Tool Wear and Machined Surface Roughness during Wood Flour/Polyethylene Composite Peripheral Up-milling using Cemented Tungsten Carbide Tools

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The effect of sharpness angle on tool wear and the effect of tool wear on machined surface roughness were investigated in wood flour/polyethylene composite (WFPEC) peripheral up-milling using cemented tungsten carbide (TC) tools. It was shown that nose width and edge recession increased with increasing feeding length. During the milling process, the wear of the nose width was smallest for the tool with a sharpness angle of 45°, followed by tools with sharpness angles of 55° and 65°. The wear of edge recession was highest for the tool with a sharpness angle of 45°, followed by tools with sharpness angles of 55° and 65°. The nose width increased with increasing sharpness angle, the edge recession decreased with increasing sharpness angle, and the machined surface roughness increased with increasing sharpness angle after a feeding length of 40 m. The nose width had a positive effect on the machined surface roughness, and the machined surface roughness increased with increasing nose width. The edge recession had little effect on the machined surface roughness. The clearance face roughness of the worn tool increased with increasing sharpness angle. The analysis of the SEM micrographs and EDS of the clearance face of the worn tool showed that the wear mechanisms of the cemented tungsten carbide tool were oxidation and abrasion in the range tested during cutting. Thus, a slight wear of the edge recession is gained in exchange for a lower machined surface roughness by decreasing the sharpness angle.

Keywords: Wood flour/polyethylene composite; Cemented tungsten carbide tools; Up milling; Sharpness angle; Tool wear; Surface roughness

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INTRODUCTION

Wood flour/polyethylene composite (WFPEC) is one type of wood plastic composite (WPC). Currently, WFPEC is the most attractive composite because the material has advantages in terms of low cost, high strength, biodegradability, recyclability, and environmental safety (Hamdan *et al*. 2010; Segerholm *et al*. 2012). It is widely used in the construction, automotive, and packaging industries (Hong *et al.* 2010; Klyosov 2007; Selke and Wichman 2004). With the use of WFPEC in a broadening range of applications, second processing requirements for the final product, such as turning, routing, milling, and sawing, are emerging (Saloni *et al.* 2011). However, the machining of wood flour reinforced plastic composites is different from that of conventional wood and wood-based materials and can cause excessive tool wear (Saloni *et al.* 2011). Because WFPEC contains two material phases with drastically different mechanical and thermal properties, there are complicated interactions between the matrix and the reinforcement during machining.

Cemented tungsten carbide tools consist primarily of a large volume fraction of fine grain refractory metal carbide in a metal binder (Brookes 1979). They are widely used in wood and wood-based materials cutting (Bayoumi *et al*. 1983). For almost three decades, the use of cemented tungsten carbide cutting tools in the wood working industry has provided significant improvements in tool life, primarily because of the superior hardness of these alloys. Recently, cemented tungsten carbide tools have been applied in the WPC cutting process. Despite their wide use in the metal and wood working industries, little information is known concerning their machinability in wood plastic composites.

Tool wear and machined surface roughness are two important aspects that reflect tool performance during the machining of composite materials. The wear of the cutting tool is the process that makes a usable tool unfit for continued use. During the cutting of materials, several wear mechanisms may simultaneously contribute to the general wear of the cutting tool. Among these wear mechanisms are gross fracture or chipping, abrasion, erosion, micro fracture, chemical and electrochemical corrosion, and oxidation (Sheikh-Ahmad 1999). The wear of a cutting tool is significantly affected by several factors during the machining process, which consist of tool geometry and cutting parameters. Alternatively, machined surface roughness is an important characteristic that describes the quality of the machined surface, which is, in most cases, a technical requirement for machined products. In addition, the surface roughness also affects several attributes of machined parts, such as adhesion, friction, and water absorption (Ayrilmis 2011; Buyuksari *et al.* 2010, 2011; Soury *et al.* 2013).

The sharpness angle is the most important parameter for cutting. There is a direct influence of the sharpness angle on cutting tool strength, tool wear, and machined surface quality. The objective of this work was to investigate the effects of sharpness angle on tool wear and the effect of tool wear on machined surface roughness during cutting of WFPEC. The study of tool wear processing and the fundamental mechanisms of wear may lead to data that will indicate whether wear is truly unavoidable, and if so, a feasible means of minimizing wear during the cutting of one type of composite material, WFPEC.

EXPERIMENTAL

Materials

The WFPEC used as the test samples in these experiments was supplied by the Polyplank Company (Sweden). The samples (n = 4), with the dimensions of 1000 mm (*L*) × 140 mm (*W*) × 25 mm (*T*), consisted of 48 wt.% pine (*Pinus sylvestris* L.) wood, 13 wt.% talc, and 34 wt.% polyethylene, as well as some additives such as pigments and lubricants. The wood particles were screened through a sieve with a mesh size of 0.7 mm × 2.1 mm.

