Patterns of Knife Edge Recession in an Industrial Chipper-Canter

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Abstract

Chipper-canters are used in primary wood industries for processing small-diameter logs. Knife geometry is one of the principal parameters significantly affecting the chip size and cant surface properties. This work studied the patterns of tool wear as edge recession (ER) in chipping and canting knives of a chipper-canter head. In addition, analytical investigation of wear mechanisms was carried out to better understand the ER phenomenon. The test head contained eight sets of separate chipping and canting knives. ER was measured after 0, 8, 16, 32, 48, and 80 hours of machining. Microscopic measurements at intervals of 1 mm along the cutting edge were carried out to characterize ER from knife replicas. The ERs after 80 hours of machining were 544 and 549 µm for chipping and canting knives, respectively. There was no significant variation in ER between the types of knives at 0 and 80 hours of machining. However, significantly different ERs were found between the chipping and canting knives at the intermediate stages of machining. Scanning electron microscopic observation showed that apart from abrasion and chipping phenomenon, there were also deformation of chipping knives and cracking of canting knives.

Tool wear during wood cutting is characterized by the phenomenon of the tool edge being unfit for continued use due to large-scale deformation and/or fracture of the cutting edge. Tool wear directly affects the quality of the finished product (Klamecki 1979) as well as other machining parameters, such as noise (Lemaster and Tee 1985), increased power consumption (Ratnasingam and Perkins 1998), and vibration (Haddadi et al. 2008). Thus, regular sharpening or replacement of cutting tools is necessary to keep them suitable for machining. This ultimately has economic impacts for industries because frequent maintenance or removal of tool parts requires compromise either with the production flow or with the product quality. Hence, monitoring tool wear and its mechanisms to increase tool life is of significant industrial and research interest. In general, tool wear can be monitored directly and indirectly. Direct measurements can be done by observing the changes in the edge geometry (Sheikh-Ahmed et al. 2003). Contact (Miklaszewski et al. 2000), scanning electron microscopy (SEM; Nordström and Bergström 2001, Okai et al. 2006), and optical (Kowaluk et al. 2009) techniques are typically used for characterizing the tool tip. The indirect measurements involve data acquisition of a given process variable from which tool wear can be estimated using a known relationship, such as observing the changes in cutting forces (Aknouche et al. 2009), power consumption (Cuppini et al. 1990), and acoustic emission (Lemaster et al. 2000). The direct method is reliable but provides discontinuous measurements because the wear land is not visible while the tool cuts. The indirect methods conversely permit continuous estimation of wear while the tool is in operation (Cuppini et al. 1990).

Several studies have been carried out to investigate the degradation of cutting tools in the wood transformation industry (Klamecki 1979, Mohan and Klamecki 1981, Nordström and Bergström 2001, Aknouche et al 2009). The effects of different parameters on tool wear, such as wood type, geometrical characteristics of tools, working time, and feed rate, were investigated. Abrasive wear as well

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Forest Prod. J. 65(7/8):358–364.
doi:10.13073/FPJ-D-14-00057

as tribochemical wear are the most important mechanisms reported in the pertinent literature. In Canada, chipper-canters are used in primary wood industries for transforming small-diameter logs into chips and squared lumber in a single operation. The effect of cutting speed on chip quality has been studied by Hernández and Boulanger (1997). Influences of knife clamp (Hernández and Quirion 1993), cutting width and cutting height on chip quality (Hernández and Lessard 1997), and cant surface quality (Hernández et al. 2010) have also been reported. However, further research and development of process optimization using this machine is required to achieve higher quality of pulp chips and cant surfaces. The aspects of wearing of knives and its impact on the finished products are yet to be studied. Nati et al. (2010) reported that knife wear caused significant reduction of productivity and increase of fuel consumption while chipping with a drum chipper. The objective of this work was therefore to study the wear pattern or edge recession (ER) development together with the characterization of wear mechanisms of chipper-canter knives.

Materials and Methods

Materials

The chipper-canter used for this experiment was equipped with eight knife holders, each with a set of two knives joined at an angle (Fig. 1). The longer knife (chipping knife) severs a slice of wood from the log, and the shorter knife (canting knife) smoothes the surface of the cant. The knives were made of AISI A8 tool steel with the following chemical composition (% by weight): 0.55 percent C, 5 percent Cr, 1.25 percent W, and 1.25 percent Mo. They were hardened at 1,010°C and tempered twice at 530°C. The hardness of the knives was 56 HRC.

