EFFECTS OF CUTTERHEAD DIAMETER AND LOG INFEED POSITION ON SURFACE QUALITY OF BLACK SPRUCE CANTS PRODUCED BY A CHIPPER-CANTER

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Abstract. The effects of the cutterhead diameter and log infeed position on surface quality of black spruce (*Picea mariana* [Mill] B.S.P.) cants processed by a conical chipper-canter were evaluated. Three cutterhead diameters (345.2, 448.7, and 661.5 mm) combined with three infeed positions or vertical distance from the cutterhead axis to the bedplate on which the log was supported, were studied. The nominal linear cutting speed was fixed at 23.5 m/s. Rotation and feed speeds were adjusted to obtain a nominal feed per knife (chip length) of 25.4 mm. For each cutting condition, two sides of the log were machined at either frozen or unfrozen wood temperatures. Surface quality was analyzed according to waviness and roughness standard parameters. Results showed that surface quality was affected by the cutterhead diameter, infeed position, and wood condition (frozen and unfrozen). Surface quality improved as the vertical distance from the cutterhead axis to the bedplate increased. The global action of the bent knife induced some vibration into the canting edge, which could explain the variation in surface quality among infeed positions. Moreover, frozen logs produced smoother surfaces compared with unfrozen logs. In addition, the effect of the angle of the canting edge with respect to the wood grain on cant surface quality depended on the orientation of the growth rings and on the wood condition (frozen and unfrozen). These results give useful information to improve surface quality within the studied range of infeed positions and cutterhead diameters.

Keywords: Chipper-canter, infeed position, attack angle, surface quality, black spruce (*Picea mariana* [Mill] B.S.P.).

INTRODUCTION

Surface quality is an essential concern in many areas of the woodworking industry. Its assessment is an important performance control tool for wood products manufacturing. Indeed, it is a criterion to determine final product quality and general wear of cutting tools as well as errors that are arising in the machining centers (Lemaster and Taylor 1999). However, assessing the wood surface quality is very complex due to

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the wood anisotropy and property variations including anatomy, density, and MC, along with the kinematics of the cutting process and machine conditions (Sandak and Negri 2005).

In fact, the surface geometry of wood can be considered as a superposition of various subgeometries related to the manufacturing process, and to the tool workpiece dynamic relationship. Also, some surface irregularities are consequence of wood properties and microstructure (Sandak 2011). In addition, wood surface characteristics might be different due to variable anatomical structures along and across the grain directions. Higher values of surface roughness are generally obtained from measurements made across the grain than along the grain (de Moura and Hernández 2006; Hernández and Cool 2008).

In eastern Canada, chipper-canters are frequently used in softwood sawmills, due to the beneficial effect of producing squared lumber and chips in a single operation. Although the surface of cants is frequently obtained by finishing or canting knives, its quality is, in certain cases, unsatisfactory. Some machine manufacturers install a thin circular saw to increase this quality. However, the saw increases the proportion of fines (sawdust), which is not desirable as raw material for the pulp and paper industry. Therefore, improving the surface of cants produced by the canting knives is certainly desirable. In fact, producing a good surface from the first step of log processing should contribute minimizing production costs, material losses from lumber oversizing, lumber grading, and expenses during secondary breakdown operations.

The most common chipper-canter used in eastern Canada has a conical-shaped cutterhead fitted with uniformly distributed knife holders, each with a bent knife and a knife clamp (Fig 1). The bent knife has two cutting edges that are joined at an angle; a longer or chipping edge and a shorter or canting edge. In some cases, the bent knife is replaced by a dual-knife set. The cutting work is performed by the simultaneous action of both cutting edges. The chipping edge severs a slice nearly across the end-grain (tendency to a 90-90° mode) to produce chips and the canting edge smooths the cant when cutting across the side-grain (tendency to a 0-90° mode) (Fig 2a-c). The feed per knife defines the thickness of the slice, which will correspond with the length of produced chips. The type of wood failure (splitting or shear parallel) during fragmentation mainly depends on the attack angle formed by the rake face of the chipping edge and wood grain (Kuljich et al 2017).

