Improved Life of Circular Saws Used in Primary Wood Processing

Maryam Torkghashghaei,[a] William Shaffer,[b] Bruna Ugulino,[c] Rémi Georges,[c]
Roger E. Hernández,[d] and Carl Blais [a],*

The effects of the Engineered Micro-Geometry (EMG) of the carbide teeth of circular saws on their wear rate and resulting sawing variation for 2-time intervals were studied. The objective was to improve the wear resistance of circular saws used during the primary transformation of wood. The tests were carried out under industrial production conditions with two series of circular saws; 1- with up-sharp tips, and 2- with cutting edges honed to adopt a waterfall geometry. The duration of the tests was 255 min and 645 min. Wood studs were sampled to measure sawing variation. Recession on the rake and clearance faces of the tips as well as the width of the wear land were measured. The wear mechanisms of the cutting edges of both types of saws were studied. Chipping and cracking were the two dominant wear mechanisms observed on the up-sharp tips. Saws with waterfall hone tips showed remarkably reduced chipping and cracking. Wear rate of the latter was notably lower than that of saws with up-sharp tips at both periods of sawing. Between-stud, within-stud, and total sawing variations decreased when saws with modified cutting edges were used.

DOI: 10.15376/biores.18.1.2024-2044

Keywords: EMG; Circular saw; Wear; Chipping; Sawing variation

Contact information: a: Department of mining, metallurgical and materials engineering, Université Laval, Quebec City, Canada; b: Conicity Technology Inc, Turtle Creek, PA, USA; c: FPInnovations, Quebec City, QC, Canada; d: Department of wood and forest sciences, Université Laval, Quebec City, Canada
** Corresponding author: carl.blais@gmn.ulaval.ca*

INTRODUCTION

As for many manufacturing sectors, wear control of cutting tools is critical in the wood industry. Indeed, cutting tools suffer damages of fluctuating severity that stem from various tribological phenomena (Naylor and Hackney 2013). These damages contribute to the loss of productivity and product quality (Etele and Magoss 2013). Circular saws are common cutting tools used in the first and second transformation of wood. The performance of saws is mainly related to the wear resistance of their cutting edges. Cutting edges in circular saws used for wood processing are mainly made from tungsten carbide-cobalt (WC-Co) inserts, which are well known for providing superior wear resistance. The level of sharpness of these tips affects the quality of the finished products. Thus, periodic resharpening and/or replacement of carbide tips are required throughout the useful life of circular saws. The amplitude and frequency of such operations have a remarkable effect on production costs, which can be improved by minimizing tool wear (Nasir and Cool 2020). The blunting and wear of cutting tools generally depend on several factors such as tool geometry, cutting parameters (cutting speed, feed speed, *etc.*), and workpiece conditions (wood species, moisture content, temperature, wood density, knottiness, *etc.*) (Geetha and

Jegatheswaran 2010).

Nordström and Bergström (2001) reported that abrasion, localized corrosive attack, chipping, and cracks took place on the cutting edges of swaged saw teeth used in the primary transformation of wood. Abrasion was the prevailing wear mechanism due to the presence of sand particles. As discussed by Bayoumi *et al.* (1988) wood species with acidic content tend to cause chemical or electrochemical reactions, which remove the cobalt binder found in the WC-Co cutting tips. Bailey *et al.* (1983) reported the same results during cutting oak wood.

The high abrasive wear resistance of cemented carbide tools can be attributed to their high hardness (Prakash 1995). However, abrasion, crack, chipping, and fracture can occur, and these wear mechanisms may simultaneously lead to the gradual and/or sudden failure of carbide tools when facing severe loads (Sugihara *et al.* 1979). Some of these mechanisms may play a dominant role, depending on the cutting conditions (Ekevad *et al.* 2012). The sawing process entails intense contact between the cutting edges of the saw and the wood, which leads to increased temperature and stress in primary shear zone (Nordström and Bergström 2001). Additionally, the wear level of the cutting edges has a decisive influence on wood surface finish as well as its geometrical conformance (Ghosh *et al.* 2015). Therefore, optimization of the cutting edge is an important issue that involves the generation of a controlled geometry to minimize the impact of edge defects and micro-chipping that are inherent in all cutting tools (Zhuang *et al.* 2021).

Ventura *et al.* (2017) demonstrated that properly applied edge preparation improves the performance of cutting tools during machining of metals by retarding the onset or reducing the rate of chipping and abrasive wear on their clearance face. In metal cutting, typical cutting edge profiles applied by tool manufacturers are rounded (radius or waterfall hone shapes), chamfered, or a combination of the two (Kandráč *et al.* 2013).

For example, Ventura *et al.* (2015) surveyed the influence of different form factors of chamfers on tool wear performance of CBN tools in interrupted hard turning of metals. They found that a lower form factor resulted in a larger contact length between tool and workpiece which increased the force acting on the tool.

The cutting edges of circular saws used in North American sawmills are typically up-sharp. The lower toughness of up-sharp cutting edges is the root cause of the failure and excessive wear of saws. Several studies have been conducted regarding edge preparation of tools in the metal industry but not in the industry of wood transformation. Therefore, the present work summarizes studies on the effect of Engineered Micro-Geometry applied on the carbide tips of circular saws used in the first transformation of wood with the intent of maximizing their tool life. Comparison of sawing variations and prevailing wear mechanisms of circular saws with up-sharp tips and saws with waterfall hone tips are presented and discussed.

EXPERIMENTAL

The circular saws used in this study consisted of a steel body where carbide tips were brazed on the teeth of the saws. The saw specifications are presented in Table 1.

Table 1. Circular Saw Specifications

Parameters	Value
Saw body material	AISI 8670
Tip material	88% WC and 12% Co
Number of tips	42
Saw diameter (mm)	610
Saw thickness (mm)	2.79
kerf width (mm)	4.14
Wedge angle	52°
Rake angle	30°
Top clearance angle	8°
Radial clearance angle (left and right)	1.1° and 1°
Left side clearance (mm)	0.660
Right side clearance (mm)	0.635
Supplier of the saws: Haskin Industrial Co.	

Following the brazing operations, the carbide tips of each saw were ground by a grinding machine (Vollmer) at the manufacturer. Therefore, after grinding all the faces, the cutting edge of the tips is defined as up-sharp geometry as presented in Fig. 1a. Three brand new commercial circular saws had the geometry of their tips modified at Conicity Technology, PA, USA. The modification was performed by honing the cutting edge of each tip using abrasive filament brushes made of nylon bristles loaded with micrometric natural diamond particles. The prepared cutting edge had waterfall hone profile as illustrated in Fig. 1b.

The dimensions of these profiles on the clearance face ($S\alpha$) and rake face ($S\gamma$) are very important. A form factor $K = 1$ ($K = S\gamma / S\alpha$) defines a symmetrical cutting edge microgeometry, whereas the slope tendency of honing towards rake face ($K > 1$) or clearance face ($K < 1$) are asymmetrical microgeometries (Denkena *et al.* 2011). For metals, the advantages of an asymmetrical honed cutting edge (waterfall hone shape) over a symmetrical one (radius hone shape) in minimizing tool wear were reported in several studies. The new profile developed on the carbide tips of the saws used in this study measured 20 microns on the rake face of the tip ($S\gamma$) and 10 microns on the clearance face ($S\alpha$). The geometry of this profile was selected based on previous work performed internally at Conicity Technology.

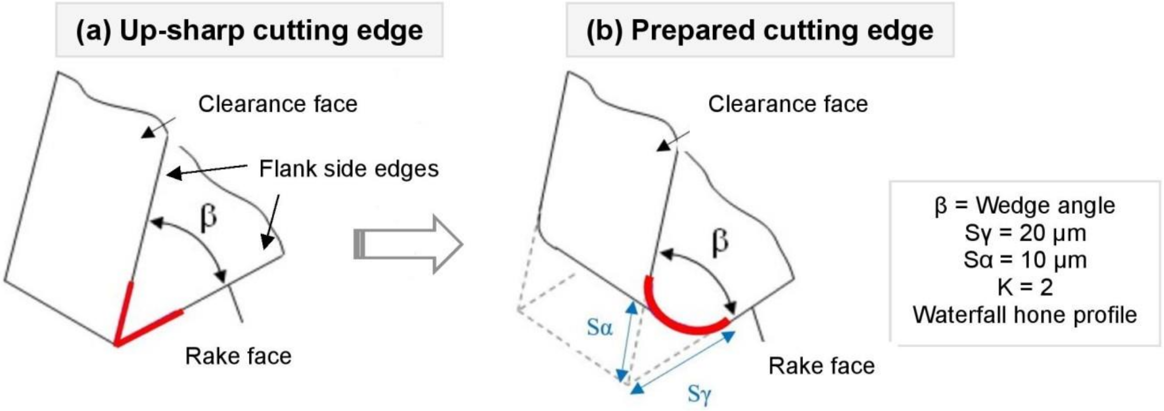

Fig. 1. Schematic representation of the (a) up-sharp cutting edge and (b) prepared cutting edge

To perform wood cutting tests in an industrial mill, six new commercial circular saws were sent to a partnering sawmill located in the Province of Quebec, Canada. Three saws had prepared cutting edges, while the remaining three had up-sharp tips. The industrial wood cutting tests lasted for two different periods of time *i.e*., 255 and 645 min. All saws were mounted on the vertical arbor of the gang saw system (USNR VSS) as shown in Fig. 2. The tests were carried out by sawing cants of black spruce and balsam fir. These types of softwood are currently processed together and are used in similar situations at sawmills across Eastern Canada as they have similar properties.

