EFFECT OF KNIFE WEAR ON SURFACE QUALITY OF BLACK SPRUCE CANTS PRODUCED BY A CHIPPER-CANTER

S. C. Ghosh
Postdoctoral Fellow
E-mail: shyamal-chandra.ghosh.1@ulaval.ca

*R. E. Hernández**
Professor
Centre de recherche sur les matériaux renouvelables
Département des sciences du bois et de la forêt
Université Laval
Quebec, Canada
E-mail: roger.hernandez@sbf.ulaval.ca

C. Blais
Professor
Département de génie des mines, de la métallurgie et des matériaux
Université Laval
Quebec, Canada
E-mail: carl.blais@gmn.ulaval.ca

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Abstract. Effect of knife wear on surface quality of black spruce (*Picea mariana* (Mill) B.S.P.) cants machined by a chipper-canter was evaluated. A set of eight canting knives with six levels of edge recession (207, 290, 349, 449, 519, and 549 μm) was studied. Logs were fed at 145 m/min through the canter head rotating at 726 rpm yielding a nominal feed per knife of 25 mm. For each edge recession, two sides of the logs were machined at either unfrozen (above 14°C) or frozen (below −23°C) wood temperatures. Laser-scanned profiles across the grain of 16 knife marks on each cant were evaluated for roughness and waviness parameters and depth of torn grain. The results showed that, regardless of log temperature, waviness and roughness were positively affected by edge recession. Roughness was more sensitive than waviness to changes in edge recession. Surfaces in general were smoother in frozen logs than in unfrozen logs. Maximum depth of torn grain appeared to not be significantly affected by knife wear. The results provided useful information for improving the performance of the chipper-canter in terms of surface quality.

Keywords: Knife wear, surface quality, black spruce, chipper-canter, roughness, waviness.

INTRODUCTION

The time-dependent complex interaction of wooden raw material and machining process results in various surface characteristics (Sinn et al 2009). Surface quality assessment is significant for industries, because it determines the necessity of further processing and possible end uses. The quality of a machined surface is often measured in terms of roughness and waviness parameters (Jackson et al 2002; Hernández and Cool 2008) as well as the occurrence of certain machining defects such as raised grain, fuzzy grain, and torn grain (Stewart 1980). Both the variability of the wood piece and the machining parameters influence surface quality (Jackson et al 2002; Sandak et al 2003). Variables such as cutting rate, feed direction, tool geometry, and wear affect the surface quality produced. Again, wood surface roughness might differ because of variable anatomical structures along and across-the-grain directions. Greater values of surface roughness are generally obtained from measurements made across the grain than along the grain

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* Corresponding author

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(de Moura and Hernández 2006; Hernández and Cool 2008). MC of wood also influences surface quality and tool wear (Stewart 1980). Other intrinsic properties of the work piece, such as extractive and silica contents, also influence the cutting tool characteristics (Darmawan et al 2011). Generally, tool wear increases as moisture, extractive, and silica contents increase.

Tool wear is defined as the loss of material from the cutting edge while machining caused by interaction between the tool and the work piece. This modifies the geometry of the tool edge, which has direct implications in terms of changes in cutting forces and quality of the surfaces produced. At a certain level of wear, the cutting tool is unsuitable for continuous use and requires maintenance or replacement. The measurement of the edge recession is considered to be an effective method for analysis of wear (Klamecki 1979). Three stages of tool wear in wood machining have been reported in the literature. Csanády and Magoss (2013) distinguished them in terms of radius of the tool edge as initial or sharp, working sharp, and blunt stages. Aknouche et al (2009) described the wear stages as running (abrupt wear), linear (stability period), and catastrophic wear (leading to tool failure). Similar stages of tool life have been explained in metal processing through Taylor curves (Trent and Wright 2000). Generally, woodworking tool wear shows a positive correlation with cutting forces (Kivimaa 1950; Stewart 1991; Hernández and de Moura 2002; Hernández and Rojas 2002). According to Koch (1964), the effective rake and clearance angles decreased as wear progressed, which increased cutting forces and altered surface quality. For instance, higher normal forces caused compression of the upper layers of the wood surface resulting in severe damage and surface instability (Stewart and Crist 1982; Murmanis et al 1986). Thus, surface quality deteriorated at the later stages of tool wear while machining. Keeping the desired form of cutting tool edge for long periods is important for the quality of the machined product. The process industries are always interested in this to avoid frequent maintenance of cutting tools, which hinders the production flow.