Methods

The knives were installed on a chipper-canter head 610 mm in diameter in a sawmill that processes principally black spruce (*Picea mariana* (Mill.) B.S.P.) logs (100 to 150 mm in diameter). The cutter head of this machine rotated at 580 rpm, and the logs were usually fed at a speed of 137 m/min. The feed per knife (corresponding to the length of the chips) was thus around 29 mm. The simulation (SolidWorks, Waltham, Massachusetts) of the cutter head machining a 150-cm-diameter log showed that the nominal rake angle was 54° for the canting knife and 49° for the chipping knife. The clearance angles were 1° and 3° for canting and chipping knives, respectively. The cutting speed at the point of intersection of these two knives was 18.5 m/s. Before using the knives in the chipper-canter, replicas of each knife were casted using Bondo fiberglass resin and Bondo filler. The knives were then removed from the chipper-canter after 8, 16, 32, 48, and 80 hours of use for casting replicas. Each time, the knives were mounted back in the same knife holder. Thus, wear of the knives occurred intermittently covering a period from April to October 2012 in the sawmill.

The first 25 mm of both chipping and canting knives from their point of intersection were the most active parts while cutting. Thus, the cross sections of the knife replicas were sanded with a belt sander for observation at each 1 mm with a Multicheck PC 500 microscope (Blickle GmbH) mounted with a ×30 lens. Cross-sectional images of the replicas were captured and analyzed by an associated software working with MS-Windows. Both types of freshly sharpened knives had an initial angle of 30°. However, a bevel of 5° was made on the rake face, resulting in an actual knife angle of 35°. The ER was measured as the distance between the point of intersection between the rake (without considering the beveled area) and clearance faces and the tip of the cutting edge (Fig. 2). Thus, 25 measurements were taken for each knife replica.

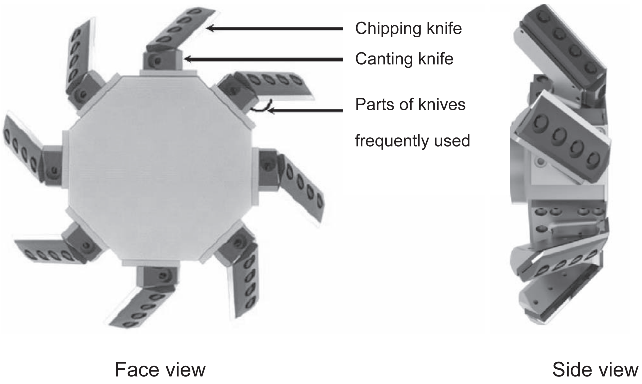

Figure 1.—Chipper-canter cutter head with separate chipping and canting knives.

Statistical analysis

ER data were studied using analysis of variance (ANOVA) with repeated measures. The first type of repeated measures was the ER mean values coming from the same knife after different hours of operation in the chipper-canter. The second type of repeated measures was the ERs taken on the same knife at each 1 mm along the cutting edge, i.e., points of measurement. The knife type was considered as a two-level factor in the model, that is, the chipping and the canting knives. The type of dependency that best fits the data was chosen based on the Akaike information criterion. A heterogeneous first-order autoregressive dependency type was chosen to take into account the fact that the variability increased over time and because two successive observations were more correlated than two observations more spaced in time. In order to meet the normality assumption, the square root of the response variable was taken following the Box-Cox procedure. The

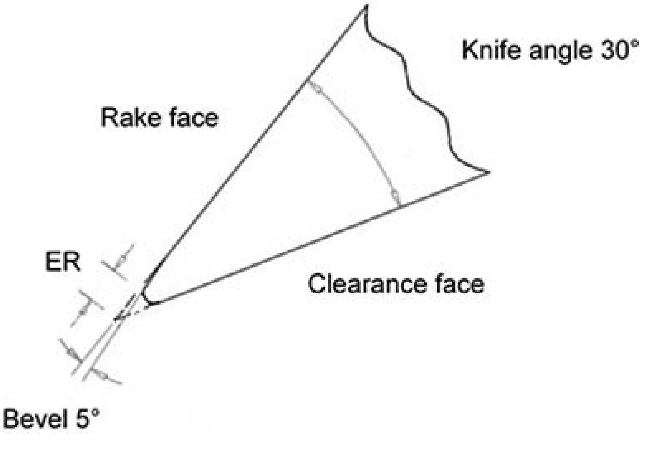

Figure 2.—Knife geometry showing the method of edge recession (ER) measurement.

edge shape of freshly sharpened knives (initial ER) was considered a covariate in the model to rule out the variability raised due to the manufacturing process of the knives. The comparison of ER values during 8 to 80 hours of machining thus would show how the knife edge shape varies in chipping and canting knives. The significance level was fixed at 0.05, and the analysis was done using the mixed procedure of SAS software (SAS Institute Inc. 2013).