Methods

Experimental set up

Up-milling was adopted for the cutting test of tool wear using a Model TF130 milling machine manufactured by the SCM Group (Rimini, Italy) with a mechanical feed mechanism, as shown in Fig. 1. The samples were machined using a single cutting edge.

The cutting head (diameter of 154 mm) was made for two blades, so a blunt counterweight was inserted into the opposing slot to balance the cutting head (Fig. 2) and avoid any effect of small differences between the teeth to maintain constant cutting conditions. The cutting edge, which consists of 10% cobalt, 89.5% tungsten carbide, and 0.5% other compounds, was provided by Sandvik Hard Materials (Sandviken, Sweden). The Vickers hardness (HV30) was 1600 and the Rockwell hardness (HRA) was 92.1.

Fig. 1. The SCM milling machine used in this study

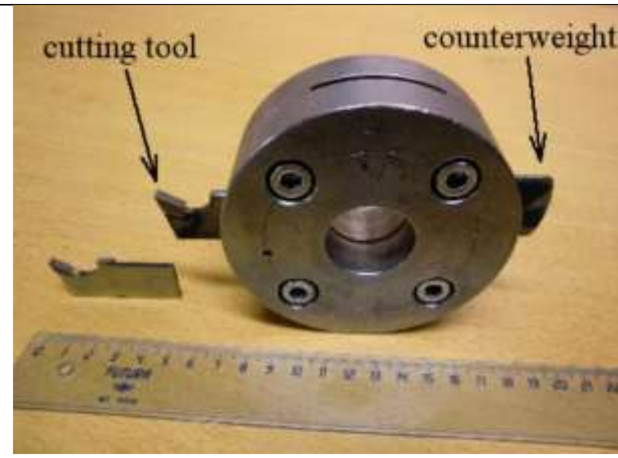

Fig. 2. Cutting head with sharpened blade and blunted counterweight

Experimental design

The experiments were performed with tools of sharpness angle (β) ranging from 45° to 65° with 10-degree intervals. The cutting edge width was 3.9 mm, the clearance angle (α) was constant (15°), and the rake angle (γ) ranged from 30° to 10°. Rotational speed of the spindle, feed rate, and depth of cut were fixed at 4400 rpm, 8.57 m/min, and 2.00 mm, respectively.

Wear measurement

There are many parameters that are used to quantify tool wear. Nose width (NW) and edge recession (ER) of cutting tools are two important parameters for assessing the wear progress in cutting wood and wood-based materials (Fig. 3). Some researchers found that edge recession on the clearance face is the most intensive surface measured in wood cutting (Porankiewicz *et al*. 2005; Sandak *et al*. 2011). Others have used nose width measured at a surface perpendicular to the tool angle bisector (Saloni *et al.* 2011; Sheikh-Ahmad *et al*. 2003). Therefore, nose width and edge recession were adopted as the primary parameters for evaluating the propagation of the tool wear in the WFPEC cutting process (Fig. 3).

Wear of the cutting edges was observed using an Olympus SZH Zoom Stereo Microscope (Tokyo, Japan) to classify the wear of nose width and edge recession. Nose width was measured from the top view (Saloni *et al.* 2011), while the edge recession was measured from the clearance face (Kowaluk *et al.* 2009). For each cutting test, measurements were taken after 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 15, 20, 25, 30, 35, and 40 m feeding lengths from the edge that touched the WFPEC material. Before and after each test, positions were chosen at 500, 1,500, 2,500, 3,000, 3,500 μm along the length of the active cutting edge for five measurements of nose width and edge recession, and the mean and the standard deviation of these measurements was calculated as the final value.

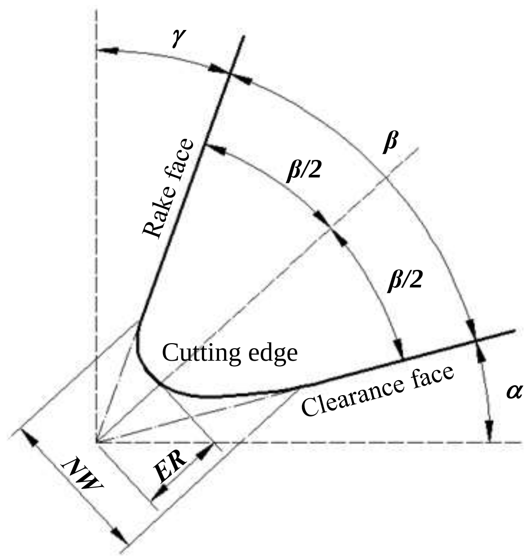

Fig. 3. Illustration of nose width (NW) and edge recession (ER) measurement on cutting blade

Analysis of SEM and EDS

The surface morphology of selected worn clearance faces was analyzed using a JEOL JSM-6460 scanning electron microscope (SEM) equipped with an Oxford INCA energy dispersive spectral (EDS) analysis system. This type of SEM equipment includes a large flexible specimen chamber that accommodates a 200 mm diameter specimen. The cutting tools were directly mounted on aluminum stubs with double-sided tape, coated with a gold alloy, and analyzed at an acceleration voltage of 25 kV to classify the wear mechanism.