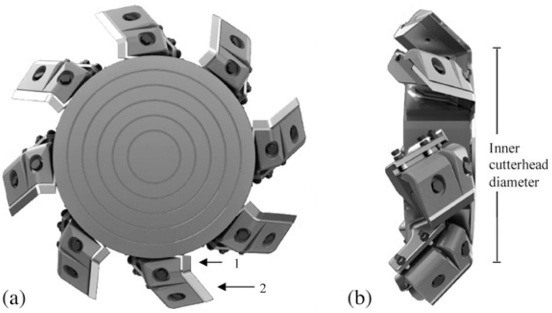

Figure 1. (a) Front and (b) side views of a conical-shaped cutterhead fitted with eight uniformly distributed knife holders, each with a bent knife and a knife clamp. The bent knife has two cutting edges that are joined at an angle; (a_1) the shorter or canting edge smooths the cant and (a_2) the longer or chipping edge severs a slice to produce chips (courtesy of DK-Spec Inc.).

Surface quality of cants produced by the chipper-canter was found to be affected by some cutting parameters like the cutting width and cutting height (Hernández et al 2010), rake angle and cutting direction of the canting edge with respect to the grain (Kuljich et al 2013; Hernández et al 2014a), and knife wear (Ghosh et al 2015). The condition of the wood, whether frozen or unfrozen, also influenced surface quality produced by chipper-canters (Ghosh et al 2015; Hernández et al 2010, 2013). On the other hand, this quality remained similar when cutting speed varied from 18.9 to 27.1 m/s (Hernández et al 2013). Cant surface quality was measured in terms of roughness (R) and waviness (W) standard parameters, as well as for the occurrence of torn grain. The correlation between R, W, and torn grain was found to be very high (Hernández et al 2010, 2014a; Kuljich et al 2013).