Results and Discussion

The means of ER for freshly sharpened chipping and canting knives were 182 (4 SE) and 207 (9 SE) µm, respectively. However, the difference between these two initial ER means was not statistically significant ($P = 0.8217$). This quite high ER for freshly sharpened knives is attributed to the beveling performed on the rake face of the knives during sharpening. ER of both chipping and canting knives increased with the time of machining. The canting knives showed a high initial rate of ER that started flattening off after 48 hours of machining. The chipping knives showed a relatively lower but uniform rate of ER that abruptly increased within the period of 33 to 48 hours of machining and was reduced afterward (Fig. 3).

The results of the ANOVA for the ER data are shown in Table 1. The triple interaction, including time, knife type, and points of measurement, was not statistically significant. However, all second-order interactions were significant in the model. This indicates that differences among the levels of a factor are dependent on the level of another factor. As expected, the ANOVA showed that machining time was the most important independent variable in the model. However, the interaction between knife type and time confirmed that the wear rate was different between the canting and chipping knives.

Wear between both types of knives was statistically different at 8, 16, and 32 hours but not at 48 and 80 hours (Fig. 3). Hence, the canting knives had higher ER values than the chipping knives at early stages of machining, but this difference was reduced afterward. The double interaction, points of measurement × time, indicated that the variation in ER within knife was dependent on the time of machining. Thus, Figure 4 shows how ER varies within knife along the cutting edge. This variation generally increased with time of machining in both types of knives. This figure also shows that differences between the canting and chipping knives were more apparent between 6 and 15 mm along the cutting edge. However, as time of machining increased, these differences disappeared (Fig. 4).

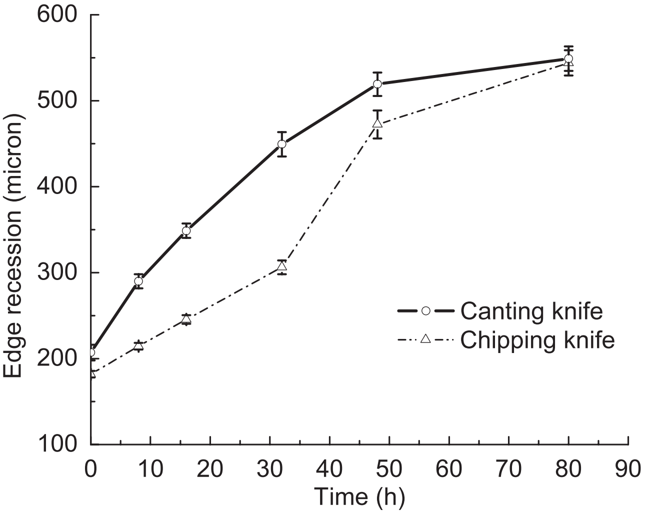

Figure 3.—Average edge recession and standard error as a function of time of chipping-canting unfrozen black spruce logs.

The wearing trend of a cutting tool edge might show a sigmoid shape if plotted. Csanády and Magoss (2013) mentioned wood machining tool wear in terms of edge shapes: initial, working sharp, and blunt. Aknouche et al. (2009) described the cutting edge wear stages as running (abrupt wear), linear (stability period), and catastrophic (leading to tool failure). Similar wear patterns have been reported as Taylor curves while machining high-speed steel (Trent and Wright 2000). The sharpening frequency for the chipper-canter knives in the sawmill was 80 hours for each set of knives. However, there is no reported information on the wear pattern of such knives. Hence, the ER data reveal that the canting knives showed a higher initial rate of ER that decreased afterward. This pattern could represent the initial and working sharp stages of knife wear. The wear pattern in chipping knives was somewhat different and appeared less typical.

Different wear phenomena were evidenced on the rake and clearance faces of chipping and canting knives while observed by SEM. The chipping knives showed signs of abrasion on the knife surface as well as chipping and deformation of the knife edge. In addition to abrasion and chipping, the canting knives showed cracking of the knife edges. A typical SEM image of grooves observed on the rake face of a chipping knife is shown in Figure 5a. The presence of grooves is a wear behavior indicating the abrasion of a worn surface (Zum Gahr 1987). Similar to

Table 1.—Statistical significance of time, knife type, and variability among knives influencing edge recession.