Chipper-canters are frequently used in the sawmills of Quebec because of the beneficial effect of producing squared lumber and chips in a single operation. However, the surface of cants produced in this process is often a concern because of their poor quality. There is limited research on the quality of cant surfaces produced by chipper-canters. Hernández et al (2010) reported on the effects of cutting width and height on the surface quality of cants produced by an industrial chipper-canter. Recently, the effect of cutting rate on surface quality has also been evaluated (Hernández et al 2013). However, the question of how much the wear of knives affects surface quality of cants produced by this machine remains unanswered. The goal of this study was to evaluate the surface quality of black spruce cants produced by knives with different levels of wear. Surface quality was assessed by means of roughness and waviness parameters and torn grain measurements.

MATERIALS AND METHODS

A total of 84 stems of black spruce (*Picea mariana* (Mill.) B.S.P.) were selected for this study. The stems were crosscut into 2.74-m logs and were freshly debarked. The crosscutting position of the stem was chosen to yield logs with a small end diameter inside the bark of 152 mm. Logs were wrapped in plastic film after debarking and kept in a freezer at −30°C to minimize moisture loss before processing. They were without crook or visible decay and had straight grain, concentric growth rings, and minimum knots.

A laboratory chipper-canter was used in this study to evaluate the effect of tool wear on cant surface. The different levels of wear to be assessed were obtained by installing the studied knives in the chipper-canter of a cooperating industrial sawmill. Both chipper-canters were mounted with DK-SPEC (St-Nicolas, Quebec, Canada) cutter heads with essentially similar configurations and with the shape of a shallow truncated cone. Each cutter head was fitted with eight uniformly distributed knife holders, each of them with a set of two knives, which were joined at an angle (Fig 1). The longer knife (chipping knife) severed a slice of wood to make chips, and the shorter knife (canting knife) smoothed the cant. Basically, the canting knife cut nearly across the grain at the point of entry on the log and more obliquely to the grain as the knife exited the log (Hernández et al 2010). The knives were made of American Iron and Steel Institute A8 tool steel with the following chemical composition (weight %): 0.55% C, 5% Cr, 1.25% W, and 1.25% Mo. They were hardened at 1010°C and tempered twice at 530°C. The hardness of the knives was 56 Rockwell Scale C (HRC).

The experiment consisted of processing black spruce logs using knives with six levels of wear. In addition, the seasonal effect on log processing was evaluated by machining one side of the log in frozen wood conditions and another side in unfrozen wood conditions. Fourteen logs were used for each wear level treatment.

Laboratory and Industrial Machining

Before each cutting experiment, replicas of each canting knife were made using Bondo (3M, St. Paul, MN) fiber glass resin and Bondo filler. The first 29 mm of all canting knife edges was the active part during industrial machining (Fig 1). Cross sections were then cut and polished from each knife replica at every 1 mm up to 25 mm in the active part. Images of the replicas were captured with a Multicheck PC 500 microscope (Blickle GmbH, Gammertingen, Germany) mounted with a ×30 lens and analyzed by MS Windows operating software (version 2.9) (Microsoft, Redmond, WA). The edge recession was measured as the distance from the apex of the angle formed by the planes of the rake and clearance faces to the tip of the cutting edge at the nearest point. Thus, 25 measurements per replica were taken and averaged to determine the worn tool edge profile.