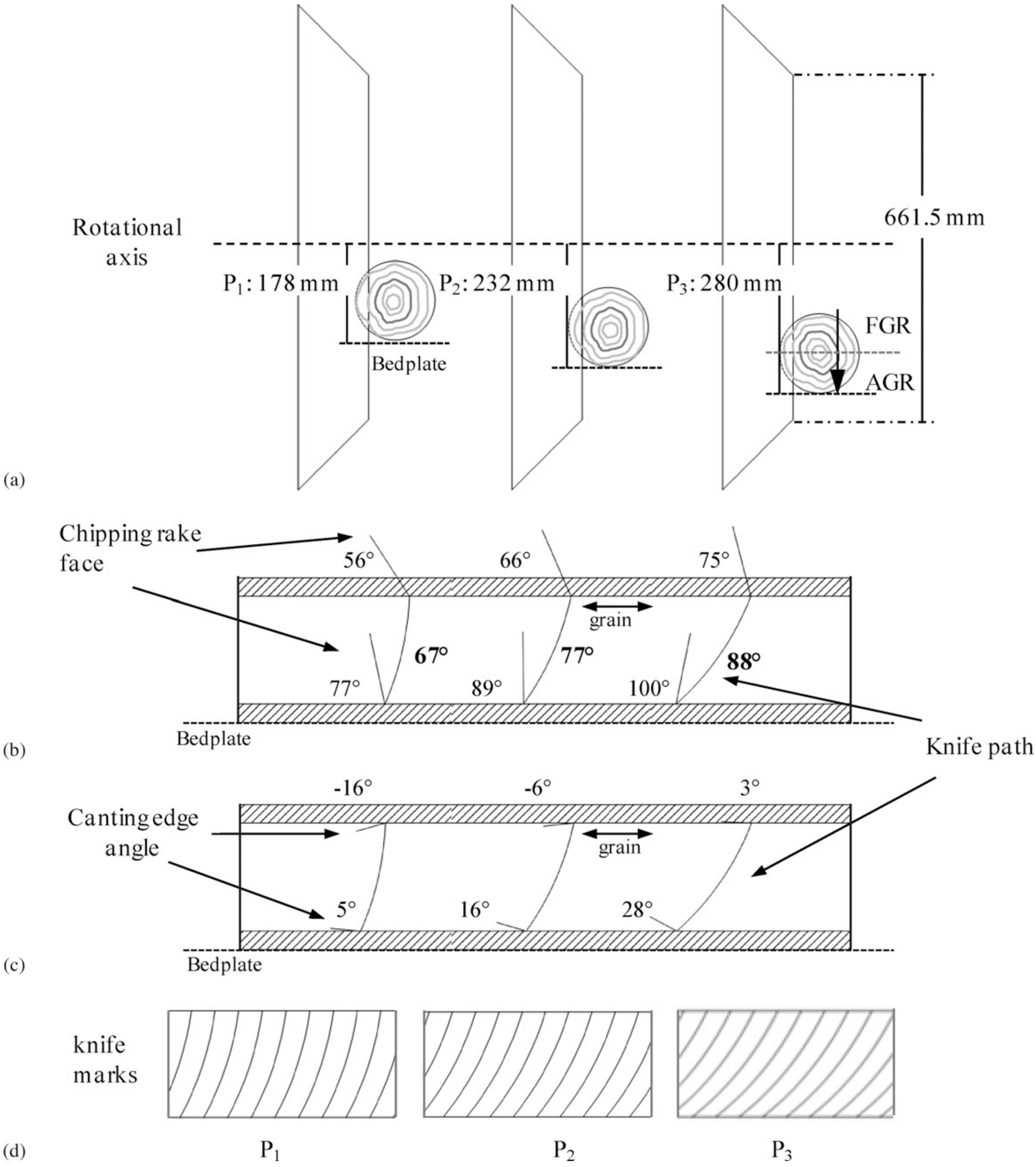

Figure 2. Diagram showing details of the three log infeed positions for the larger cutterhead tested (ø 661.5 mm). (a) Side view of P_1-P_3 infeed positions. The canting edge enters the log following the orientation of the growth rings (FGR) until it reaches the center of the cant (discontinued gray line). From this center to the knife exit, the canting edge cut against the orientation of the growth rings (AGR). (b) Front view of the attack angle formed by chipping rake face and wood grain direction. This angle varies through the cutting path. (c) Front view showing the angle between the canting edge and wood grain, which also varies through the cutting path. (d) Front view of the knife mark patterns generated for each infeed position.

The purpose of this study was to evaluate the effects of cutterhead diameter and log infeed position on the surface quality of black spruce cants produced by a conical chipper-canter. These effects were tested by machining logs under frozen and unfrozen wood conditions. Surface quality was assessed by means of waviness and roughness parameters.

MATERIALS AND METHODS

Testing Material

Tests were carried out with 126 logs of black spruce (*Picea mariana* [Mill] B.S.P.) coming from the region of Mauricie in central Quebec. This tree is one of the most important boreal species in eastern Canada and is part of the spruce-pine-fir wood group, which is widely used for construction applications and in the pulp and paper industry (Zhang and Koubaa 2008). Logs were freshly debarked and crosscut at 2.80 m long. The crosscutting position was chosen to have a small end diameter of 152.4 mm, which yielded a mean taper of 6.8 mm/m. The logs were without crook or visible decay, and had straight grain and concentric growth rings. The logs were stored green at −30°C to maintain MC until the day of the transformation.

Specific Gravity and MC Measurements

Two 100-mm-thick disks from each end of the log were first cut to prepare specimens for physical tests. The two extreme disks were used to measure sapwood thickness. The other two disks were used to assess mean specific gravity (SG) and MC of both sapwood and heartwood at the time of log transformation. SG was reported as the oven-dry weight and green volume ratio. A sample of sapwood and another of heartwood were obtained from each disk to yield a total of 504 samples. All samples were 30-mm wide and 100-mm long. Thickness of samples varied depending on sapwood thickness of each log.