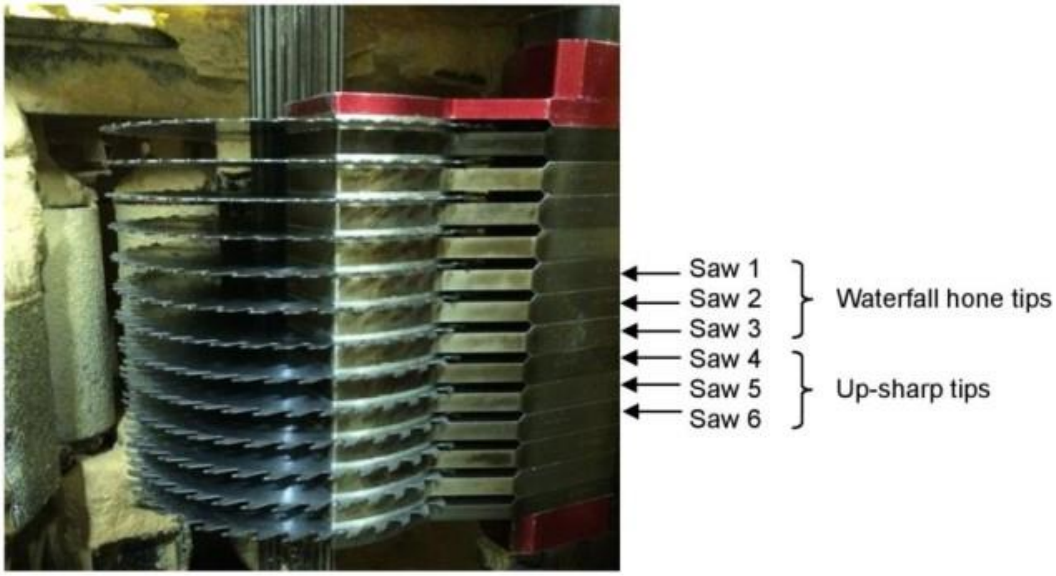

Fig. 2. Image of the arbor of the guided gang saw system used in this study

The first phase of the test involved utilizing the saws in industrial conditions for 255 min of sawing. The rotational speed of the saws and the cutting speed were 2600 rpm and 83 m/s respectively. Owing to that, the feed rates were 145 and 164 m/min for the studs with a width of 152.4 and 101.6 mm, respectively. The feed per tooth was 1.33 and 1.50 mm for the two sizes of studs mentioned. At the start of the test (during 15 min of sawing), 10 studs that were cut between saws 2 and 3 were sampled as well as 10 studs cut between saws 4 and 5. This condition represents a wear level at 0 min for these saws. At the end of the test *i.e*., after 255 min of sawing, studs originating from the same two locations were collected for a total of 20 samples, and this latter condition corresponds to the wear level after 255 min for these saws. The collected studs had a length of 3.65 m, a width of 152.4 mm and a thickness of 50 mm. All 40 specimens along with the six saws were then transferred to Université Laval to measure sawing variations and tool wear.

A large number of parameters have been reported in the literature regarding means of characterizing tool wear and bluntness of the cutting edge including cutting edge recession, recession on the rake and clearance faces, nose width, and edge radius or cutting edge rounding (Geetha and Jegatheswaran 2010; Sheikh-Ahmad and Bailey 1999a).

For saws 1, 2, 5, and 6, quantitative characterization of wear was performed using a Reichert Jung 580 optical microscope, and the images were analyzed using the software Image J 1.53e. As presented in Fig. 3, parameters used to quantify the wear of the tips were the change in recession on the rake face (RR) and clearance face (RC) of all 42 tips, as well as the change in the nose width (NW) representing the width of the wear land (Cristóvão

2013). Moreover, tips from saws 3 and 4 located at the center of the arbor were randomly selected and extracted to characterize their wear in scanning electron microscopy, FEI Inspect S50. Wear was analyzed on the primary cutting edges, rake and clearance faces of the tips. It represented the level of wear after 255 min of sawing at the sawmill.

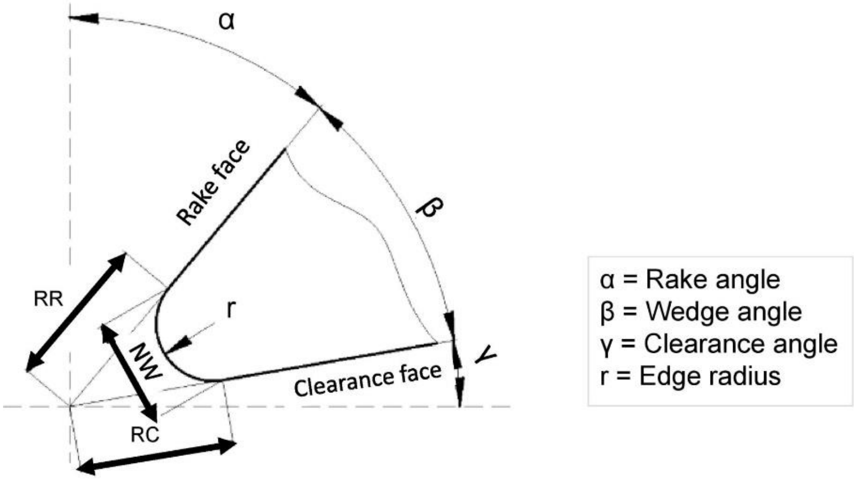

Fig. 3. Parameters used to measure tips wear (Cristóvão 2013).

Sawing variations were characterized by measuring the thickness of each stud with a caliper having a precision ± 0.02 mm at ten evenly spaced locations along each specimen. Since the surfaces that are closer to the drive shaft of the arbor typically show less deviation, it was decided to measure the sawing deviation on the edge of the studs that were furthest from the drive shaft, as in Fig. 4.

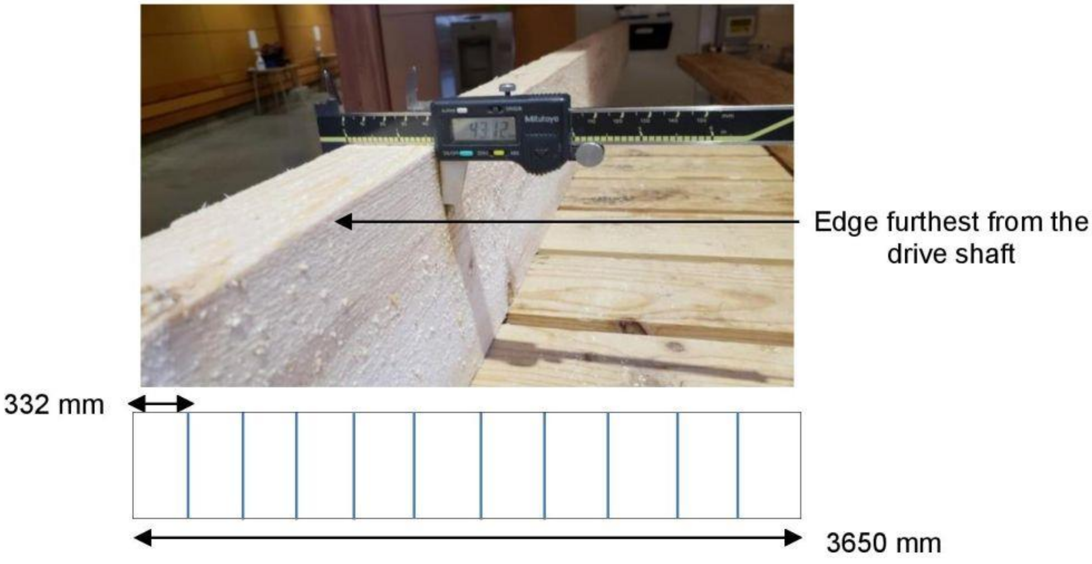

Fig. 4. Measurements of stud thickness at the edge furthest from the drive shaft

Once the measurements on the studs and wear characterization from the first test were completed, saws 1, 2, 5, and 6 were returned to the mill for the second leg of the study. They were mounted on the arbor gang saw system as described in Fig. 2 and were used during a complete work shift of 645 min. Upon completing the tests at the mill, the saws were returned to Université Laval to characterize the wear of the tips in optical and scanning electron microscopy. Wear characterization of the tips after 900 min (15 h) of utilization followed the same procedure as the one described above *i.e*., after 255 min of use.

RESULTS AND DISCUSSION

Wear Rate of Tips

A comparison of wear between the two types of circular saws (saws 1, 2 with waterfall hone tips *vs.* saws 5, 6 with up-sharp tips) *vs.* working time (0 min, 255 min, and 900 min) is shown in Fig. 5. The recession of the rake and clearance faces and the width of the wear land of all saws that were measured before the industrial tests (0 min) are presented in Table 2.

The recession on the rake and clearance faces, and the width of the wear land of circular saws with waterfall hone tips were considerably lower than those of the circular saws with up-sharp tips after 900 min of sawing at the sawmill. For the saws with waterfall hone tips, the initial values at time 0 min presented in Table 2, is due to the modification of their cutting edges according to Fig. 1b.

Table 2. Initial Measurements at 0 min on the Clearance Face, Rake Face, and the Width of the Wear Land of All Saws

Wear Index	(Saws 1,2) Waterfall Honed Tips	(Saws 5,6) Up-sharp Tips
Recession on the clearance face (µm)	10	3
Recession on the rake face (µm)	20	3
Width of the wear land (µm)	17	2

Table 3 presents the average reduction in wear brought about by using saws with waterfall hone tips (saws 1 and 2) compared to saws with up-sharp tips (saws 5 and 6).

The rate of wear on the rake and clearance faces as well as the rate of increase of the wear land are presented in Table 4. As expected, for all saws, the wear rate was more important at the beginning of the test, which corresponds to the break-in period. As the working time increased, the wear rates decreased, reaching values 2 to 3 times lower than rates that prevailed at the beginning of the test. Similarly, the wear rates of the saws with up-sharp tips were 2 to 3 times higher than those of the saws with waterfall hone tips.