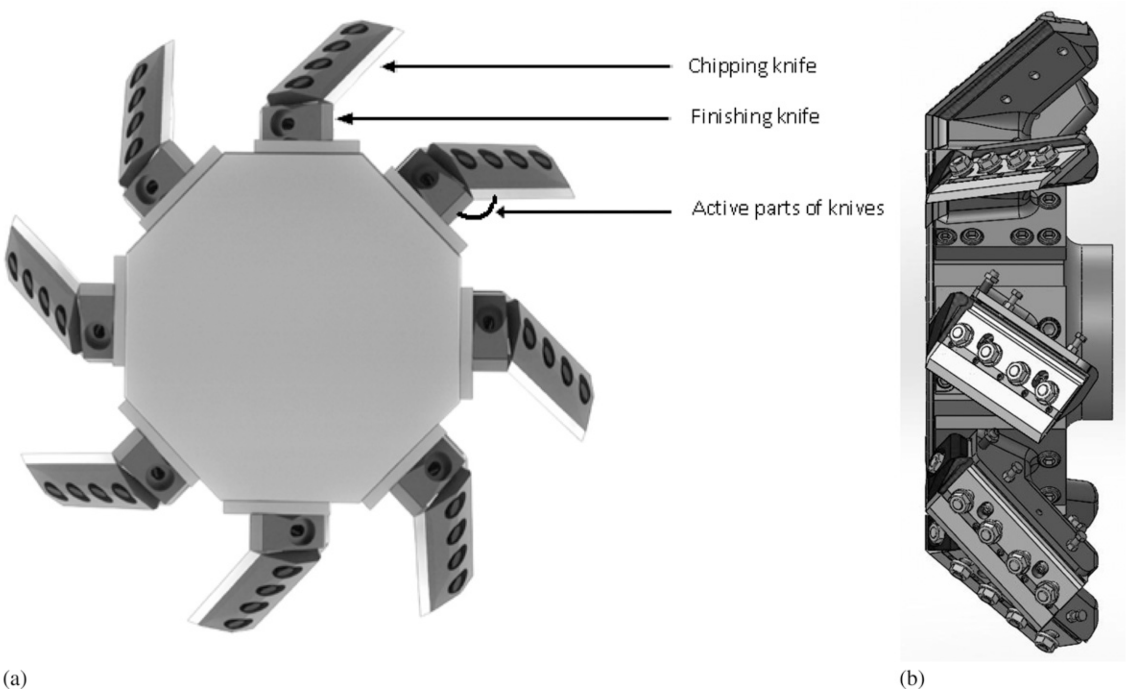

Figure 1. Front (a) and side (b) views of the industrial chipper-canter with separate chipping and finishing knives (photo published with permission of DK Spec).

The knives were then mounted in the laboratory chipper-canter. The logs were processed with rotation and feed rates set at 726 rpm and 145 m/min, respectively. These rates gave a calculated feed per knife (or chip length) of 25 mm. The maximum cutting width remained 25 mm throughout the log. The logs were fixed in the log carriage with five hydraulic arms ending with picks. Rake angle of the canting knife was set at 59° with a tool angle of 30° before the application of a bevel of 5° on its rake face. This bevelling produced an initial mean edge recession of 207 μm in the freshly sharpened knives. The nominal tool angle then became 35°, resulting in an initial rake angle of 54°. Bevelling is a current practice in sawmills to increase wear resistance of knives.

Prior to machining, log temperature was measured using a digital thermometer to the nearest 0.1°C at two uniformly spaced points at a depth of 20 mm. One side of the log was first machined in the frozen condition (below −23°C, on average). Each time, only one frozen log was transported to the laboratory for the machining test to keep wood temperature loss at a minimum. Immediately after machining, the log was wrapped with plastic again and left at ambient temperature (about 20°C) for 24 h to attain the unfrozen condition. The opposite side of the same log was machined 1 da later in the unfrozen condition (above 14°C, on average) with the same knives. The same procedure was followed to machine logs after 0 (freshly sharpened), 8, 16, 32, 48, and 80 h of working. For this, each time, the knives were removed from the laboratory chipper-canter and installed in the sawmill chipper-canter (to induce knife wear). The sawmill principally processed black spruce logs ranging between 100 and 150 mm in diameter and at variable cutting parameters. The cutter head of this machine rotated at 580 rpm, and the logs were fed at 137 m/min, giving a nominal feed per knife of 29 mm. When the specified number of hours were achieved, knives were removed from the sawmill machine and reinstalled on the laboratory chipper-canter, after first measuring the edge recession as previously explained. The details of edge recession obtained by different hours of machining are shown in Table 1.