Surface roughness measurement

Based on the literature review, it was found that the arithmetic mean deviation of the surface roughness, R_a, is the most important parameter for the evaluation of the machined surface quality (Budakçı *et al.* 2011; 2013; Hiziroglu 1996; Sütçü and Karagöz 2013; Wechsler and Hiziroglu 2007). Thus, in this study, the dependent variable is R_a, which was measured using a Wyko 1100NT 3D optical profiler (Veeco Instruments Inc., Plainview, NY).

The optical profiler is a non-contact method for measuring the surface roughness of an area and providing much of the same information as a stylus based profiler. The size of 10 mm × 10 mm × 10 mm of WFPEC samples with machined surface were made and mounted on the moving table of the optical profiler.

The tools were directly mounted on the moving table of the optical profiler, and the clearance face of tools was measured. Both machined surfaces of WFPEC samples and the worn clearance face of tools were measured after the experiments on five randomly chosen areas that measured 736 µm (L) × 480 µm (W), and the average value and the standard deviation were used in the analysis.

RESULTS AND DISCUSSION

Effect of Sharpness Angle on Tool Wear

Figure 4 shows the cutting nose width evolution relative to the feeding length for sharpness angles of 65, 55, and 45°. The nose width propagation of the cutting tool was divided into two stages: initial and monotonic, during the cutting process. The wear of the tool was the greatest in the initial stage, and became stable in the monotonic stage. The most dramatic nose width increase was in the range of 0 to 10 m for all test angles. The nose width stabilized at approximately 10 m and increased marginally to a feeding length of 40 m.

There were apparent differences between the progression of the nose width during the monotonic stage with different sharpness angles. The largest increase of cutting nose width occurred when the sharpness angle was 65°, while a sharpness angle of 45° caused the smallest increase in cutting nose width. This indicated that the wear of the cutting nose width decreased with decreasing sharpness angle.

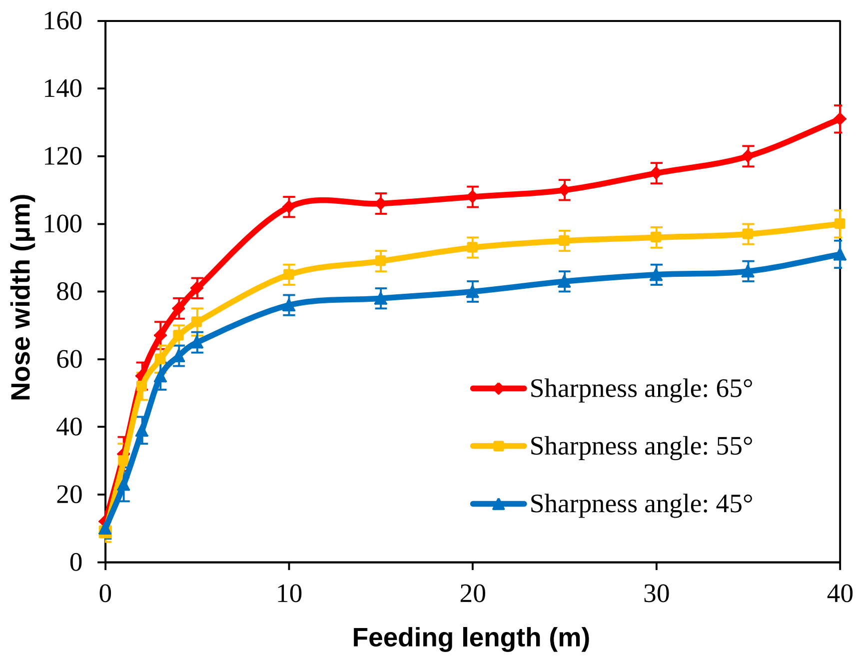

Fig. 4. Effect of feeding length on nose width evolution for sharpness angles of 65, 55, and 45°

Figure 5 shows the cutting edge recession evolution relative to the feeding length for sharpness angles of 65, 55, and 45°. The edge recession propagation of the cutting tool was also divided into initial and monotonic stages during the cutting process. The wear of the tool was the most intensive in the initial stage, and after initial stage, the wear of tool was becoming stable in the monotonic stage. The greatest edge recession increase was in the range of 0 to 10 m for all tests, and it became stabilized at approximately 10 m with little increase to a cutting distance of 40 m.

