in the same cutting conditions. Figure 8 shows the wear on the clearance face of the coated and uncoated cutting tools after cutting under the same conditions (n = 16000 rpm, v_f = 1000 mm/min, a_p = 4 mm, a_e = 10 mm, and L = 10.24 m), where image (a) shows the uncoated tool and image (b) corresponds to the YBG 302-coated tool. Through observing the number and intensity of the scratches generated in the worn zone and analyzing the size and depth of the scratches, it was found that there were many scratches in image (a), some of which were not a thin strip but complete potholes. In contrast, the wear area in image (b) shows only a few irregular scratches, which indicated that the coated tool was more wear resistant than the uncoated tool in the test.

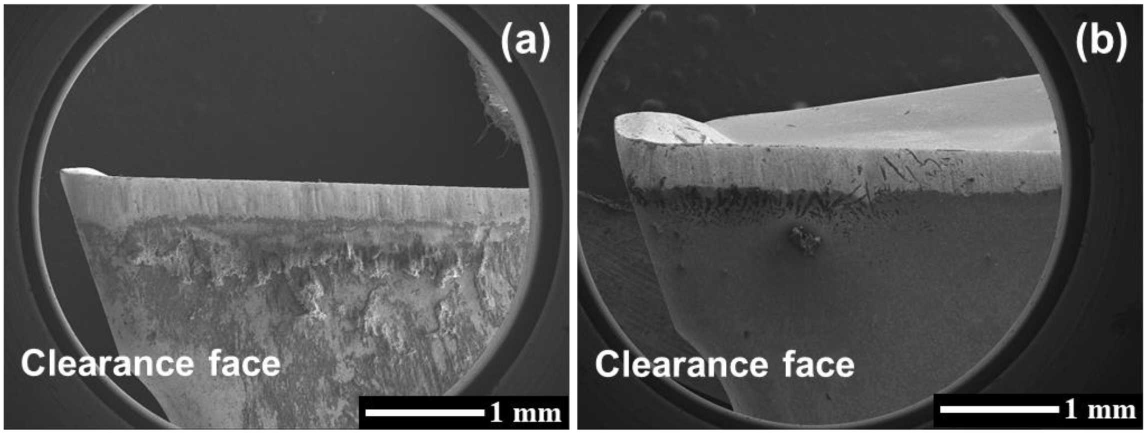

Fig. 8. The wear of clearance face on (a) the uncoated tool and (b) YBG302 coated tool

The coating peeling speed was accelerated because the intermittent impact load and the shock frequency in the process of high-speed milling were much larger than that of the normal-speed milling. Figure 9 shows the shape of the clearance face of the tool after the coating was peeled off. The performance of the tool with the ordinary carbide was essentially the same after the coating material of the coated tool peeled off. At that time, the base of the tool was directly responsible for the high-speed milling of the WPC materials, which aggravated the wear of the tool. Therefore, the coating peel-off was also an important wear mechanism for the coated tool.

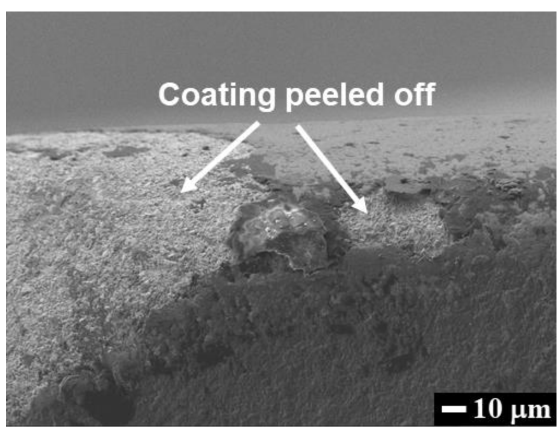

Fig. 9. The peeled off coating

CONCLUSIONS

A series of high-speed milling tests were conducted, and the influence of some cutting parameters, including spindle speed, feed rate, axial cutting depth, and radial cutting depth, on the tool wear was systematically analyzed with a single factor test method. The following conclusions can be drawn:

1. The wear loss of the tool changed with the different cutting parameters in high-speed milling of the wood-plastic composites for the same cutting length. The tool nose width was larger when either axial milling depths, spindle speeds, or radial milling depths were larger. However, the tool nose width decreased noticeably with increased feed rate.
2. The wear of the coated carbide tool was much smaller than the ordinary carbide tool in the same cutting conditions of the test. The main wear pattern of the uncoated carbide tool was the abrasive wear, while the main wear patterns of the coated cemented carbide tools included both the abrasive wear and coating peel-off.

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