Variability	Source of variation	Degrees of freedom	F value	Pr > F
Among knives	Knife type	1	5.53	0.0338
	Error 1	14	—	—
Within knife	Covariate	1	38.03	<0.001
	Time	4	390.29	<0.001
	Point of measurement	24	1.35	0.1213
	Knife type × time	4	18.78	<0.001
	Knife type × points of measurement	24	1.63	0.0276
	Points of measurement × time	96	1.72	<0.001
	Time × knife type × points of measurement	96	0.91	0.7184
	Error 2	1,735	—	—

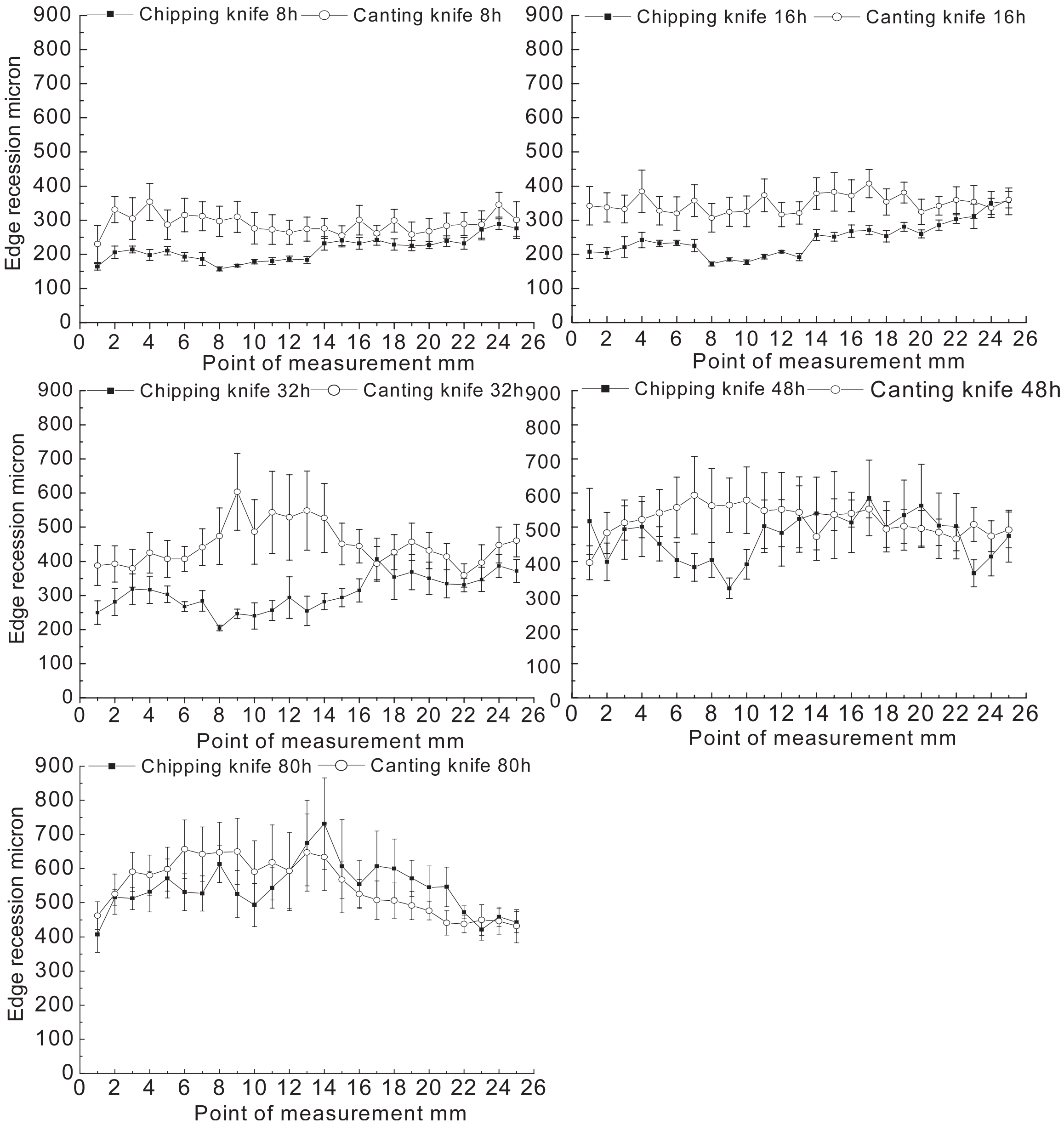

Figure 4.—Within-knife variation in edge recession (with standard error) for chipping and canting knives during 8 to 80 hours of machining.

chipping knives, the SEM observation of canting knives also showed the signs of abrasion on both rake and clearance faces. However, the abrasion grooves were variable in length, thickness, and direction. The grooves of chipping knives were more frequent and larger in dimension than those of canting knives. Regardless of knife type, the rake faces were found to contain larger grooves than those observed on the clearance faces.