Log Processing

Logs were processed with a laboratory chipper-canter equipped with one cutterhead manufactured by DK-Spec (Quebec, Canada) that had the shape of a shallow truncated cone (Fig 1). The experiment consisted of processing 2.4-m-long logs using three cutterheads with 345.2, 448.7, and 661.5 mm of inner cutting diameter (Fig 1b). The cutterhead was fitted with six or eight (depending on its diameter) uniformly distributed knife holders, each of them with a bent knife and a knife clamp. For each cutterhead, logs were fed at three infeed positions or height positions. This position is defined by the vertical distance from the cutterhead axis to the bedplate on which the log was supported (Fig 2a). Fourteen logs were processed for each of the nine cutting conditions studied.

For the chipping edge of the bent knife, the angle between its rake face and the grain direction was calculated and named angle of attack (AA). This angle varies through the cutting path (Fig 2b). Thus, a mean AA between the positions of entry and exit of the knife during cutting could be calculated (Table 1; Fig 2b). The mean AA varied according to the cutterhead diameter and log infeed position. On the other hand, the angle between the canting edge of the bent knife and the grain direction (AC) was also calculated for each cutterhead diameter and log infeed position (Table 1; Fig 2c). AC also varies through the cutting path of the bent knife and depends on the cutterhead diameter and log infeed position. One particularity of the canting edge is that it enters the log following the orientation of the annual growth rings (earlywood/latewood bands) until it reaches the center of the cant. From this point, the canting edge cuts against the orientation of the annual growth rings (Fig 2a).

The knife angle of the canting edge was 30°, with a nominal rake angle of 59° and a clearance angle of 1°. All knives were freshly sharpened before the experiment to minimize the effect of tool wear on surface quality. Cutting

Table 1. Angle of attack of the chipping rake face (AA) and angle of the canting edge respect to the grain (AC) for each cutterhead diameter and infeed position.

		AA[c]			AC[c]		
Cutterhead diameter[a] (mm)	Infeed position[b] (mm)	Entrance	Exit	Mean	Entrance	Exit	Knife path length[d] (mm)
345.2	135	49	90	70	−25	17	124
	147	53	96	75	−20	23	129
	160	60	103	82	−16	29	137
448.7	148	52	84	68	−20	11	122
	174	59	92	75	−14	19	129
	199	66	102	84	−7	29	141
661.5	178	56	77	67	−16	5	120
	232	66	89	77	−6	16	130
	280	75	100	88	3	28	148

[a] Distance between the junction point of canting and chipping edges of two opposite knives (See Fig 1b).

[b] Vertical distance from the rotational axis of the cutterhead to the bedplate on which the log was supported.

[c] See Fig 2b-c.

[d] Length of the arc formed by the engagement of the knife into the log.

width was held constant at 25.4 mm (along the log) to reduce effects of the log taper and cutting height on surface quality. Five clamps in the carriage held the log in place to reduce vibration during the log processing. The linear cutting speed was set at 23.5 m/s and calculated at the junction point between the chipping and canting edges of knife. Rotation and feed speeds were adjusted to obtain a nominal chip length of 25.4 mm. The cutting parameters for all studied conditions are shown in Table 2.

The study was done in two steps to simulate seasonal differences during log transformation (frozen and unfrozen temperature conditions). Temperature of log was measured at two uniformly distributed points at a depth of 25 mm with a digital thermometer to the nearest 0.1°C. The log was always fed by the small end first, and it was machined flat on one side at frozen temperature conditions (−25°C). The other side was processed once that the log reached room temperature (21°C, unfrozen side). As soon as the log was transformed, all chips produced were collected in plastic bags. Cants were wrapped in polyethylene and stored in a −5°C freezer along with chips bags for further analysis.

Surface Topography Evaluation

Depending on the cutterhead diameter and infeed position used for processing logs, nine

Table 2. Cutting parameters of the chipper-canter during the log transformation.