Log Properties and Surface Quality Measurement

Prior to machining, one disk from each end of a log was cut to assess mean basic density and MC of sapwood and heartwood. Basic density was calculated as the ratio of oven-dry weight and green volume. Mean thickness of sapwood was also measured from the same disks. Cants obtained after laboratory machining were cut into 660-mm-long boards from each side for surface topography assessment.

Surface topography of cants was measured using a Microtrack system 7000 (MTI Instruments, Inc., Albany, NY) provided with two MT-250 sensor laser heads. The data were collected with LabView software (National Instruments Corp., Austin, TX) using an acquisition frequency of 50 Hz and a scanning rate of 15 mm/s. Given that the knives were removed from the laboratory

Table 1. Wood properties of logs used for the six levels of knife wear studied in the experiment.[a]

Sawmill use (h)	Edge recession of knives (μm)	Log temperature (°C)		Thickness of sapwood (mm)	MC (%)		Basic density (kg/m^3)	
		Unfrozen	Frozen		Sapwood	Heartwood	Sapwood	Heartwood
0	207	16.0 (0.2) B	−6.9 (1.6) A	11.9 (0.6) A	114 (9) BC	33 (1) A	455 (12) A	452 (8) AB
8	290	16.6 (0.5) B	−24.1 (0.3) BC	12.4 (0.7) AB	106 (7) B	34 (1) AB	485 (9) B	464 (6) B
16	349	18.2 (0.3) C	−23.6 (0.3) B	14.3 (0.6) B	130 (7) C	38 (1) BC	455 (9) A	450 (8) AB
32	449	26.4 (0.3) E	−24.1 (0.3) BC	12.9 (0.8) AB	84 (9) A	37 (3) ABC	453 (14) A	442 (10) AB
48	519	20.6 (0.2) D	−24.4 (0.3) BC	13.4 (0.8) AB	133 (5) C	41 (2) C	444 (8) A	440 (7) A
80	549	14.6 (0.4) A	−25.9 (0.3) C	13.8 (0.8) AB	126 (5) C	47 (2) D	449 (8) A	444 (7) AB

[a] Values are means (standard errors of the means) of 14 replicates. Means within a column followed by the same letter are not significantly different at the 5% probability level.

cutter head repeatedly and were sent to the sawmill for wearing, only across-the-grain measurements were performed to avoid errors related to knife reinstallation. Sixteen profiles (one per knife mark) representing two rotations of the cutter head were taken per board. The length of each profile corresponded to the width of each board. Following the procedure described in Hernández et al (2010), 12 surface quality parameters (ISO 1997) were determined using the task software developed with LabView (Table 1). A cutoff length of 2.5 mm and the robust Gaussian filter (ISO/DTS 2007) were applied for calculations. Maximum depth in each profile was also measured and was considered as the maximum torn grain depth.