Table 3. Average Reduction in Wear after 255 and 900 min of Sawing While Using Saws with Waterfall Hone Tips Compared to Saws with Up-sharp Tips

Wear Index	Reduction in Wear After 255 min of Sawing (%)	Reduction in Wear After 900 min of Sawing (%)
Reduction in recession on clearance face	38	52
Reduction in recession on rake face	36	41
Reduction in width of wear land	38	36

Table 4. Rate of Wear of Saws 1, 2, 5, and 6 as a Function of Working Time

	After 255 min of Utilization (Between 0 and 255 min of Sawing)			**After 645 min of Utilization (Between 255 and 900 min of Sawing)**		
Saw	Rate of wear on clearance face (µm / h)	Rate of wear on rake face (µm / h)	Rate of increase of wear land (µm / h)	Rate of wear on clearance face (µm / h)	Rate of wear on rake face (µm / h)	Rate of increase of wear land (µm / h)
1	11.9	11.2	8.3	3.3	4	6
2	13.3	12.6	9.6	2.6	2.6	2.6
5	23	23.8	19.3	9.3	7.3	7.5
6	23.9	26.4	21.9	8.5	6	5.3

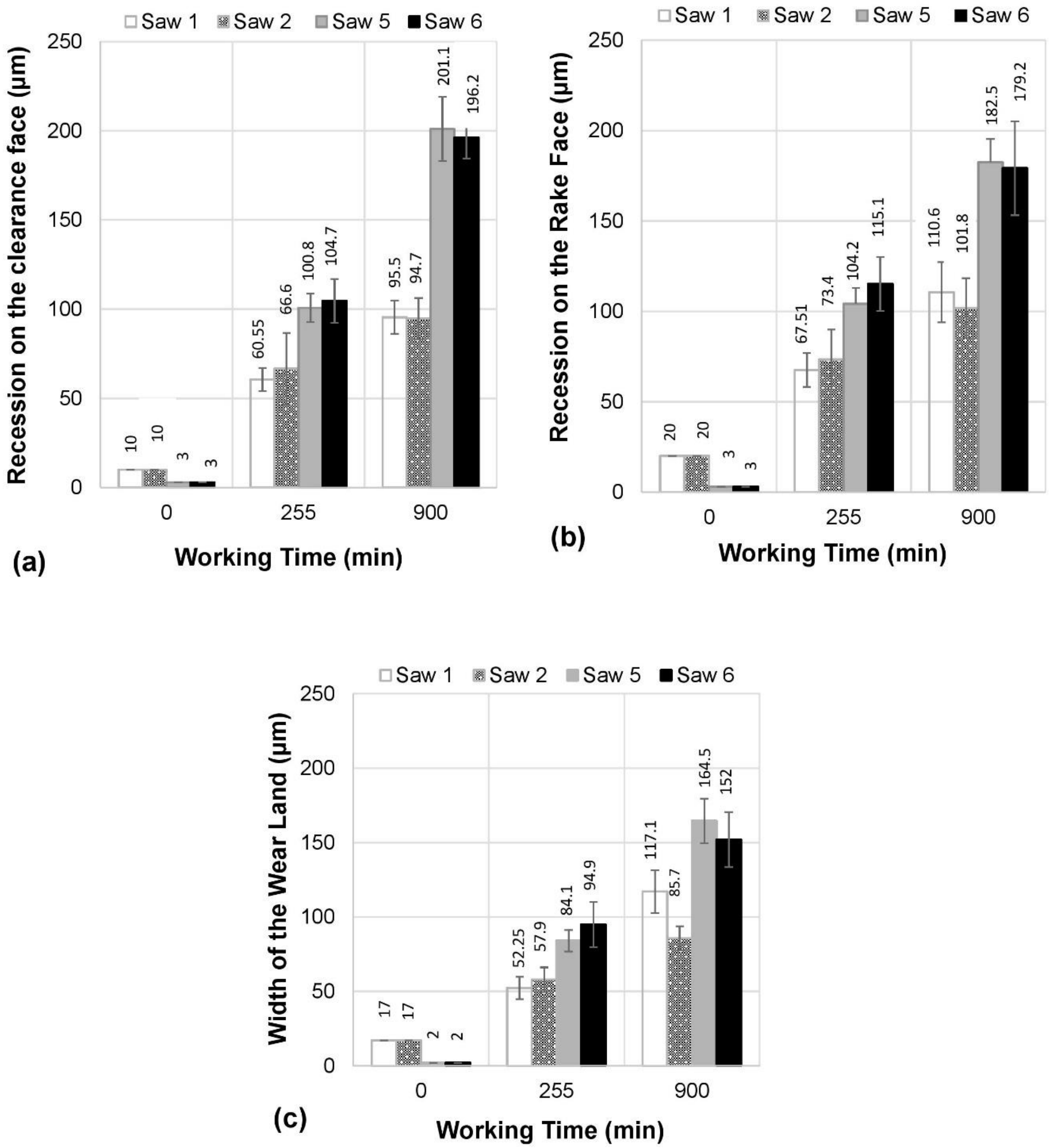

Fig. 5. Average wear of circular saws *vs.* working time: (a) recession on the clearance face, (b) recession on the rake face, and (c) width of the wear land

The results of tips characterization by optical microscopy after 255 and 900 min of sawing are shown in Figs. 6 through 9. The symmetric geometry of the up-sharp tips (Fig. 6a) was converted into an asymmetric one having a slope toward the clearance face (Fig. 6b) or rake face (Fig. 6c). This wear profile was rarely observed in the case of waterfall hone tips (Fig. 7b, c). Most of the up-sharp tips had small and large chippings at their corners after 900 min of sawing (Fig. 8a-c). On the contrary, waterfall hone tips showed notably less chipping (Fig. 9a-c).

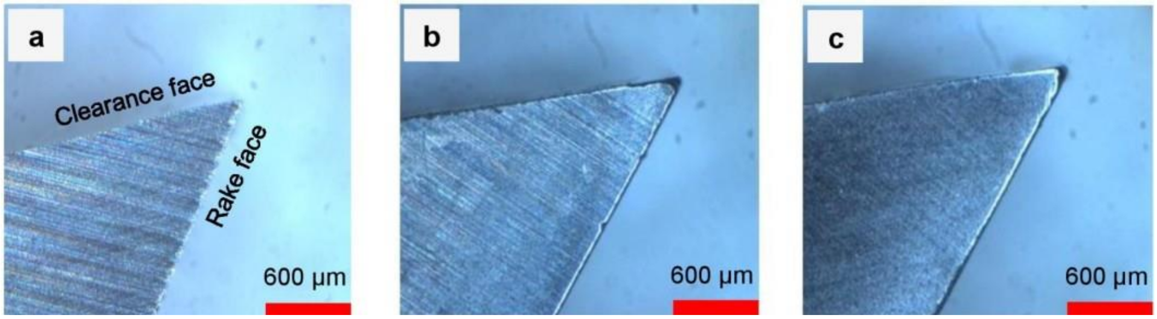

Fig. 6. Optical micrographs of randomly selected up-sharp tips at 60X magnification: (a) non-used tip, (b and c) after 255 min of sawing

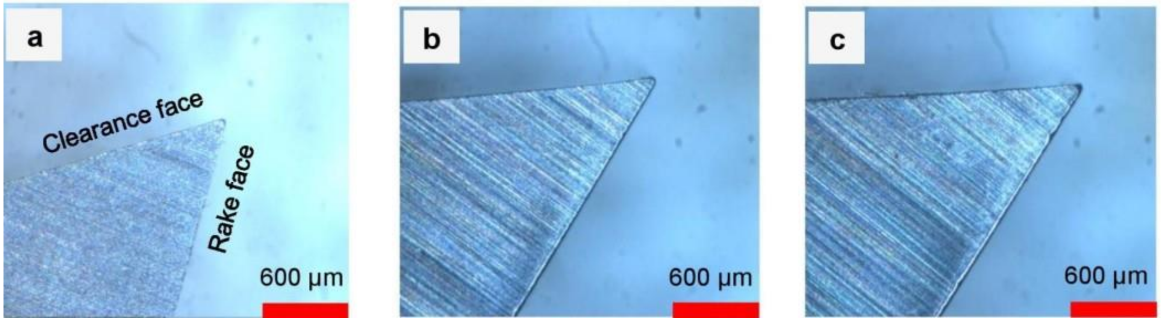

Fig. 7. Optical micrographs of randomly selected waterfall hone tips at 60X magnification: (a) non-used tip, (b and c) after 255 min of sawing

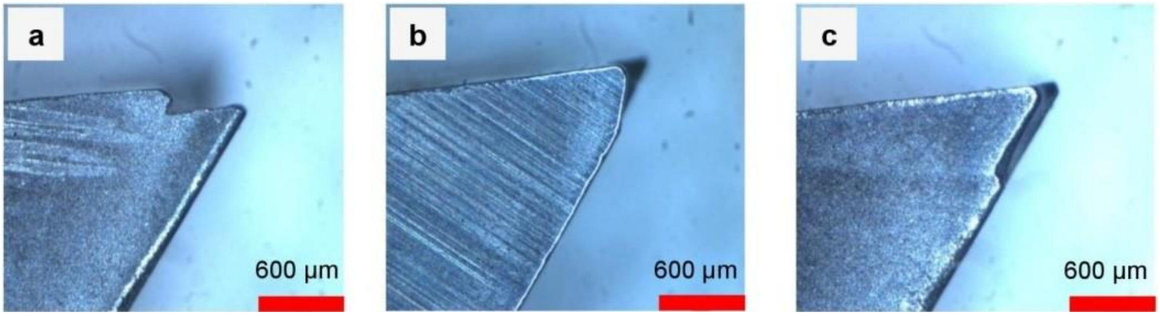

Fig. 8. (a-c) Optical micrographs of randomly selected up-sharp tips after 900 min of sawing at 60X magnification