Cutterhead diameter[a] (mm)	Number of knives	Infeed position[b] (mm)	Nominal linear cutting speed[c] (m/s)	Rotation speed (rpm)	Feed speed (m/min)	Nominal chip length (mm)
345.2	6	135	23.5	1300	198	25.4
		147				
		160				
448.7	6	148		1000	152	
		174				
		199				
661.5	8	178		679	138	
		232				
		280				

[a] Distance between the junction point of canting and chipping edges of two opposite knives (see Fig 1b).

[b] Vertical distance from the rotational axis of the cutterhead to the bedplate on which the log was supported.

[c] Calculated at the junction point between the canting and chipping edges of the knife.

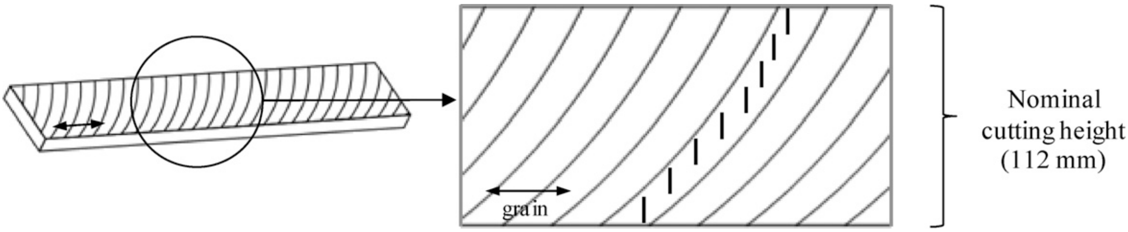

Figure 3. Diagram showing the knife mark pattern produced when machining logs with the larger cutterhead diameter (661.5 mm) at 280 mm of infeed position. Eight profiles of 14-mm long across the grain were taken within each knife mark. Six or eight knife marks were assessed according to the number of knives to cover one entire tour of the cutterhead.

different knife mark patterns were produced (Fig 2d). Thus, the surface topography was assessed at the middle of the mark left by each knife to avoid any interference of the mark boundary (Fig 3). The evaluation covered one complete rotation of the cutterhead at the middle of each cant. Thus, six or eight knife marks were assessed on each cant according to the number of knives in the cutterhead (Table 2). Eight profiles of 14-mm long across the grain were taken within each knife mark. The addition of these eight profiles covered the entire path of each knife mark.

Surface profiles of cants were measured using an MTI Microtrack system 7000 (MTI Instruments Inc., Albany, NY) provided with two MT-250 laser sensor heads. The data were collected with LabView^{TM} software (National Instruments Corporation, Austin, TX) using an acquisition frequency of 100 Hz and a scanning speed of 30 mm/s. A task software developed with LabView^{TM} software was used to calculate the roughness (R) and waviness (W) parameters according to ISO 4287 (1997). The arithmetical mean deviation of the assessed profile (R_a and W_a), root mean square deviation of the assessed profile (R_q and W_q), maximum profile peak height (R_p and W_p), maximum profile valley depth (R_v and W_v), maximum height of profile (R_z and W_z), and total height of profile (R_t and W_t)) were determined using a cutoff length of 2.5 mm combined with a robust Gaussian filter (ISO 16610-31 [2010]). The first 750 μm at each end of profiles were cut to have an evaluation length with five complete cutoffs.

Statistical Analysis

Statistical analyses were performed by means of the SAS package version 9.4 (SAS Institute 2014, Cary, NC). A multivariate analysis of variance (MANOVA) was first performed to test if the physical properties were equal among the nine groups of logs used for testing the cutting conditions studied. SG and MC of sapwood and heartwood, mean thickness of sapwood, and wood volume removed during each cut were the variables tested.