Statistical Analysis

Statistical analysis was performed using the statistical analysis system (SAS) package version 9.3 (SAS Institute 2013) following the mixed procedure with the significance level fixed at 0.05. There was a large variation in log temperature for the frozen condition while machining with freshly sharpened (0 h) knives (Table 1). Thus, this group of data were discarded from all statistical analyses. Raw data were first evaluated with the Box and Cox method showing the more fitted transformation if required. All surface parameters were thus transformed using the logarithmic transformation. Given the number of roughness and waviness parameters involved, a principal component analysis (PCA) was then applied to data to regroup them in common factors and facilitate their analysis. A univariate analysis of variance (ANOVA) was used to evaluate the variation in surface quality of the processed cants with different wear levels. All variables related to log properties such as temperature, sapwood and heartwood MC, basic density, and sapwood thickness were used as covariates and were included in the model if they were statistically significant at the 0.05 level. Covariates not showing significant effect were gradually removed from the ANOVA to keep only those with significant influence on surface quality. The normality of data was verified using the Shapiro–Wilk test (SAS Institute 2013). Means were compared with the least square means statement from the SAS general linear model procedure (SAS Institute 2013). Correlation analyses were performed between the maximum depth of torn grain and the common factors obtained in the PCA describing roughness and waviness. Statistically significant variables were used to construct multiple regression models to estimate surface quality of frozen and unfrozen logs separately. Additional correlation analyses were made between surface parameters and physical properties of logs: temperature, thickness of sapwood, basic density, and MC of sapwood and heartwood.

RESULTS AND DISCUSSION

Physical Properties of Black Spruce Logs

Mean values of temperature, sapwood thickness, MC, and basic density of logs used for each knife wear condition are shown in Table 1. The groups of logs used for the tests had significant differences among them in terms of temperature, MC, and basic density of sapwood and heartwood. Greater difference was observed for logs used for 449 μm of edge recession, which had lower values of sapwood MC. Because of these differences among the groups of logs, log properties were considered as covariates in the statistical analyses. Nonetheless, one frozen log group (corresponding to 0 h of machining) was omitted from the analysis because its temperature was different from the others (Table 1).

Roughness and Waviness across the Grain

Principal component analysis. The purpose of a PCA is to determine the number of common factors and their factor loading (Tabachnich and Fidell 2007). The factor loading, which is obtained for each component within the factors generated by the PCA, is a type of correlation coefficient in which a higher value is associated with greater significance. A factor loading of 0.7 was selected as the lowest level to consider a given factor as significant. The number of factors was defined according to the Kaiser criterion (Kaiser 1960), which retains only the

Table 2. Factor analysis scores for all surface quality parameters following principal components initial factor method.[a]

Variable	Factor 1	Factor 2
R_a	**0.92**	0.20
R_q	**0.97**	0.20
R_p	**0.96**	0.17
R_v	**0.96**	0.17
R_z	**0.96**	0.17
R_t	**0.72**	0.31
W_a	0.17	**0.97**
W_q	0.20	**0.96**
W_p	**0.86**	0.38
W_v	**0.87**	0.39
W_z	**0.86**	0.39
W_t	0.39	**0.86**
Eigenvalue	8.89	1.93
Variance percentage	74.1	16.1
Cumulative percentage	74.1	90.2

[a] See Table 1 for variable definitions. Factor loadings higher than 0.7 are shown in bold.

factors with an eigenvalue greater than 1 (Table 2). In addition, a varimax rotation was required for the measurements.

The PCA of the profiles measured across the grain showed that 90.2% of the variance of the scaled data was explained by two factors (Table 2). The first represents all parameters of surface roughness (R_a, R_q, R_p, R_v, R_z, and R_t) and three of waviness (W_p, W_v, and W_z) and explained 74.1% of the total variance. The second was less important and accounted for 16.1% of the total variance and represented three other waviness parameters (W_a, W_q, and W_t). The latter parameters were less sensitive to changes in wear, which explained the lower participation to the explained variance. For example, W_a increased 13% for unfrozen logs between 207 and 519 μm of edge recession (from 167 to 188 μm of W_a). In contrast, roughness and waviness parameters included in factor 1 were more sensitive to changes in wear. Thus, R_a increased 60% for unfrozen logs between 207 and 519 μm of wear (from 25.4 to 39.9 μm of R_a). Hence, factor 1 was considered a better descriptor of the general roughness and waviness patterns. Also, the analysis showed that all roughness parameters were more sensitive than waviness to changes in tool wear (even for those included in factor 1).