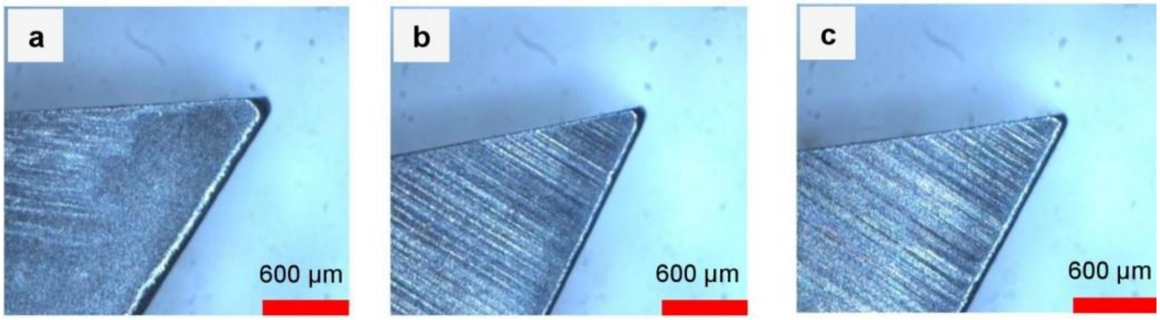

Fig. 9 (a-c) Optical micrographs of randomly selected waterfall hone tips after 900 min of sawing at 60X magnification

Wear Characterization

Analyses of the wear patterns of the tips revealed that their primary cutting edges were no longer straight after the industrial test at the sawmill. Representative SEM micrographs of the cutting edge after 255 and 900 min of working time are presented in Figs. 10 and 11. A comparison of Figs. 10a and b shows that the modified cutting edge was notably less damaged than that of unmodified tips after 255 min of sawing. This difference is even more obvious when comparing the tips tested for 900 min of sawing (Fig. 11a, b).

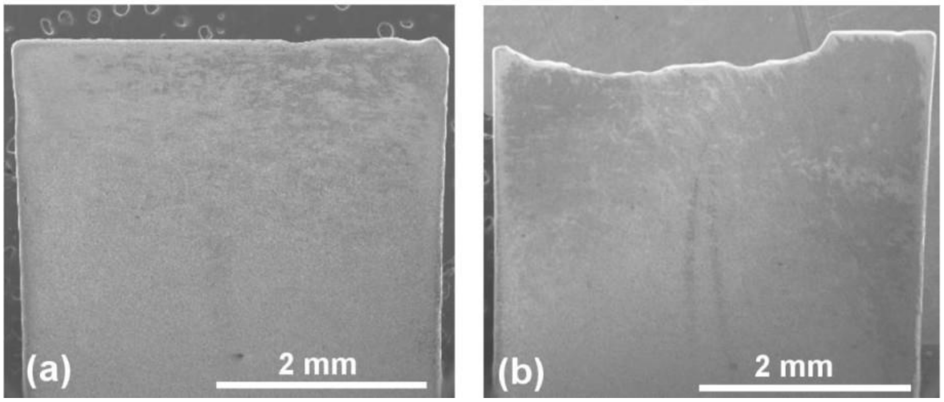

Fig. 10. Typical aspect of the cutting edge of carbide tips (clearance face view) after 255 min of sawing at 70X magnification: (a) with up-sharp tips, and (b) with waterfall hone tips

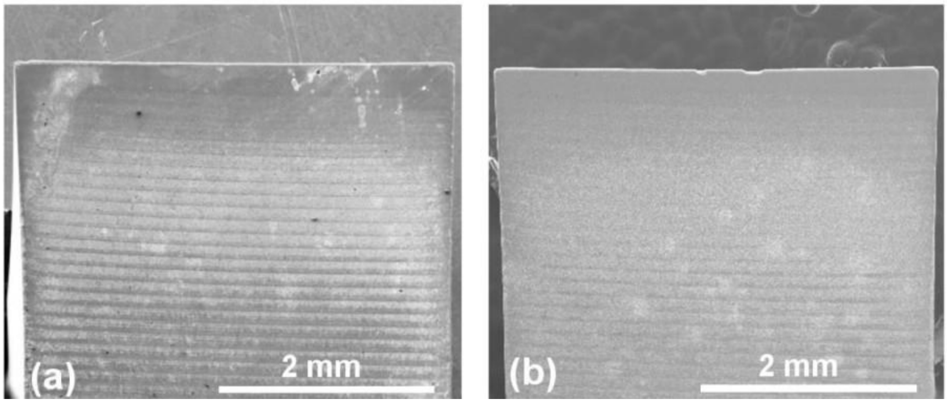

Fig. 11. Typical aspect of the cutting edge of carbide tips (clearance face view) after 900 min of sawing at 70X magnification: (a) with up-sharp tips, and (b) with waterfall hone tips

The SEM micrographs presented in Fig. 12 exhibit different manifestations of wear on the primary cutting edges of the up-sharp tips after 255 min of sawing. Cracking, chipping, and abrasive wear appear to be the main wear mechanisms responsible for the degradation of the cutting edges as seen in Fig. 12a-e. Crack formation is most likely the first mechanism to take place, leading to chipping as cracks grow and merge. Cracking and chipping appear to be more prevalent at the corners of the tips as local tool breakage can be easily observed in those locations. Corner wear or rounding edges were also common on the cutting edge of the carbide tips. The central sections of the cutting edges indicate that chipping and abrasion were the principal wear mechanisms in those locations. Plastic deformation was seen on the primary cutting edges of some tips, as shown in Fig. 12f.

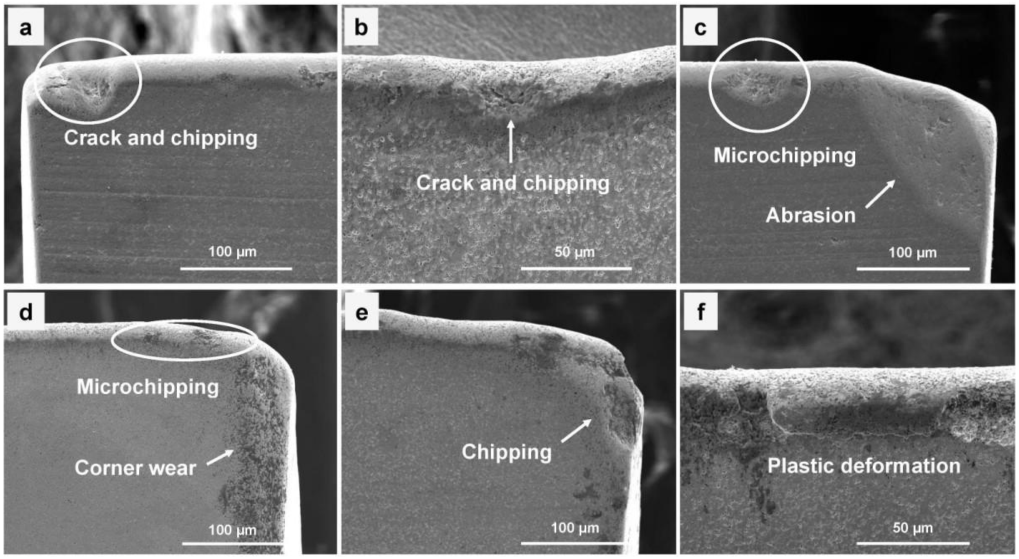

Fig. 12. SEM micrographs of the cutting edges of the up-sharp tips (clearance face view) after 255 min of sawing at 50X and 100X magnifications: (a, b) crack and chipping, (c) abrasion and microchipping, (d, e) microchipping and corner wear, and (f) plastic deformation

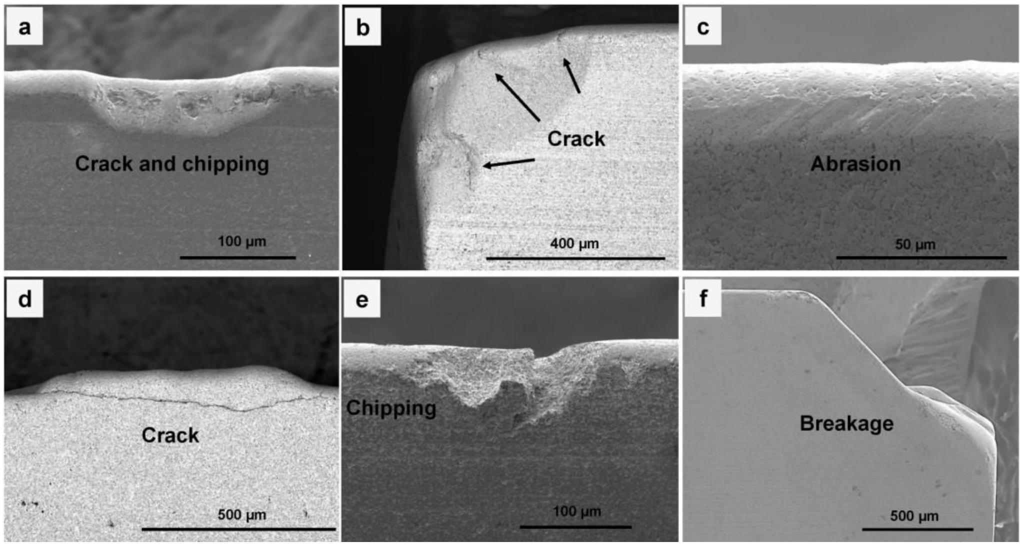

Fig. 13. SEM images of the cutting edges of the up-sharp tips (clearance face view) after 900 min of sawing at 50X-500X magnifications: (a, b) crack and chipping, (c) abrasion, (d) crack, (e) chipping, and (f) breakage

Typical SEM micrographs of unmodified tips used during 900 min of sawing are shown in Fig. 13. The wear mechanisms are identical to those observed for the same tips after 255 min (Fig. 12). Cracking, chipping, and abrasive wear were the principal wear mechanisms involved as seen in Fig. 13a-e. Fig. 13d shows a crack parallel to the cutting edge that is the product of impact wear followed by a chip on the primary cutting edge of the tip. Edge chipping was the dominant failure mode after 900 min of sawing (Fig. 13e). The corners of the tips (Fig. 13f) sustained substantial local breakage, once again highlighting the weakness in the strength of this area of the cutting tools.