There were apparent differences between the cutting edge recession progressions tested during the monotonic stage under different sharpness angles. The greatest increase in cutting edge recession belonged to the tool with a sharpness angle of 45°, while the tool with a sharpness angle of 65° was the most resistant to the increase of cutting edge recession. This indicated that sharper cutting angles led to smaller cutting edge recession.

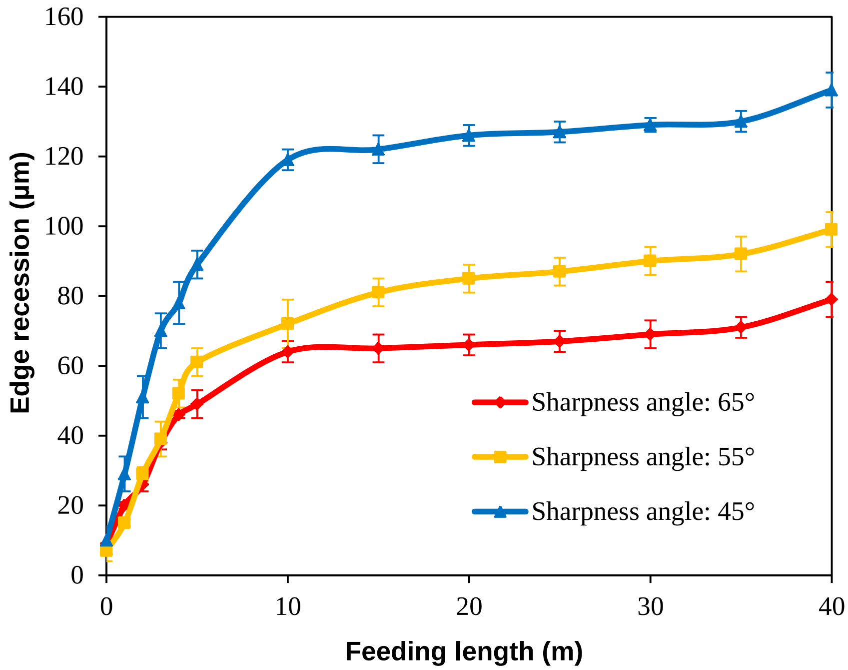

Fig. 5. Effect of feeding length on the cutting edge recession evolution for sharpness angles of 65, 55, and 45°

From Figs. 4 and 5, it can be seen that the nose width and the edge recession did not show similar tendencies with the increase in sharpness angle while the feeding length increased. The nose width of the tool with the larger sharpness angle increased faster than the tool with smaller sharpness angle. However, the edge recession of tools with smaller sharpness angle increased faster than that of tool with larger sharpness angle. For cutting tools with different sharpness angle, tool wear cannot be represented by only the cutting nose width or by the edge recession. Thus, each single wear parameter did not provide full information about the shape and geometry of a worn edge.

Effect of Tool Wear on Machined Surface Roughness

Figure 6 shows the nose width and the machined surface roughness for different tools with different sharpness angles after the feeding length of 40 m. Figure 7 shows that the edge recession and the machined surface roughness for different tools with different sharpness angle after the feeding length of 40 m. Sharpness angle had a positive impact on nose width and machined surface roughness, but a negative impact on edge recession. The nose width and the machined surface roughness increased with increasing the sharpness angle, but the edge recession decreased with increasing sharpness angle.

The results just described indicate that the tool with larger sharpness angle, which had a larger nose width and smaller edge recession, can produce a rougher machined surface, while the tool with lower sharpness angle, which had larger edge recession and smaller nose width, can produce a smoother machined surface. Therefore, the nose width has a positive impact on the machined surface roughness. However, a larger edge recession did not produce a rougher machined surface.