The abrasion of knife surfaces was the dominant wear phenomenon of both chipping and canting knives. The presence of abrasive particles, such as sand or silica, in wood is responsible for such wear behavior (Klamecki 1979, Nordström and Bergström 2001). While machining logs with a chipper-canter, the abrasive particles come into direct contact with the knives and leave marks in the form of grooves on the surfaces. Relatively harder abrasive particles often partly take off knife material and leave deep grooves on their way over the knife surface. Thus, the size and distribution of abrasive particles, as well as the extent to which they come into contact with the knife surface, determine the grooving pattern. Nevertheless, the cutting force also influences the contact of abrasive materials with the knife surfaces (Zum Gahr 1987). Thus, the variable cutting forces of chipping and canting knives might also have influenced the different appearance of grooves on the knife surfaces.

Apart from abrasion, chipping (Fig. 5b) was the second most prevalent wear phenomenon observed on the knives. Abrasion of knives gradually damages the surface, while chipping has an abrupt effect on the cutting edge. The sudden impact while machining causes propagation of cracks on the knife edges. Such a cracking phenomenon was visible on the canting knives (Fig. 5c). The signs of deformation (Fig. 5d) were more visible on the chipping

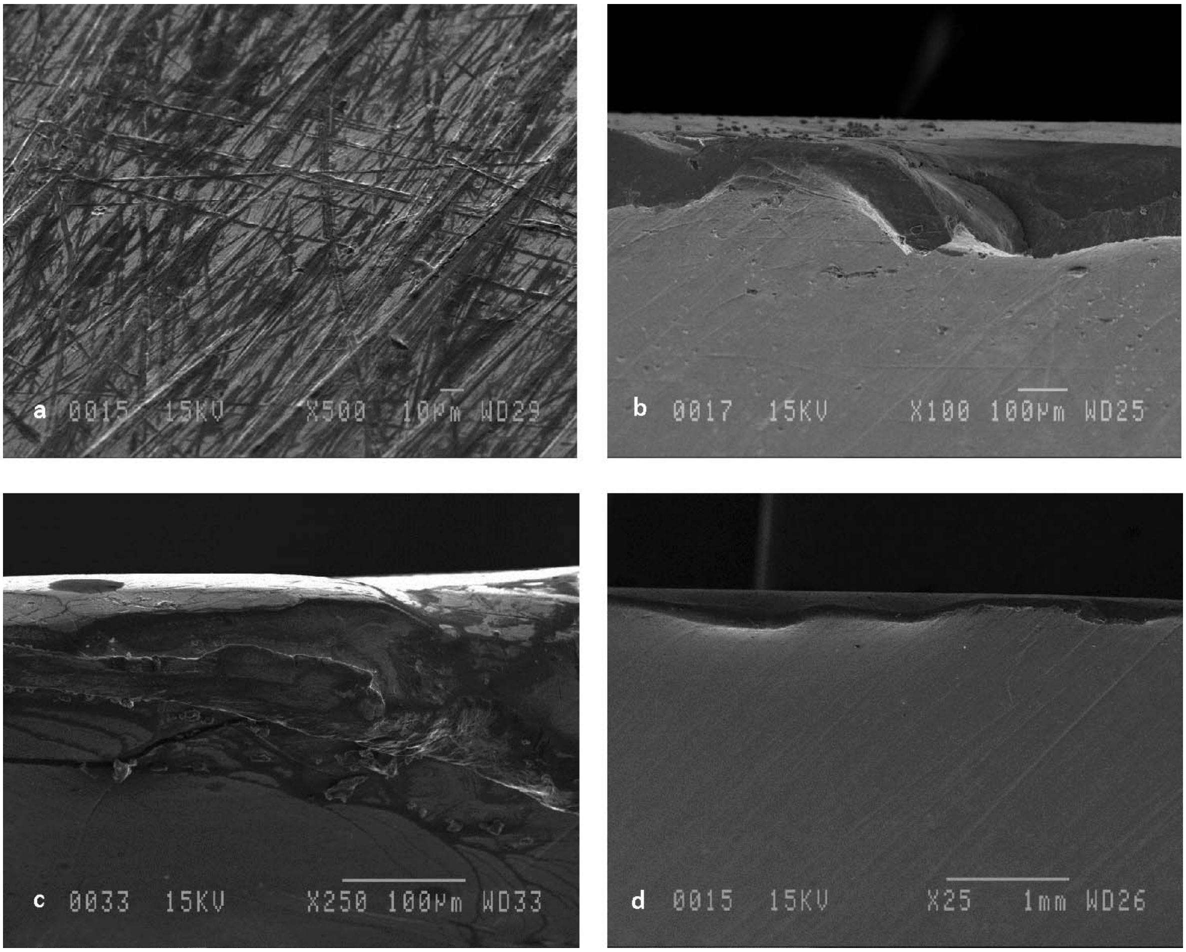

Figure 5.—Scanning electron micrographs of worn knives: (a) abrasion on chipping knife rake surface, (b) edge chipping of chipping knife, (c) cracking damage on canting knife, and (d) deformation of chipping knife.

knives and might be attributed to the higher cutting forces applied by such knives. A summary of different wear phenomena observed by the SEM analysis is presented in Table 2.