Analysis of variance. Variance in the topography measured across the grain was hence explained by two factors as indicated in the PCA. The ANOVA showed that factor 1 was significantly affected by the wear of knives both in frozen and unfrozen conditions (Table 3). Factor 2 was also significantly influenced by knife wear but only for logs machined in unfrozen conditions.

The arithmetic mean values of roughness (R_a) and waviness (W_a), two of the 12 parameters included in the PCA, are given in Table 4 as an example. R_a was generally lower in the frozen condition compared with the unfrozen condition regardless of knife wear. All parameters included in factor 1 had the same tendency. Some of the waviness parameters of factor 2 showed opposite behavior with higher values for frozen logs but only for some levels of wear. The differences in surface quality between frozen and unfrozen logs can be explained by the effect of temperature and MC on mechanical properties of wood (Gerhards 1982; Hernández et al 2014a). Because temperature in frozen logs was below 0°C, wood strength

Table 3. *F*-values obtained from the variance analysis for roughness, waviness, and maximum depth of torn grain along with covariates showing statistically significant effects in the model.

	Surface roughness and waviness				Torn grain	
	Frozen		Unfrozen			
Source of variance	Factor 1	Factor 2	Factor 1	Factor 2	Frozen	Unfrozen
Sapwood MC	—	9.71**	5.71*	—	—	—
Sapwood thickness	—	—	—	8.09**	—	4.98*
Sapwood density	4.75*	—	6.64*	—	—	—
Heartwood density	4.11*	—	—	—	—	—
Knife wear	3.24*	0.04^{ns}	16.11**	4.29**	0.46^{ns}	1.26^{ns}

** Significant at least at 1% probability level, * significant at least at 5% probability level, ^{ns} not significant.

Table 4. Values of R_a (arithmetic mean deviation of the roughness profile) and W_a (arithmetic mean deviation of the waviness profile) for analysis across the grain.[a]

Parameter	Condition of logs	Edge recession (μm) 207	290	349	449	519	549
R_a (μm)	Unfrozen	25.4 (0.6) A	30.2 (0.7) Ba	37.0 (0.9) CDa	38.2 (1.1) Da	39.9 (1.0) Da	34.3 (0.8) Ca
	Frozen	—	27.9 (0.7) Aa	35.3 (0.9) Ba	33.7 (0.9) Bb	33.6 (0.8) Bb	33.4 (0.8) Ba
W_a (μm)	Unfrozen	167 (5) AB	173 (3) Aa	172 (6) ABa	141 (5) ABa	188 (5) Aa	161 (4) Ba
	Frozen	—	172 (6) Aa	195 (5) Ab	162 (5) Ab	191 (5) Aa	177 (6) Ab

[a] Values are means (standard errors of the means) of 14 replicates. Means within a row or column followed by the same letter are not significantly different at the 5% probability level. Uppercase letters are for comparison of means within a row. Lowercase letters are for the comparison of means within a column, for R_a or W_a separately.

increased, causing more brittle fracture behavior, which improved surface quality (Lundstrum 1985).

Differences in log properties among the groups slightly affected cant surface quality. The analysis showed that dense wood generally produced better surfaces than light wood (Table 3). It is known that denser wood normally gives lower values of roughness (Kuljich et al 2013; Hernández et al 2014b). MC of sapwood also positively affected factor 2 for frozen logs. Thus, this factor increased as MC increased. This effect could probably be related to the logs used for 449 μm of edge recession as previously mentioned. Also, MC did not affect factor 1, which appeared to be more sensitive to changes in tool wear. However, the ANOVA took into account these differences in log properties. Therefore, estimates of factors 1 and 2 were adjusted accordingly.