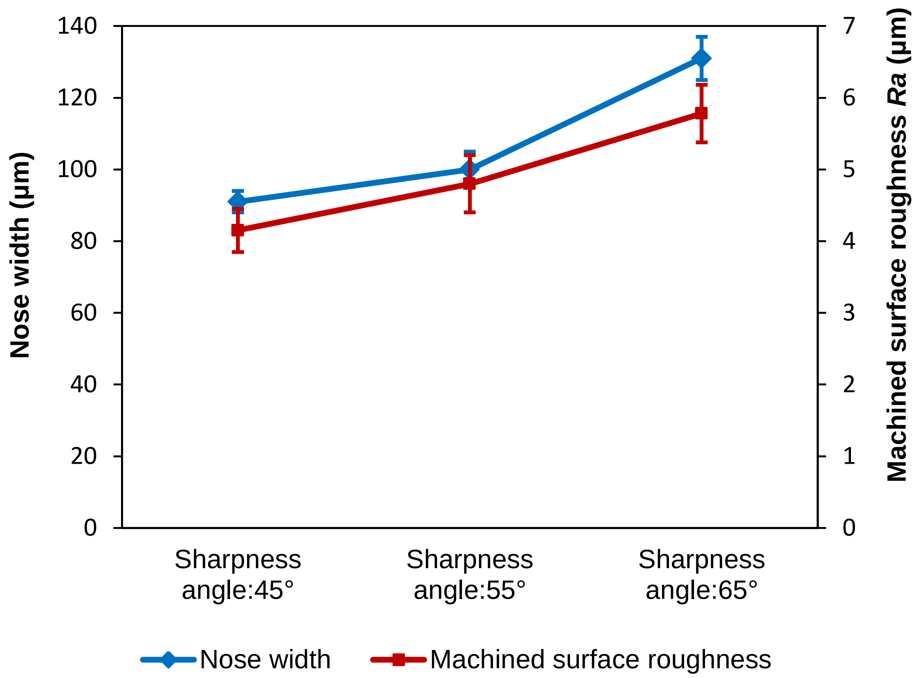

Fig. 6. Nose width and machined surface roughness for different tools with different sharpness angle after the feeding length of 40 m

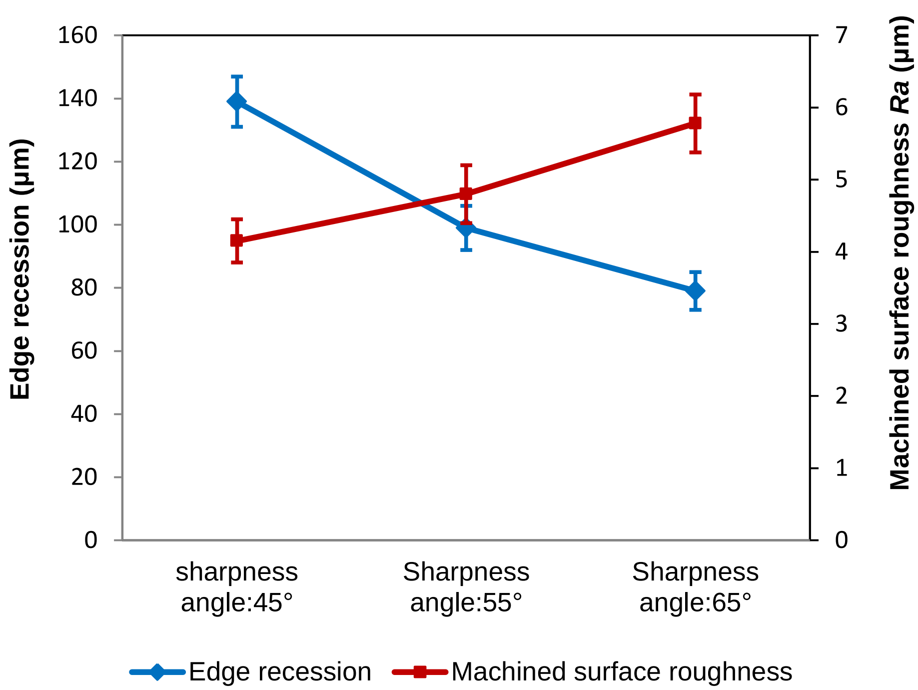

Fig. 7. Edge recession and machined surface roughness for different tools with different sharpness angle after the feeding length of 40 m

The edge recession has little impact on the machined surface. This also confirms that the lower sharpness angle had certain function of self-sharpening. The lower sharpness angle means quicker wear of edge recession, but better cutting quality. Alternatively, the edge recession measurements of wear may not give a true indication of the value of the cutting tool wear for tools with different sharpness angle. Thus, a slightly reduced wear of the edge recession is gained in exchange for a lower machined surface roughness by decreasing the sharpness angle.

Figure 8 compares the worn clearance face roughness of tools and the machined surface roughness for different tools with different sharpness angles after the feeding length of 40 m. It can be seen that both the worn clearance face roughness and the machined surface roughness was increased with increasing sharpness angle. The trend in the evolution of the worn clearance face roughness was consistent with the trend in the evolution of machined surface roughness with increasing the sharpness angle. A better explanation is that a larger sharpness angle induced a lower rake angle at a constant clearance angle, and a lower rake angle increased the normal negative force (pushing action downward on the workpiece), which means that a larger sharpness angle can induce higher friction between the clearance face and the machined surface roughness and cause rougher clearance face and machined surface (Iskra and Hernández 2012).