The canting and chipping knives are placed at an angular setup in the chipper-canter head (Fig. 1). Thus, the knives produced two different cutting planes while machining a log. The canting knife acts in orthogonal cutting and is responsible for generating the flat surface of the cant. This knife cuts the log nearly across the grain at the point of entry and more obliquely to the grain as the knife exits the log (Hernández et al. 2010). In fact, the orientation of the canting knife's edge with respect to wood grain changes according to the diameter of the cutter head and the vertical feed position of the log. For instance, for a 152-mm log diameter and 25-mm cutting width, the orientation of the knife edge increased from about 2° with respect to the wood grain (orientation 2° to 88°) at the entrance to 28° (orientation 28° to 62°) at the exit (Hernández et al. 2010). Thus, the cutting forces will decrease from the entrance to the exit of the cutting path (Kuljich et al. 2013, Hernández et al. 2014). The variation in cutting forces is explained by the changes in the mechanical properties of wood with respect to the wood grain.

Table 2.—Wear phenomena observed by the scanning electron microscopic analysis on the different faces of knives.

Knife type	Geometric face of knife	Presence of wear phenomena			
		Abrasion	Chipping	Cracking	Deformation
Chipping	Rake	X	X		X
	Clearance	X	X		
Canting	Rake	X	X	X	
	Clearance	X	X		

On the other hand, the chipping knife could produce higher cutting forces given that the cutting is oriented even more across the grain and that the cutting depth (chip length) is higher. The chipping knife works in the log by oblique cutting. Oblique cutting differs from orthogonal cutting by the inclination given to the knife's edge with respect to the cutting direction. This inclination is called oblique angle (*i*; de Moura and Hernández 2007). The edge of the chipping knife is inclined at an angle *i* with respect to the cutting direction. This angle induces several changes on tool geometry, cutting forces, and the quality of machined surfaces (Stewart 1989; Jin and Cai 1996, 1997; de Moura and Hernández 2007). Thus, when *i* increases, the rake angle increases, while clearance angle, knife angle, and cutting forces decrease (Jin and Cai 1996, 1997; de Moura and Hernández 2007). Another important aspect of oblique

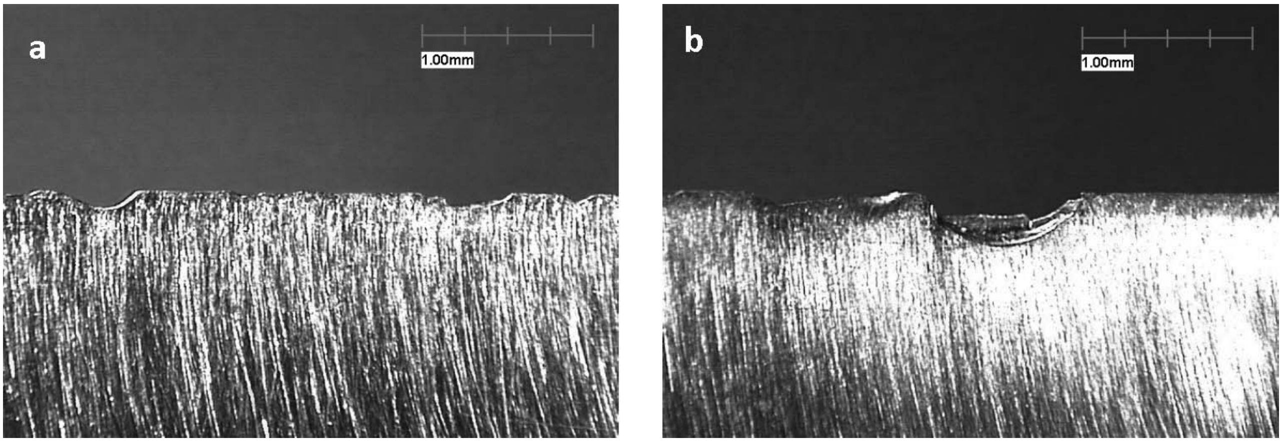

Figure 6.—Edge damage in canting knife (a) and chipping knife (b), viewed on the clearance face after 48 hours of machining.

cutting is the reduction of the knife's edge radius as *i* increases, enhancing tool sharpness. This could have limited the differences in wear between the canting and chipping knives. On the other hand, the rubbing action on the clearance face appeared to be higher in the canting knife than in the chipping knife. In fact, the clearance angle was smaller for the canting knife (1°), producing a shiny surface in its clearance face. The clearance angle of the chipping knife was higher (3°) and appeared more adequate.