Typical SEM micrographs of modified tips are presented in Fig. 14. By comparing the micrographs of Fig. 14 with those of Fig. 12 and 13, the wear manifestations for the waterfall hone tips were notably less severe than that of the up-sharp tips. EMG edge preparation considerably reduced the tendency of the carbide tips to chip. For modified edges, the main wear mechanism involved was abrasive wear after 900 min of sawing (Fig. 14f). However, the abraded areas are less compared to those observed for unmodified edges (Fig. 12c, 13c).

Crack formation and propagation were markedly reduced, resulting in a much lower volume fraction of chipping of the primary cutting edges. Furthermore, corner strength was distinctly increased by the honing process to a point where none of the tips characterized showed localized corner breakage after 900 min of sawing. The latter observation certainly constitutes the most important contribution of edge preparation to the improvement of the wear resistance of circular saws used in the wood industry.

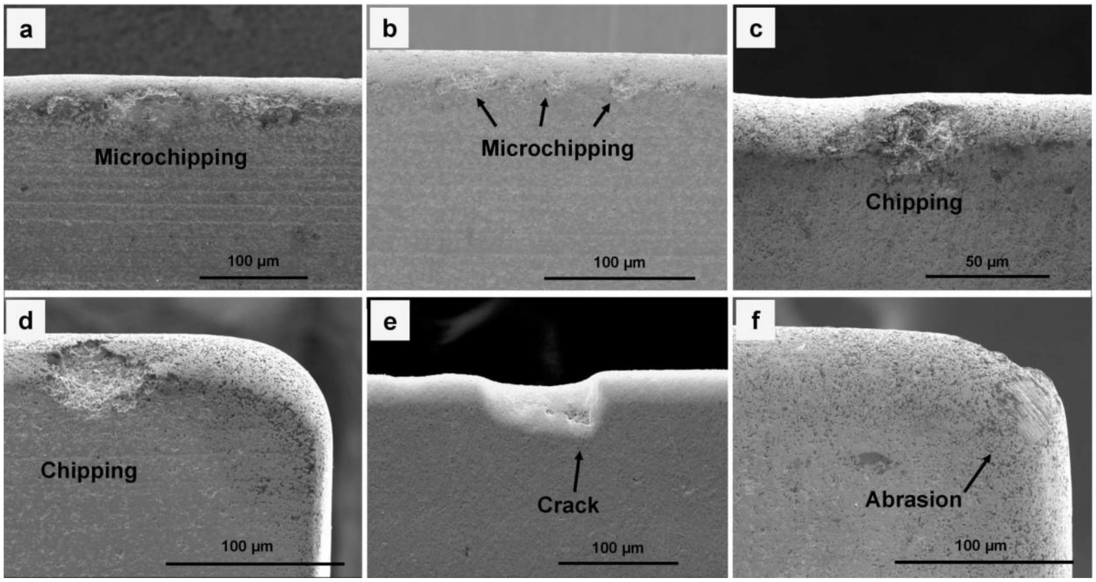

Fig. 14. SEM micrographs of the cutting edges of the waterfall hone tips (clearance face view) at 900X-2000X magnifications: (a, b) microchipping after 255 min of sawing, (c, d) chipping after 255 min and 900 min of sawing respectively, (e) crack after 900 min of sawing, and (f) abrasion after 900 min of sawing

The different types of wear manifestations on the clearance faces of the unmodified tips after 255 min and 900 min of sawing are presented in Fig. 15. As it could be expected from the results shown in Fig. 12 and 13, cracking and abrasion were the principal causes of wear. They mainly took place at the corners of the tips as shown in Fig. 15a, 15b. Transgranular and intergranular cracking was also visible in some of the carbide grains located on the clearance face, especially near the cutting edge and corners, such as those circled in Fig. 15c. Disarrangement in the microstructure of the WC-Co matrix is due to intergranular cracks that resulted in WC particles being pulled out. Transgranular cracking caused grain crushing as seen in Fig. 15d. Fragments of carbide grains were mostly present in the vicinity of the cutting edge as well as at the corners. Figure 15e shows the worn surface on the clearance face of the tip that presents a rough surface. This was due to the loss of a remarkable volume of the Co-matrix that facilitates debonding and pull-out of carbide grains (Fig. 14f). It is also evident that most grains on the worn surfaces lost their angular appearances forming smoother surfaces, as shown in Fig. 15f.

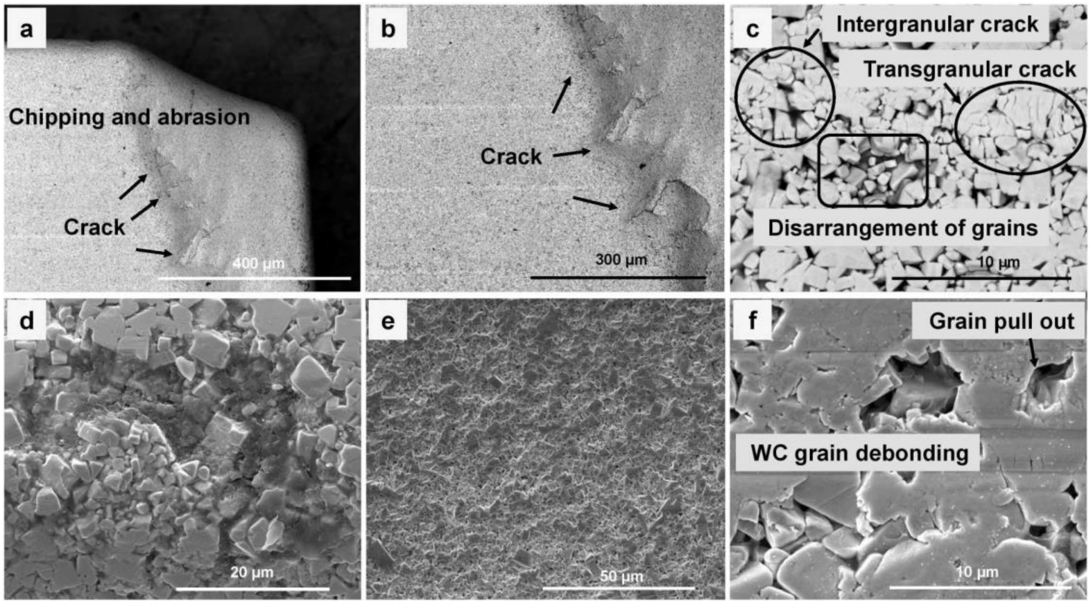

Fig. 15. SEM micrographs of the clearance face of the up-sharp tips at 400X-15000X magnifications: (a, b) chipping, abrasion, and crack, (c) crack in grains, (d) crushed grains, (e) worn surface, and (f) grain debonding and pull out

The micrographs of Figs. 16a-e illustrate the different types of wear on the rake face of the up-sharp tips after 255 min and 900 min of sawing. Wear manifestations were very similar to those seen on the clearance face of tips from the same series of specimens (ref. Fig. 15). The rake face of most tips, such as those presented in Figs. 16a-c, experienced cratering due to abrasive wear. It was mostly located closer to the corners of the tips. Crushed WC grains, cobalt binder removal, carbide grains pull-out, as well as abraded surfaces were also common on the rake face mainly near the cutting edges and the corners (Fig. 16e). Softening of cobalt binder occurred due to severe heat generation, which was followed by crushing of WC grains because of continuous shock owing to interrupted cutting and ultimately grain fall out.

As stated by Sheikh-Ahmad and Bailey (1999), the temperature gradient near the cutting edge of the tool during wood machining depends on several parameters including cutting speed, depth of cut, feed rate, wood temperature, and type of wood. Cristóvão (2013) and Guo *et al.* (2014) demonstrated that during wood cutting, the synergetic interaction between mechanical wear and heat generation, mostly frictional heat, were the principal reasons for the partial extrusion of the cobalt binder, followed by removal of the carbide grains. Chipping and cracking were also visible on the rake faces of some tips, particularly close to the corners as shown in Figs. 16d and f.