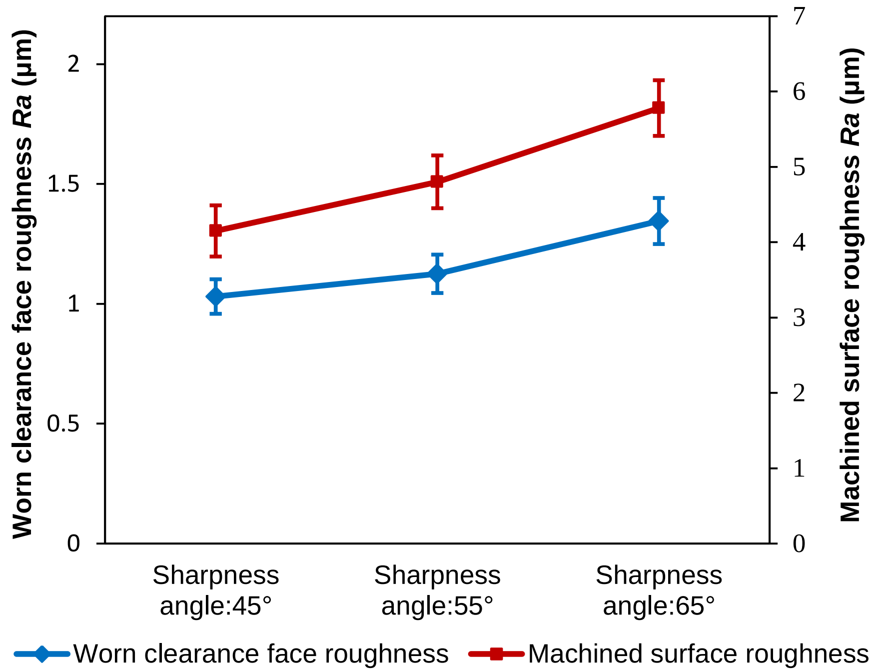

Fig. 8. Worn clearance face roughness and machined surface roughness for different tools with different sharpness angle after the feeding length of 40 m

Wear Mechanisms

The wear of the cutting edge occurs primarily on the clearance face (Okumura *et al*. 1987; Sugihara *et al*. 1979). Figure 9 (a, b, c, and d) shows SEM photomicrographs of the microstructure of the unworn clearance face of a new cutting edge and the worn clearance face of the cutting tools with sharpness angles of 45, 55, and 65°, with the measured worn areas the same distance from the edge. It can be seen that the unworn clearance face of a new cutting edge was relatively smooth in Fig. 9 (a). Some tungsten carbide grains were standing in relief on the wear surface as well as the cavities were once occupied by carbide grains which have been removed in Figs. 9 (b, c, and d). In addition, some areas of the wear surface, appear to remain smooth in Fig. 9 (b). It is believed that the smooth appearance of these areas is caused by removal of the binder phase to a lesser extent than for the other grades and due to smearing of the binder phase on the wear surface.