Profiles measured across the grain follow the movement of every single canting knife along the corresponding cutting plane. Canting knives are responsible for generating flat surfaces while breaking down the logs. Patterns of surface topography both in unfrozen and frozen conditions showed an increasing trend with increase of knife wear (Table 4; R_a is an example). Rake angle decreased as edge recession increased. Measurements from the replicas showed that rake angle changed from 54° at 0 h to about 48° after 80 h of industrial use. According to previous studies, this provokes greater cutting forces and lower surface quality (Kuljich et al 2013; Hernández et al 2014b). Also, the canting knife of the tested chipper-canter had a clearance angle of 1°. The low clearance could have caused excessive rubbing of the knife on the wood surface. The clearance angle decreased and even became negative as wear occurred. Higher friction and cutting forces resulted when the newly formed surface sprang back just behind the knife edge (Stewart 1991). These increasing forces, together with the resulting vibration, can explain the increase in roughness and waviness observed in canted surfaces.

Torn Grain Evaluation

Maximum depths of torn grain for the six studied edge recession levels while machining logs in frozen and unfrozen conditions are shown in Fig 2. The ANOVA showed that knife wear did not have any significant effect on torn grain, regardless of log temperature (Table 3). Some variability in torn grain for the unfrozen condition was explained by the variation in sapwood thickness.

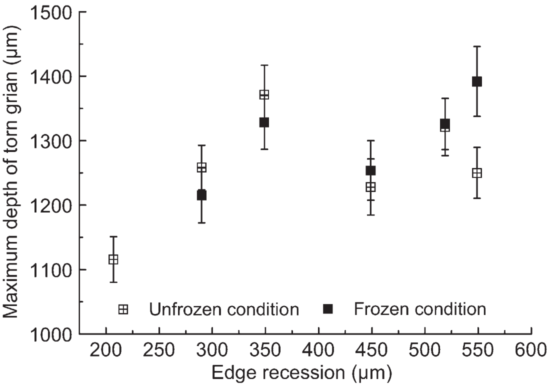

Figure 2. Effect of knife edge recession on maximum depth of torn grain. Mean values of maximum depth valley of 16 profiles in each cant are included.

The results of torn grain showed that changes in geometry of the cutting edge caused by wear did not appear to modify the type of chip formed. According to Stewart (1979), machining wood across the grain (0-90°) at high rake angles forms chip type A. This chip type forms when the wood splits ahead of the tool by cleavage following shearing failures at the knife edge until failure in bending. Chip type A is similar to type I formed when wood is machined along the grain (0-90°). Therefore, chip type A is dependent on grain deviation in logs. Maximum depth of torn grain was generally observed on surfaces near knots. The higher slope of grain near knots favored torn grain production during machining. This aspect was more important than possible effect of tool wear on torn grain production.

Nonetheless, a correlation analysis was done between the maximum depth of torn grain and roughness and waviness parameters. Factors 1 and 2 were incorporated into the correlation analysis assuming that the individual parameters would have a strong correlation with torn grain. A statistically significant correlation among the principal factors and maximum depth of torn grain existed. The corresponding regression model explained 83.1% of variation in torn grain both in frozen and unfrozen conditions. The equations obtained were as follows:

$$\begin{aligned}&\ln(\text{mean depth of torn grain})\\&\quad = 7.15 + 0.10\,\text{factor}\,1 + 0.15\,\text{factor}\,2\\&\qquad(\text{in frozen condition})\end{aligned} \tag{1}$$

$$\begin{aligned}&\ln(\text{mean depth of torn grain})\\&\quad = 7.11 + 0.12\,\text{factor}\,1 + 0.15\,\text{factor}\,2\\&\qquad(\text{in unfrozen condition})\end{aligned} \tag{2}$$

These equations indicate that the torn grain was deeper as the principal factors, ie roughness and waviness, increased. Similar results were found by Hernández et al (2010). As suggested by Hernández et al (2013), torn grain should be favored as a good predictor of surface quality. Therefore, any change in the cutting conditions for decreasing torn grain should also decrease the level of waviness and roughness. Additional correlation analyses were made between depth of torn grain and physical properties of wood, such as temperature, thickness of sapwood, basic density, and MC of sapwood and heartwood. However, no significant correlation was found among these properties.