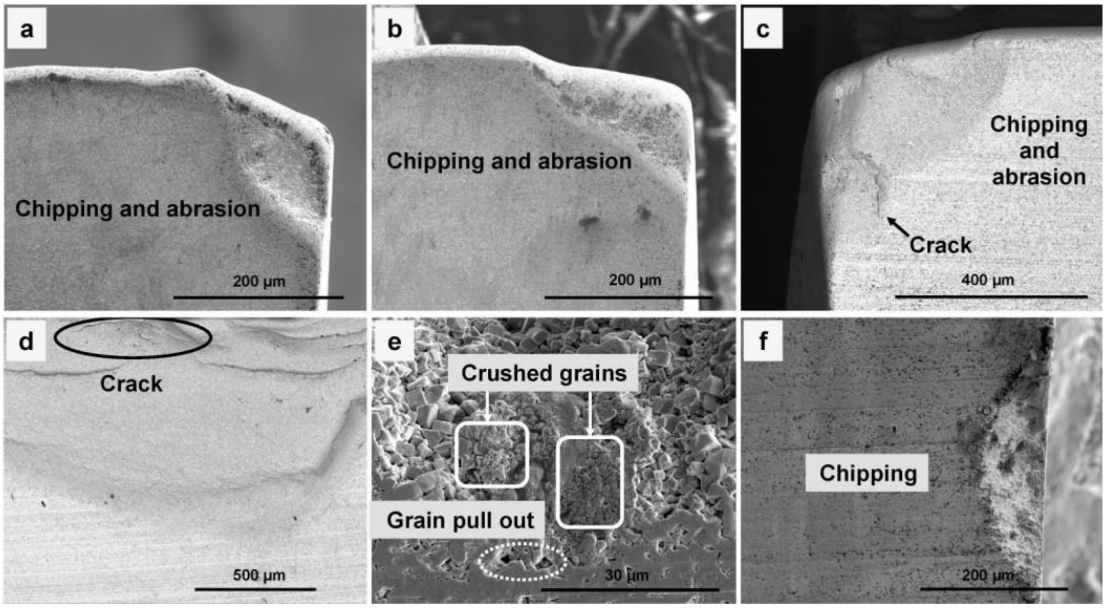

Fig. 16. SEM micrographs of the rake face of the up-sharp tips at 200X-5000X magnifications: (a, b, and c) chipping and abrasion, (c, d) crack (e) crushed and pulled out grains, and (f) chipping

The types of wear on the rake and clearance faces of the waterfall hone tips after 255 min and 900 min of sawing are shown in Figs. 17a to f. Limited localized removal of cobalt binder and a few cracks in the binder phase took place on the rake face (Fig. 17a). Moreover, the clearance face of some tips, such as the one shown in Fig. 17b, had few particles pulled out due to cobalt extraction, particularly near the corners.

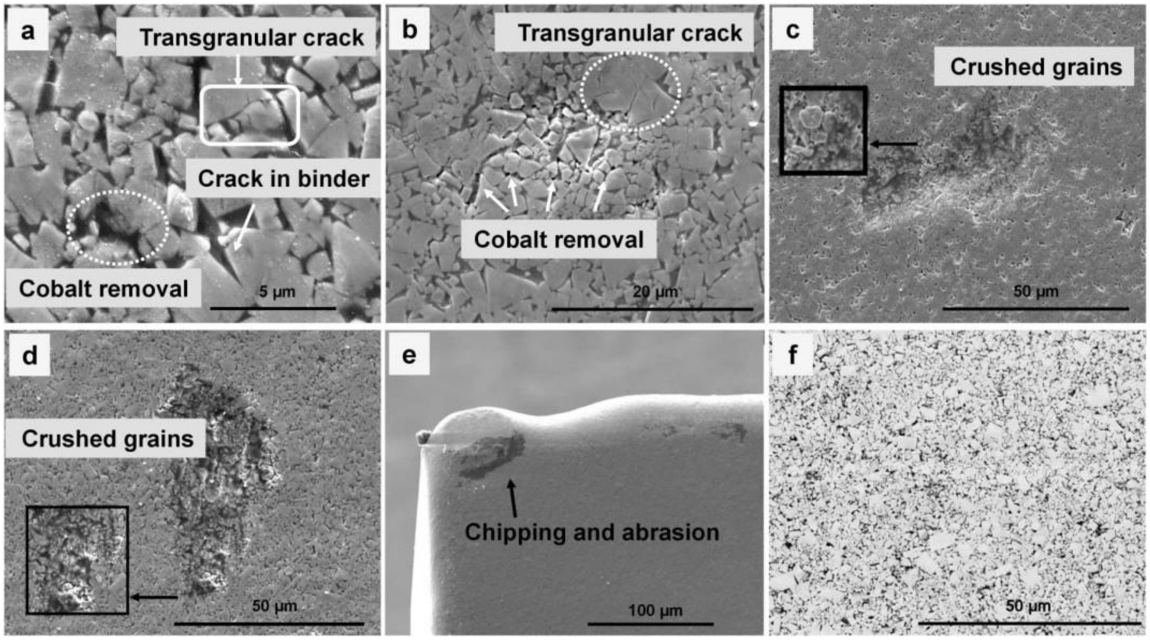

Fig. 17. SEM micrographs of the waterfall hone tips at 1000X-20000X magnifications: (a, b) crack and binder removal on the rake and clearance faces, (c, d) worn surface on the rake and clearance faces, (e) chipping and abrasion on the clearance face, and (f) appearance of the clearance face

According to Figs. 17a and b, few transgranular cracks in WC grains were present on both faces. In addition, according to Figs. 17c and d, the appearance of the worn surfaces on the rake and clearance faces were dissimilar to that of up-sharp tips (ref. Fig. 17e, 16e). Indeed, there were fewer fragmented carbide grains on both faces of the waterfall hone tips, and most regions on these faces near the cutting edges and the corners remained intact. Wear on the clearance face was not observed after 255 min of sawing. However, a few tips experienced wear on a small area of the clearance faces after 900 min of sawing.

As can be seen in Fig. 17e, chipping and abrasion took place near the corner on the tip clearance face. Reduction of wear on this face should allow the saw to cut straight for a much longer period of time and enable the blade to continue operating efficiently. Additionally, as shown in Figs. 17a, b, and f, the majority of carbide grains observed on the rake and clearance faces of the latter series of specimens kept their angular appearances, and few grains had rounded edges and smooth or flat surfaces, as opposed to what was reported for the up-sharp tips (ref. Fig. 15f). This is most likely the reason why cratering was not visible on the surfaces of the waterfall hone tips.

Sawing Variation

The sawing variation for the two series of circular saws as a function of time 0 min (start of sawing) and 255 min of sawing are shown in Table 5. Saws with waterfall hone tips yielded lower sawing variations than saws with up-sharp tips. At the beginning of sawing (0 min), the between-stud and within-stud sawing variations of the formers decreased by 47% and 28% respectively compared to the other saws. Similarly, after 255 min of sawing between-stud and within-stud sawing, variations were reduced by 36% and 38% respectively using saws with waterfall hone tips. Accordingly, the modified saws gave rise to lower total sawing variation.

Table 5. Sawing Variations of Stud Obtained by the Two Types of Circular Saws

	Sawing Variation at 0 min (mm) *			**Sawing Variation at 255 min (mm)**		
	Total Variation	**Between-stud Variation**	**Within-stud Variation**	**Total Variation**	**Between-stud Variation**	**Within-stud Variation**
Saws (Up-sharp tips)	0.65	0.49	0.47	0.74	0.53	0.58
Saws (Waterfall hone tips)	0.40	0.26	0.34	0.48	0.34	0.36
Reduction of sawing variation (%)	38	47	28	35	36	38
* Standard deviation of the stud thickness						

Results of the evaluation of wear presented in Fig. 5 and Tables 3 and 4 show that circular saws with waterfall hone tips performed much better compared to those with up-sharp tips. Edge preparation adds corner strength and slows down the rounding and breakage of the primary cutting edge. As presented by Jug *et al.* (2017) in sawing beech and oak wood, a larger cutting edge radius or wider wear land increases the cutting energy, resulting in higher temperature at the cutting edges of the tips. During sawing, the rake face of the tip receives a higher chip load while the saw enters the wood. For the saws with waterfall hone tips, the size of edge preparation on the rake face (20 µm) was large enough to withstand the shock of interrupted cutting. Additionally, the smaller edge preparation on the clearance face (10 µm) keeps the saws from rubbing the workpiece, thus reducing frictional heat. Based on the results of wear rate presented in Table 4, the modified saw could potentially continue sawing up to 960 min (16 h) before reaching the same value of wear as the saw with up-sharp tips after 900 min of sawing. Additionally, since most of the up-sharp tips sustained severe chipping, cracking, abrasion, and plastic deformation after 900 min of sawing (ref. Figs. 6 to 17), the unmodified saws would require replacement of tips that were too severely damaged followed by regrinding prior to becoming reusable beyond 900 min of utilization. According to the results shown in Table 4 and the calculation presented above, it can be expected that the interval between resharpening could be extended by at least 12 h or one extra work shift. This results in a 100% increase in the useful life of the saw, leading to considerable savings in maintenance and production costs.

As can be seen in Figs. 6 to 11, saws with up-sharp tips suffered chipping and breakage at the primary cutting edges and at the corners. Up-sharp edges involve increased stress concentration, particularly in the vicinity of the cutting edge. It has been found that stress concentration can be the cause of chipping and early breakdown of the cutting edge (Rodríguez 2009). Furthermore, the presence of knots in wood is another influential factor in the occurrence of chipping and breakage on the up-sharp cutting edges (Ko *et al.* 1999). Cáceres *et al.* (2018) showed that, on average, knots are 2.4 times more dense than clear wood. Therefore, when a cutting edge moves from clear wood and hits a knot, the forces applied on the cutting tools increase abruptly over a very short period of time, similar to shock loading. For example, during cutting of white spruce, the forces when cutting through knots were approximately eight times higher compared to clear wood. The reason was attributed to higher density of knots and the change in cutting direction from 90°-0° in clear wood to approximately 90°-90° in a knot (Aknouche *et al.* 2009). According to Ghosh *et al.* (2015), canting and chipping knives typically cut knots in 90°-90° and 0°-90° directions, respectively, during the first transformation of black spruce logs. This situation was the main reason for the higher rate of edge recession measured on canting knives. The results summarized above show that EMG strengthens the cutting edge and the corners of carbide tips. This is a principal reason for the reduction of chipping after 900 min of sawing as shown in Figs. 7, 9, 10b, and 11b. Moreover, EMG mitigates typical edge defects such as microfractures, irregularities, and poor surface finish, leading to higher geometrical precision and improved cutting performances (Shaffer 2004).