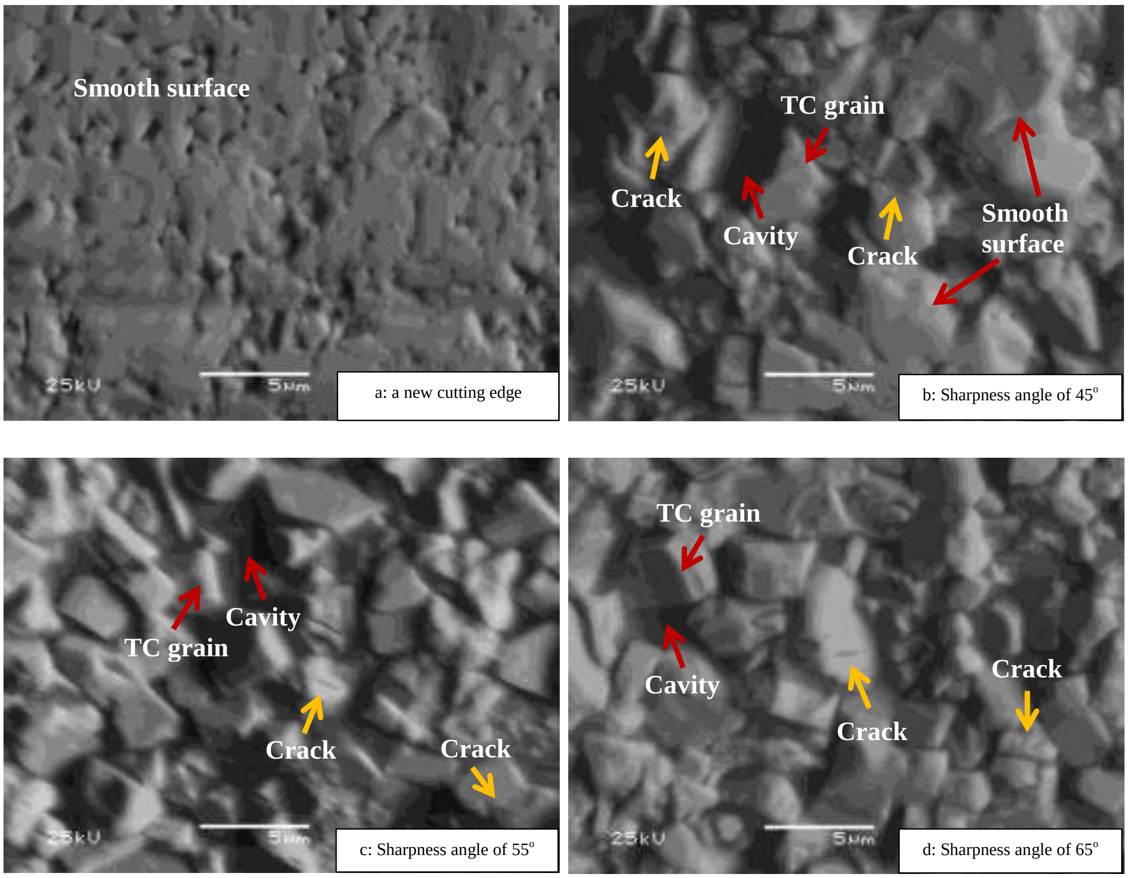

Fig. 9. SEM micrographs of unworn clearance face of a new tool and worn clearance face of tools with different sharpness angles after a feeding length of 40 m. (a) control; (b) 45°; (c) 55°; and (d) 65°

There is a clear evidence of the fragmentation of tungsten carbide grains in Figs. 9 (b, c, and d). The micrographs show the presence of transgranular cracks in the tungsten carbide grains. However, there was no evidence of wear on the tungsten carbide grains themselves, and they appear to have retained their original angular sharp appearances. Previous research on wood cutting tool wear has also reported similar wear surfaces in machining particleboard and fiberboard (Okumura 1987; Prakash 1995; Sheikh-Ahmad *et al*. 1999). Thus, the observations drawn from studying the microstructures in these photomicrographs indicate that wear of the tungsten carbide cutting edge in machining WFPEC occurred by preferential removal of the cobalt binder, followed by the removal of tungsten carbide grains.