The different patterns of cutting knots by the chipping and canting knives could also influence the wear process. It is assumed that knots are on average 2.5 times denser than the surrounding wood (Hackspiel et al. 2014), making this feature very important in terms of wear produced by impact and cracking. The canting knives cut many of the knots across their grain, with a tendency to the 90°-to-90° direction. Conversely, the chipping knives cut the knots at oblique angles but with more tendency to the 0°-to-90° direction. Cutting forces are higher in the 90°-to-90° direction than the other cutting directions (Koch 1964). Hence, the effect of knots on wear could be higher for canting knives than for chipping knives. Again, with respect to the cutting paths of canting and chipping knives, all the knots present in the potential cant surface were necessarily cut by the canting knives. In contrast, the chipping knives cut knots falling only along their respective cutting path. The incidents of denting and fracture of cutting edge were observed in both canting (Fig. 6a) and chipping (Fig. 6b) knives. However, several identical large fractures of cutting edge were observed in chipping knives (Fig. 6b), resulting in sudden increases of ER during 33 to 48 hours of machining.

The highest ER rate in the chipping knives during 33 to 48 hours of machining could also be attributed to other factors, such as low moisture content, different provenance of logs, and contamination of log surfaces. The month of the year in which the machining was done in the sawmill and the mean temperature during that period are shown in Table 3. Logs machined during 33 to 48 hours were stored in a log yard during the highest mean temperature of the year. This might have led to higher loss of moisture from sapwood. Hence, relatively drier logs were probably machined during 33 to 48 hours, and this could result in higher ER in chipping knives.

Table 3.—Mean temperature of months when machining was done in a sawmill.[a]

	Machining time (h):				
	0–8	9–16	17–32	33–48	49–80
Month of the year 2012	Apr	May	Jun	Aug	Oct
Mean temp. (°C)	1.4	7.6	13.2	15.9	5.2

[a] Source: The Weather Network 2013.

The logs in the sawmill come from different sources, and during handling, their surfaces can be contaminated by sand, stone particles, or metal parts. Even though the logs were debarked before passing through the chipper-canter, parts of bark might still remain on the log. If contamination of log surfaces is higher, then the contaminants caught by the bark remains may pass through the chipper-canter head while machining. The cutting path of the chipping knives caused a higher contact with the log surface than the canting knives. Thus, contamination of the log surface might cause higher ER of chipping knives during 33 to 48 hours of machining due to the abrasion mechanism. In addition, the higher variability in ER of the chipping knives during this period (Fig. 4) could indicate that edge chipping occurred from impact and friction with hard materials (Fig. 6b). Nevertheless, further studies are required to validate the assumptions made to explain the wear pattern of chipper-canter knives.

Conclusions

This study revealed the ER pattern of chipper-canter knives working under industrial conditions. ER increased with the time of machining. The ER pattern of canting and chipping knives varied significantly from each other during the initial hours of use. The ER rate of the canting knives was generally found to be higher than the chipping knives. However, the ER rate of both types of knives was similar after 80 hours of use. Apart from abrasion and the chipping phenomenon of knife edges, there was evidence of deformation in chipping knives and cracking in canting knives. The edge sharpness of canting and chipping knives might influence the surface quality of cants and the size distribution of chips produced. The effect of ER on chip quality and cant surface properties will be reported in other articles.

Acknowledgments

The authors hereby acknowledge the financial support of NSERC (Natural Sciences and Engineering Research Council of Canada) and DK Spec Canada for the project.

Literature Cited

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

Csanády, E. and E. Magoss. 2013. Mechanics of Wood Machining. 2nd ed. Springer-Verlag, Berlin. 158 pp.

Cuppini, D., G. D'errico, and G. Rutelli. 1990. Tool wear monitoring based on cutting power measurement. *Wear* 139(2):303–311.

de Moura, L. F. and R. E. Hernández. 2007. Characteristics of sugar maple wood surfaces machined with the fixed-oblique knife pressure-bar cutting system. *Wood Sci. Technol*. 41(1):17–29.

Hackspiel, C., K. de Borst, and M. Lukacevic. 2014. A numerical simulation tool for wood grading model development. *Wood Sci. Technol*. 48(3):633–649.

Haddadi, E., M. R. Shabghard, and M. M. Ettefagh. 2008. Effect of different tool edge conditions on wear detection by vibration spectrum analysis in turning operation. *J. Appl. Sci*. 8(21):3879–3886.