As reported previously, crack formation was one of the most prevailing manifestations of wear after 255 min and 900 min of sawing when considering the unmodified saws (ref. Fig. 12a, b and Fig. 13a, b, d). It is well known that cyclic loading during interrupted cutting leads to the initiation of cracks (Ghosh et al. 2015; Nordström and Bergström 2001). When the primary cutting edge is up-sharp, the resultant cutting force remains essentially perpendicular to it, allowing loading conditions that promote cracking.

Some cracks were deeper after 900 min of sawing, such as the one presented in Fig. 13d, as the cutting edge could not support as efficiently the cutting forces any longer. The micrograph of Fig. 12f shows that the cutting edge sustained plastic deformation. This manifestation is most likely due to a localized temperature increase brought about by remarkable heat build-up between the up-sharp tip and the wood fibers being cut. This observation also points to the likelihood that the crack formation observed in Figs. 12a, and b and Figs. 13a, b, and d was exacerbated by thermal cycling. This situation combined with the cyclic nature of the cutting force during sawing resulted in crack initiation and propagation, explaining the substantial level of chipping on the up-sharp cutting edges (Fig. 12c-e and Fig. 13e). These failures have detrimental effects on sawing stability as well as cutting accuracy.

Orlowski *et al.* (2020) also reported that the quality of the cutting edge has a substantial impact on sawing accuracy. Indeed, accelerated wear leads to chipping of the primary cutting edge, reducing the saw's ability to cut the wood fibers. Therefore, the pressure on the cutting edge increases with increasing wear, leading to an intensification of spring-back of the freshly cut wood surfaces within the kerf. The effect of the spring-back means that the wood expands and contacts the sides of the cutting tips. In other words, the saw starts rubbing the spring back layer of the workpiece, creating frictional heat. In sawing processes, this is one of the main sources of heat (Lehmann 2007; Mohammadpanah and Lehmann 2019). On top of that, the spring-back in wood progressively increases as the primary cutting edge of the tip wears and it is well established that an increase in the saw temperature negatively affects sawing variation (Danielson and Schajer 1993).

The modified saws showed better performance in terms of sawing variation, as presented in Table 5. Utilization of the latter saws led to a decrease of between-stud and within-stud sawing variations of 36% and 38%, respectively, after 255 min of sawing. The total variation decreased by 35% as well. The reason for this improvement is attributed to mitigating the chipping issues in the corner areas of the cutting edges and minimizing wear rate. As the primary cutting edges of the tips are modified, edge chipping, corner wear (edge rounding), and breakage are markedly reduced as a result of edge strengthening (Shaffer 2004). Therefore, it minimizes the build-up of pressure at the tip and at the same time delays the increase of spring back in the wood. This situation gives rise to less frictional heat and an increase in cutting efficiency and precision.

To compensate for sawing variation, warping, planing, dimensional changes, and deformations in sawn wood caused by shrinkage after drying, margins are applied to nominal lumber dimensions. The green thickness or width of lumber is targeted from all these components. Sawmills seek to reduce their lumber target size in order to decrease the cost of raw materials (Axelsson and Fredriksson 2017; Lundgren *et al.* 2011). Maness and Lin (1995) showed that reduction in lumber target sizes in the sawing stage substantially increased volume yield and sawmill profit. According to Young *et al.* (2007), reduction in target size at 3 different sawmills resulted in increased lumber recovery ranging from 0.2 percent to 1.6 percent annually. The results presented in Table 5 clearly demonstrate that EMG can allow reducing the green target sizes, thereby helping to lower costs, increase productivity as well as sawmill revenues accordingly.

Abrasion is the most common type of tool wear in the wood cutting process (Sheikh-Ahmad and Bailey 1999b). However, characterization of the cutting edges of the modified saw tips shows the efficiency of edge preparation in delaying the onset of abrasive wear compared to unmodified saws.

The worn up-sharp tips showed that abrasive wear was most intense on the primary cutting edges and at corners after 255 min and 900 min of sawing (Fig. 12, 13). This can be attributed to the movement of chips over the rake face of the tips as well as the frictional heat generated at the wood-tip interface. Additionally, chipping, abrasion, and severe cracking on the clearance face of the up-sharp tips (Fig. 15a, b) undoubtedly have detrimental effects on sawing efficiency. The primary cutting edge encounters the highest chip load during sawing. As it becomes dull, the corner radius increases. This condition promotes an increase in the ploughing area in front of the tip, which increases cutting forces and frictional heat (Padmakumar and Shiva Pradeep 2020), and this is the root cause of all failures on the clearance face of the up-sharp tips. On the contrary, the modified tips experienced fewer occurrences of chipping and abrasion on the clearance face as shown in Fig. 17e.

Particularly, in waterfall hone edge preparation, the size and shape of the edge preparations were varied along the corner radius of the tips which minimizes edge chipping. On top of that, variable edge preparation reduces the heat built-up of the cutting tool (Sima *et al.* 2011), as the flank side edges of the tips remain sharp to cut the spring back wood, thereby reducing ploughing action. This is a key factor in retarding the wear on the clearance face of the tips. These results are quite promising, with remarkably less damage on the clearance faces of the waterfall hone tips, which lowers sawing variation (ref. Table 5) and eases chip flow on the rake face. Regarding the latter, it also explains why abrasion and chipping were not observed on the rake faces of the modified tips. Karpat and Özel (2008) also stated that the oval-geometry of waterfall hone edge preparation facilitates the flow of workpiece material in front of the cutting edge.

On the other hand, these wear manifestations were predominant on the rake face of most up-sharp tips characterized. Cratering arises from the frictional heat developed by abrasive wear. It is caused by the synergetic effect of frictional heat on the clearance face and the abrasive action of chips over the rake face. According to Fig. 16a-c, cratering is located closer to the corner of the tool. It is the first location where the tip begins rubbing, thus the level of heat and friction is concentrated in this area. As crater wear gets deeper, the chips exert more pressure on the rake face of the tip, thereby expanding the size of the crater.

Cracks on the rake face, as shown in Figs. 16c and 16d, were probably caused by heat build-up on this face and was the cause of the chipping, as can be seen in Fig. 16f. The evidence of transgranular and intergranular cracks (Fig. 15c) explains the disarrangement in the microstructure of the WC-Co, fragmentation of carbide grains, and WC particles release from the matrix. During wood machining, strongly fluctuating forces are generated at the tool-workpiece interface. As a result of these forces, combined with the frictional force on the rake and clearance faces, WC-grains start oscillating. This condition leads to a partial extrusion of the cobalt binder and cracking across the grains, which is followed by grains falling out from the matrix (Sacks 2003; Ndlovu 2009).

According to Figs. 15 and 16, carbide grains are fragmented and chipped, giving the impression that the majority of the cracking was transgranular. The evidence of reduced extrusion of Co binder from the matrix, fewer grain cracks, as well as reduced grain fragmentation as presented in Figs. 17a to d is explained by the strengthening of the cutting edge. This reduces heat generation on the rake and clearance faces of the tips with waterfall hone edge preparation.

CONCLUSIONS

1. The wear rates on rake and clearance faces and the rate of increase of wear land of saws with waterfall hone tips were 2 to 3 times lower than those of the saws with up-sharp tips at both periods of sawing.

2. Cracking and chipping were the main wear mechanisms responsible for the degradation of the cutting edges and corners of saws with up-sharp tips after 255 and 900 min of sawing. Abrasive wear and plastic deformation were also observed but to a lesser extent.
3. Saws with waterfall hone tips showed remarkably less chipping, cracks, and abrasion on their cutting edges and corners after both periods of sawing.
4. The results showed that Engineered Micro-Geometry (EMG) applied to the cutting edges of carbide tips increases their useful life by 100%.
5. The lapse of time where saws require tip replacement and resharpening could be extended by an additional 12 h. In other words, under normal industrial conditions, the saw with waterfall hone tips could efficiently operate 24 h without the need for resharpening instead of 11 h as it is currently the case in a typical North American sawmill.
6. Saws with waterfall hone tips showed better performances in terms of sawing variation. At the beginning of sawing, between-stud and within-stud sawing variations as well as total sawing variation were reduced by 47%, 28% and 38%, respectively, when saws with waterfall hone tips were used. Those values reached 36%, 38%, and 35%, after 255 min of sawing.
7. The effect of waterfall hone edge preparation on the surface quality of black spruce and balsam fir was investigated as well and is yet to be published.
8. More studies need to be carried out under different conditions including season of the year, wood supply, cutting parameters, grade, composition of carbide tips, *etc.* to corroborate the level of improvement in the useful life of circular saws.

ACKNOWLEDGEMENTS

The financial support for this project was provided by Natural Sciences and Engineering Research Council of Canada (NSERC) and FPInnovations through a Cooperative Research and Development grant (project #CRDPJ-518967-17). The authors hereby thank Daniel Marcotte, Simon Paradis-Boies, Antoine Henry, Élie Landry and Suzie Côté for their technical assistance. Thanks to Bruce Lehmann from FPInnovations for his guidance. The authors would also like to thank Bois Daaquam Sawmill (Division St-Pamphile) as an industry participant for their valuable cooperation.