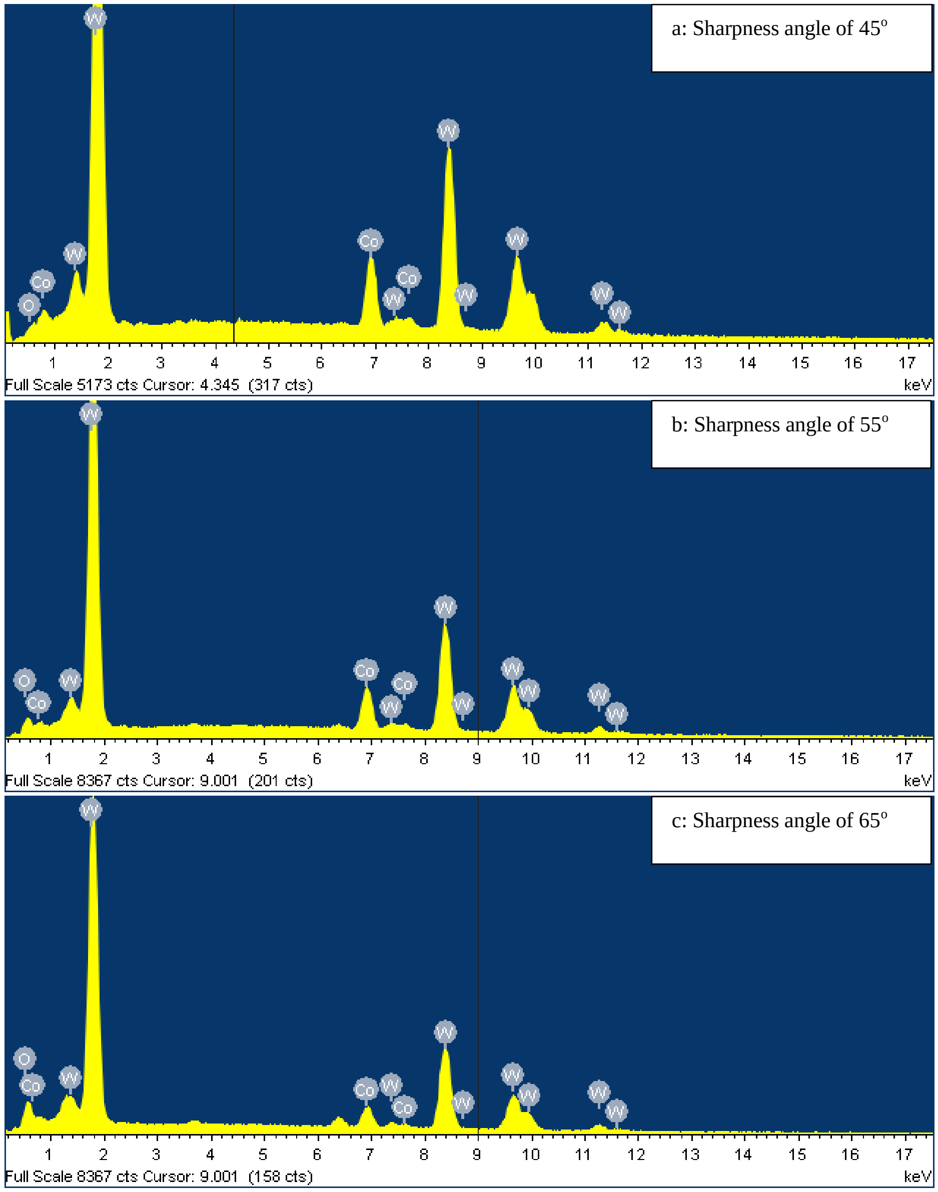

Fig. 10. EDS analysis of the samples in Fig. 9b, Fig. 9c, and Fig. 9d. (a) 45°; (b) 55°; and (c) 65°

Figure 10 (a, b, and c) shows the EDS analysis of the samples shown in Fig. 9 (b, c, and d). The element O (oxygen) appeared on the worn clearance face of all tools, irregardless of sharpness angle; this indicates the presence of oxidation wear. However, as investigated above, the tungsten carbide grains retained their original angular sharp appearance and did not show significant wear, so it is believed that only the oxidation of cobalt took place. The main corrosion mechanism was the oxidation of the cobalt binder, which deteriorates the structure of the material in the surface layer.

In addition, the content of element O (Figs. 10a, b, and c) was 2.85 wt.%, 11.51 wt.%, and 14.62 wt.%, respectively. The content of element of Co (Figs. 10a, 10b, and 10c) was 8.86 wt.%, 5.79 wt.%, and 4.63 wt.%, respectively. The content of element of W (Figs. 10a, 10b, and 10c) was 88.29 wt.%, 82.7 wt.%, and 80.75 wt.%, respectively. The content of element O of the tool with a sharpness angle of 45° was the lowest, followed by the tools with sharpness angles of 55° and 65°, respectively. This confirms that both the normal force of the cutting tool and the friction between the worn clearance face and machined surface decreased with decreasing sharpness angle; therefore, the lower sharpness can decrease the effect of oxidation wear on the clearance face.

CONCLUSIONS

1. The nose width and the edge recession increased with increasing feeding length of WFPEC.
2. The wear of the nose width was smallest for the tool with a sharpness angle of 45°, followed by the tools with sharpness angles of 55 and 65°, during the milling process. The wear of the edge recession was higher for the tool with a sharpness angle of 45°, followed by the tools with sharpness angles of 55 and 65°, respectively, during the milling process.
3. The single tool wear parameter did not provide complete information about the shape and geometry of a worn edge.
4. The nose width of the cutting tool increased with increasing sharpness angle during cutting. The edge recession of the cutting tool increased with decreasing sharpness angle during cutting.
5. The nose width increased, the edge recession decreased, and the machined surface roughness increased with increasing sharpness angle after a feeding length of 40 m.
6. The nose width had a positive effect on the machined surface roughness, and the machined surface roughness increased with increasing nose width. The edge recession had a little effect on the machined surface roughness. The clearance face roughness of the worn tool increased with increasing sharpness angle.
7. The wear mechanisms for the cemented tungsten carbide tool included oxidation and abrasion on the clearance face in the tested range during the cutting process. Initially, the binder phase between the tungsten carbide grains was removed by oxidation and mechanical wear, followed by the removal of the tungsten carbide grains from tools by mechanical wear.
8. Thus, a slight wear of the edge recession is gained in exchange for a lower machined surface roughness by decreasing the sharpness angle.

ACKNOWLEDGMENTS

The authors are grateful for the support from the Project Funded by the Priority Academic Program Development of Jiangsu Higher Education Institutions (PAPD), Key Projects in China National Science and Technology Pillar Program during the Twelfth Five-year Plan Period (2012BAD24B01), and Polyplank AB for supplying the samples of WFPEC.

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Article submitted: January 13, 2014; Peer review completed: March 29, 2014; Revised version received and accepted: May 1, 2014; Published: May 6, 2014.