Hernández, R. E. and J. Boulanger. 1997. Effect of the rotation speed on the size distribution of black spruce pulp chips produced by chipper-canter. *Forest Prod. J*. 47(4):43–49.

Hernández, R. E., S. Kuljich, and A. Koubaa. 2010. Effect of cutting width and cutting height on the surface quality of black spruce cants produced by a chipper-canter. *Wood Fiber Sci*. 42(3):273–284.

Hernández, R. E. and J. Lessard. 1997. Effect of cutting width and cutting height on the size distribution of black spruce pulp chips produced by a chipper-canter. *Forest Prod. J*. 47(3):89–95.

Hernández, R. E. and B. Quirion. 1993. Effect of a chipper-canter knife clamp on the quality of chips produced from black spruce. *Forest Prod. J*. 43(9):8–14.

Hernández, R. E., A. M. Llavé, and A. Koubaa. 2014. Effects of cutting parameters on cutting forces and surface quality of black spruce cants. *Eur. J. Wood Wood Prod*. 72(1):107–116.

Jin, W. and L. Cai. 1996. Study and analysis on cutting forces of oblique cutting of wood. *Holz Roh- Werkst*. 54(4):283–286.

Jin, W. and L. Cai. 1997. Study on the normal component force in oblique cutting of wood. *Holz Roh- Werkst*. 55(2–4):118–120.

Klamecki, B. E. 1979. A review of wood cutting tool wear literature. *Holz Roh- Werkst*. 37(7):265–276.

Koch, P. 1964. Wood Machining Process. Ronald Press, New York. 530 pp.

Kowaluk, G., W. Szymanski, B. Palubicki, and P. Beer. 2009. Examination of tools of different materials edge geometry for MDF milling. *Eur. J. Wood Wood Prod*. 67(2):173–176.

Kuljich, S., R. E. Hernández, A. M. Llavé, and A. Koubaa. 2013. Effects of cutting direction, rake angle, and depth of cut on cutting forces and surface quality during machining of balsam fir. *Wood Fiber Sci*. 45(2):195–205.

Lemaster, R. L., L. Lu, and S. Jackson. 2000. The use of process monitoring techniques on a CNC wood router. Part 2. Use of a vibration accelerometer to monitor tool wear and workpiece quality. *Forest Prod. J*. 50(9):59–64.

Lemaster, R. L. and L. B. Tee. 1985. Monitoring tool wear during wood machining with acoustic emission. *Wear* 101(3):273–282.

Miklaszewski, S., M. Zurek, P. Beer, and A. Sokolowska. 2000. Micromechanism of polycrystalline cemented diamond tool wear during milling of wood based materials. *Diamond Relat. Mater*. 9(3):1125–1128.

Mohan, G. D. and B. E. Klamecki. 1981. The susceptibility of wood-cutting tools to corrosive wear. *Wear* 74(1):85–92.

Nati, C., R. Spinelli, and P. Fabbri. 2010. Wood chips size distribution in relation to blade wear and screen use. *Biomass Bioenergy* 34(5):583–587.

Nordström, J. and J. Bergström. 2001. Wear testing of saw teeth in timber cutting. *Wear* 250(1–12):19–27.

Okai, R., C. Tanaka, and Y. Iwasaki. 2006. Influence of mechanical properties and mineral salts in wood species on tool wear of high-speed steels and stellite-tipped tools—Consideration of tool wear of the newly developed tip-inserted band saw. *Holz Roh- Werkst*. 64(1):45–52.

Ratnasingam, J. and M. C. Perkins. 1998. An investigation into the tool wear characteristics of rubberwood (*Hevea brasiliensis*) laminated veneer lumber. *Holz Roh- Werkst*. 56(1):31–35.

SAS Institute Inc. 2013. SAS/STAT User's Guide, version 9.3. SAS Institute Inc., Cary, North Carolina.

Sheikh-Ahmed, J. Y., J. S. Stewart, and H. Feld. 2003. Failure characteristics of diamond-coated carbides in machining wood-based composites. *Wear* 225(7–12):1433–1437.

Stewart, H. A. 1989. Fixed-knife pressure-bar planing method reduces or eliminates subsurface damage. *Forest Prod. J*. 39(7/8):66–70.

Trent, E.M. and P. K. Wright. 2000. Metal Cutting. 4th ed. Butterworth-Heinemann, Woburn Massachusetts. 164 pp.

The Weather Network. 2013. Statistics. www.theweathernetwork.com/forecasts/statistics/temperature/cl7052605. Accessed May 8, 2013.

Zum Gahr, K.-H. 1987. Microstructure and Wear of Materials. Tribology series 10. Elsevier Science Publishers, Amsterdam. 133 pp.