REFERENCES CITED

Aknouche, H., Outahyon, A., Nouveau, C., Marchal, R., Zerizer, A., and Butaud J. C. (2009). "Tool wear effect on cutting forces: In routing process of Aleppo pine wood," *J. Mater. Process. Technol.* 209 (6), 2918-2922. DOI: 10.1016/j.jmatprotec.2008.06.062

Axelsson, A., and Fredriksson M. (2017). "Potential for increasing volume yield by reducing planing allowance," *Wood Mater. Sci. Eng.* 12(5), 301-306. DOI: 10.1080/17480272.2016.1262448

Bailey, J. A., Bayoumi, A. M., and Stewart J. S. (1983). "Wear of some cemented tungsten carbide tools in machining oak," *Wear* 85 (1), 69-79. DOI: 10.1016/0043-1648(83)90336-8

Bayoumi, A. M., Stewart, J., and Baily, J. A. (1988). "The effects of cemented carbide-binder composition on tool wear encountered in surfacing green lumber," *Wood Fiber Sci.* 20 (4), 457-476.

Cáceres, C. B., Uliana, L., and Hernández, R. E. (2018). "Orthogonal cutting study of wood and knots of white spruce," *Wood Fiber Sci.* 50 (1), 55-65. DOI: 10.22382/wfs-2018-006

Cristóvão, L. (2013). *Machining Properties of Wood: Tool Wear, Cutting Force and Tensioning of Blades*, Ph.D. Thesis, Luleå University of Technology, Luleå, Sweden.

Cristóvão, L., Ekevad, M. and Grönlund, A. (2013). "Industrial sawing of pinus sylvestris L.: power consumption," *BioResources* 8(4), 6044-6053. DOI: 10.15376/biores.8.4.6044-6053

Danielson, J. D., and Schajer, G. S. (1993). "Saw blade heating and vibration behavior in a circular gang edger," *Proc. Saw Tech 93*, 117-136.

Denkena, B., Lucas, A., and Bassett, E. (2011). "Effects of the cutting edge microgeometry on tool wear and its thermo-mechanical load," *CIRP Ann. - Manuf. Technol.* 60 (1), 73-76. DOI: 10.1016/j.cirp.2011.03.098

Ekevad, M., Cristóvão, L., and Marklund, B. (2012). "Wear of teeth of circular saw blades," *Wood Mater. Sci. Eng.* 7 (3), 150-153. DOI: 10.1080/17480272.2012.669405

Etele, C., and Magoss, E. (2013). *Mechanics of Wood Machining,* University of West Hungary Publisher, Sopron, Hungary.

Geetha, R., and Jegatheswaran, R. (2010). "A review of cemented tungsten carbide tool wear during wood cutting processes," *J. Appl. Sci.* 10 (22), 2799-2804. DOI: 10.3923/jas.2010.2799.2804

Ghosh, S. C., Heidari, M., Hernández, R. E., and Blais, C. (2015). "Patterns of knife edge recession in an industrial chipper-canter," *For. Prod. J.* 65 (7-8), 358-364. DOI: 10.13073/fpj-d-14-00057

Guo, X., Ekevad, M., Grönlund, A., Marklund, B., and Cao, P. (2014). "Tool wear and machined surface roughness during wood flour/polyethylene composite peripheral upmilling using cemented tungsten carbide tools," *BioResources* 9 (3), 3779-3791. DOI: 10.15376/biores.9.3.3779-3791

Jug, M., Lučić, R. B., Čavlović, A. O., and Šafrana, B. (2017). "Effect of feed speed on bluntness and warming of circular saw in sawing beech and oak wood," in: *23rd International Wood Machining Seminar Proceedings*, Warsaw, Poland, pp. 240-249.

Kandráč, L., Maňková, I., and Vrabeľ, M. (2013). "Cutting edge preparation in machining processes," *Zesz. Nauk. Politech. Rzesz. Mech.* 30 (85), 149-159. DOI: 10.7862/rm.2013.14

Karpat, Y., and Özel, T. (2008). "Mechanics of high speed cutting with curvilinear edge tools," *Int. J. Mach. Tools Manuf.* 48 (2), 195-208. DOI: 10.1016/j.ijmachtools.2007.08.015

Ko, P. L., Hawthorne, H. M., and Andiappan, J. (1999). *Wear Processes in Wood Manufacturing,* ASTM Special Technical Publisher, USA.

Lehmann, B. (2007). "Heating and cooling of circular saws," in: *18th International Wood Machining Seminar,* Vancouver, Canada, pp. 1-12.

Lundgren, N., Ekevad, M., and Flodin, J. (2011). "Choosing green sawing dimensions for Norway spruce from stochastic simulations," *J. Wood Sci.* 57 (2), 94-99. DOI:

10.1007/s10086-010-1142-1

Maness, T. C., and Lin, Y. Z. (1995). “The influence of sawkerf and target size reductions on sawmill revenue and volume recovery,” *For. Prod. J.* 45 (11-12), 43-50.

Mohammadpanah, A., and Lehmann, B. (2019). “Critical temperature of guided circular saws.” in: *Proceeding 24th International Wood Machining Seminar,* Corvallis, OR, USA, pp. 25-28.

Nasir, V., and Cool, J. (2020). “A review on wood machining: characterization, optimization, and monitoring of the sawing process,” *Wood Mater. Sci. Eng.* 15 (1), 1-16. DOI: 10.1080/17480272.2018.1465465

Naylor, A., and Hackney, P. (2013). “A review of wood machining literature with a special focus on sawing,” *BioResources* 8 (2), 3122-3135. DOI: 10.15376/biores.8.2.3122-3135

Ndlovu, S. (2009). *The Wear Properties of Tungsten Carbide-cobalt Hardmetals from the Nanoscale up to the Macroscopic Scale*, Ph.D. Thesis, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Bavaria, Germany.

Nordström, J., and Bergström, J. (2001). “Wear testing of saw teeth in timber cutting,” *Wear* 250 (1-12), 19-27. DOI: 10.1016/s0043-1648(01)00625-1

Orlowski, K. A., Sandak, J., and Chuchala, D. (2020). “Thickness accuracy of sash gang sawing,” *BioResources* 15 (4), 9362-9374. DOI: 10.15376/biores.15.4.9362-9374

Özel, T., Karpat, Y., and Srivastava, A. (2008). “Hard turning with variable micro-geometry PcBN tools,” *CIRP Ann. - Manuf. Technol.* 57 (1), 73-76. DOI: 10.1016/j.cirp.2008.03.063

Padmakumar, M., and Shiva Pradeep, N. (2020). “Effect of cutting edge form factor (K-factor) on the performance of a face milling tool,” *CIRP J. Manuf. Sci. Technol.* 31 (4): 305-313. CIRP. DOI: 10.1016/j.cirpj.2020.06.004

Prakash, L. J. (1995). “Application of fine grained tungsten carbide based cemented carbides,” *Int. J. Refract. Met. Hard Mater.* 13 (5), 257-264.DOI: 10.1016/0263-4368(95)92672-7

Rodríguez, C. J. C. (2009). *Cutting Edge Preparation of Precision Cutting Tools by Applying Micro-abrasive Jet Machining and Brushing,* Ph.D. Thesis, Kassel University, Kassel, Germany.

Sacks, N. (2003). *The Wear and Corrosive-wear Response of Tungsten Carbide-cobalt Hardmetals under Woodcutting and Three Body Abrasion Conditions,* Ph.D. Thesis, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Bavaria, Germany.

Shaffer, W. R. (2004). “Effects of engineered micro-geometry on burr formation in PCD milling of aluminum,” in: *Proceeding of 7th International Conference Deburring Surface Finish,* Oakland, CA, USA.

Sheikh-Ahmad, J. Y., and Bailey, J. A. (1999a). “The wear characteristics of some cemented tungsten carbides in machining particleboard,” *Wear,* 225-229, 256-266. DOI: 10.1016/s0043-1648(98)00361-5

Sheikh-Ahmad, J. Y., and Bailey, J. A. (1999b). “High-temperature wear of cemented tungsten carbide tools while machining particleboard and fiberboard,” *J. Wood Sci.* 45 (6), 445-455. DOI: 10.1007/bf00538952

Sima, M., Ulutan, D., and Özel, T. (2011). “Effects of tool micro-geometry and coatings in turning of Ti-6Al-4V titanium alloy,” in: *Proceeding NAMRI/SME 39 Conference,* Corvallis, OR, USA, pp. 395-402.

Sugihara, H., Okumura, S., Haoka, M., Ohi, T., and Makino, Y. (1979). "Wear of tungsten carbide tipped circular saws in cutting particleboard: Effect of carbide grain size on wear characteristics," *Wood Sci. Technol.* 13 (4), 283-299. DOI: 10.1007/bf00356970

Ventura, C. E. H., Chaves, H. S., Campos Rubio, J. C., Abrão, A. M., Denkena, B., and Breidenstein, B. (2017). "The influence of the cutting tool microgeometry on the machinability of hardened AISI 4140 steel," *Int. J. Adv. Manuf. Technol.* 90 (9-12), 2557-2565. DOI: 10.1007/s00170-016-9582-4

Ventura, C. E. H., Köhler, J., and Denkena, B. (2015). "Influence of cutting edge geometry on tool wear performance in interrupted hard turning," *J. Manuf. Process.* 19, 129-134. DOI: 10.1016/j.jmapro.2015.06.010

Young, T. M., Bond, B. H. and Wiedenbeck, J. (2007). "Implementation of a real-time statistical process control system in hardwood sawmills," *For. Prod. J.* 57 (9), 54-62.

Zhuang, K., Fu, C., Weng, J., and Hu, C. (2021). "Cutting edge microgeometries in metal cutting: a review," *Int. J. Adv. Manuf. Technol.* 116 (7-8), 2045-2092. DOI: 10.1007/s00170-021-07558-6

Article submitted: October 26, 2022; Peer review completed: November 29, 2022;
Revised version received and accepted: January 19, 2023; Published: January 26, 2023.
DOI: 10.15376/biores.18.1.2024-2044