It is therefore concluded that surface quality degraded as level of wear increased for unfrozen and frozen black spruce logs. However, there were also some operational laboratory conditions that could cover up the greater effect of knife wear on wood surfaces in industrial conditions. Undesirable vibration is generated during the industrial process and becomes more serious with increasing cutting forces and knife wear. The vibration could introduce a strong variability in wood surfaces and depends on the efficiency of the feeding system. The laboratory chipper-canter used a log carriage with five hydraulic arms ending with picks, which normally kept the log firm during cutting. Feed systems commonly used in industrial conditions include rugged steel frames with automatic self-centering belt mechanisms. These systems assure a steady feeding of logs at high feed rates but are less efficient at controlling vibrations compared with a log carriage. It is therefore expected that the wear effect on cant surface quality might be greater in industrial operational conditions than that observed in this study.

Log temperature also had an important effect on wood surface quality. Surfaces were smoother when logs were processed in frozen conditions. Several researchers have reported a similar effect of log temperature on surface quality but for other wood machining processes. For instance, Yu et al (1997) reported that surface finish of band-sawn frozen wood was better than that of unfrozen wood. Lundstrum (1985) also observed that frozen wood was more brittle than unfrozen wood and can therefore be sawn cleaner. In contrast, Orlowski et al (2009) found that mini gang sawn surfaces were smoother in unfrozen than in frozen wood. Hernández et al (2010, 2013) reported a similar effect of log temperature on cant surfaces produced by a chipper-canter in industrial conditions. For the latter case, the efficiency of the feeding system can again explain

Table 5. Parameters of surface quality used in the analysis.

Parameter	Surface quality	
	Roughness	Waviness
Arithmetic mean deviation of the assessed profile	R_a	W_a
Root-mean-square deviation of the assessed profile	R_q	W_q
Maximum profile peak height	R_p	W_p
Maximum profile valley depth	R_v	W_v
Maximum height of profile	R_z	W_z
Total height of profile	R_t	W_t

why machining frozen logs produced worse surfaces than unfrozen logs. Cutting forces increased as wear increased. This effect was more pronounced when wood temperature in winter fell below 0°C. Undesirable vibrations were generated that affected cant surfaces.

As indicated previously, tool wear during wood cutting has been described in terms of edge shape as initial, working sharp, and blunt stages (Csanády and Magoss 2013). Kivimaa (1950) also termed the first two stages as initial sharpness and work sharpness. The fine initial sharpness is retained for only a short time as a consequence of wear on the tool edge (Kivimaa 1950). The results of this study confirm that the canting knives had a high initial rate of edge recession, which decreased with machining time. The wearing trend of knives with machining time showed a sigmoid shape when plotted. Thus, knives showed a high initial rate of edge recession, which started flattening off after 48 h of sawmill use (Table 5). This pattern could represent the initial and working sharp stages of knife wear. The progression of surface roughness as a function of edge recession supports this proposal (Table 4). R_a (representing the roughness parameters of factor 1) increased during the initial period of machining and tended to remain stable afterward. This indicates that knives did not even reach blunt or catastrophic wear and could have continued to work additional hours.

CONCLUSIONS

This study revealed a significant positive relationship between knife edge recession and surface quality (roughness and waviness) of black spruce cants. Cants processed in both unfrozen and frozen conditions showed similar behavior. Processing of frozen logs resulted in better canted surfaces. Roughness was more sensitive than waviness to changes in edge recession of knives. No significant influence of wear was found on maximum depth of torn grain in the cants studied. However, the correlation analysis showed that roughness and waviness across the grain positively explained the variation of maximum depth of torn grain with an R^2 of 83%. This indicates that any decrease in torn grain would also have a positive effect on the roughness and waviness of cants. The results obtained give insight into how surface quality changes during knife wear in somewhat controlled conditions of the feeding system. It is expected that the effect of wear on cant surfaces will depend on the efficiency of the feeding system.

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