A principal component analysis (PCA) was applied given the number of surface parameters studied (12) to regroup them in common factors to simplify their analysis. PCA produces, mathematically, several linear combinations of observed variables, each linear combination being a component. Variables that are correlated with one another but largely independent of other subsets of variables are combined into components (Tabachnick and Fidell 2007). The number of components was estimated according to the Kaiser criterion, which retains only components with an eigenvalue greater than 1. The raw data were first transformed using a logarithm transformation. A split-plot analysis of variance (ANOVA) was then used to evaluate the surface quality variation of the processed cants (Mixed procedure). The cutterhead diameter and infeed position were the sources of variation as main plot and temperature condition (frozen and unfrozen wood) was the source of variation as subplot. The infeed position was nested within the cutting diameter since values of this parameter were specific to each cutterhead (Table 2). All these analyses (MANOVA, ANOVA, and PCA) were performed using the average value of R and W parameters per cutting condition.

In addition, a split-split-plot ANOVA was applied to determine the effect of AC on waviness of cants. The sources of variation were cutterhead diameter and infeed position, temperature condition and AC, respectively. A regression model using the ordinary least squares estimation was performed to predict waviness as a function of AC. AC values were divided in eight categories, which depended on the cutterhead diameter and infeed position. Each category of AC corresponded to a variation of 14 mm of the cant cutting height (Table 3). Statistical significance was tested at 5% and 1% probability levels. Normality of data was verified using the Shapiro-Wilk test.

RESULTS AND DISCUSSION

The wood physical properties of the nine groups of logs used for the studied cutting conditions were similar (MANOVA not shown). Therefore, mean values of SG and MC of sapwood and heartwood, thickness of sapwood, and wood volume transformed into chips during each cut were equivalent for all groups of logs. Mean SG was 0.444 for sapwood and 0.439 for heartwood. The difference was not statistically significant. However, sapwood MC (126%) and heartwood MC (38%) were statistically different. Sapwood thickness and wood volume removed during each cut were in average 15 mm and 0.00483 m^3, respectively.

The topography of cants in terms of the patterns of knife marks obtained for each cutting condition was as expected (Fig 4). In general, the length of the knife marks corresponded to the nominal feed per knife of 25.4 mm. However, the visual inspection of cants showed some particularities indicated below.

- First, the presence of knots affected negatively the cant surface quality. Surface defects like torn grain were always produced near the knots (Fig 4).
- Second, the cants in general showed coarser surfaces at their bottom half (Fig 4). This was especially important for cants produced from unfrozen logs. Through the cutting path, the canting edge travels following and against the orientation of growth rings. The increase in waviness at the bottom half of cants appeared to be, in part, a result of cutting against the orientation of growth rings. This, combined to an AC of 0°, would potentially decrease even more the surface quality at the bottom of the board. When AC is 0°, the canting edge is oriented parallel to the earlywood/latewood bands. The strength differences between bands produced a discontinuous cutting. Latewood can be as 1.7 denser than earlywood for black spruce (Zhang and Koubaa 2008). The canting edge traveled through denser/softer zones with a tendency of cutting deeply when it reached softer zones (earlywood), which

Table 3. Variation of AC through the cutting path (each angle correspond to an average of a segment of 14 mm of the nominal cutting height of the cant [112 mm]).

Cutterhead diameter (mm)	345.2			448.7			661.5		
Infeed position (mm)	135	147	160	148	174	199	178	232	280
AC	−21.9	−17.6	−13.5	−18.5	−11.9	−5.0	−14.4	−4.7	4.4
	−16.8	−12.2	−7.8	−14.6	−7.8	−0.5	−11.8	−1.9	7.6
	−11.6	−6.8	−2.1	−10.8	−3.6	4.0	−9.2	0.9	10.8
	−6.4	−1.4	3.7	−6.9	0.5	8.5	−6.6	3.8	14.0
	−1.3	3.9	9.4	−3.0	4.6	13.0	−4.0	6.6	17.2
	3.9	9.3	15.2	0.9	8.7	17.5	−1.4	9.4	20.4
	9.1	14.7	20.9	4.8	12.9	22.0	1.2	12.2	23.6
	14.2	20.1	26.6	8.7	17.0	26.5	3.8	15.1	26.8

AC, angle of the canting edge respect to the grain.

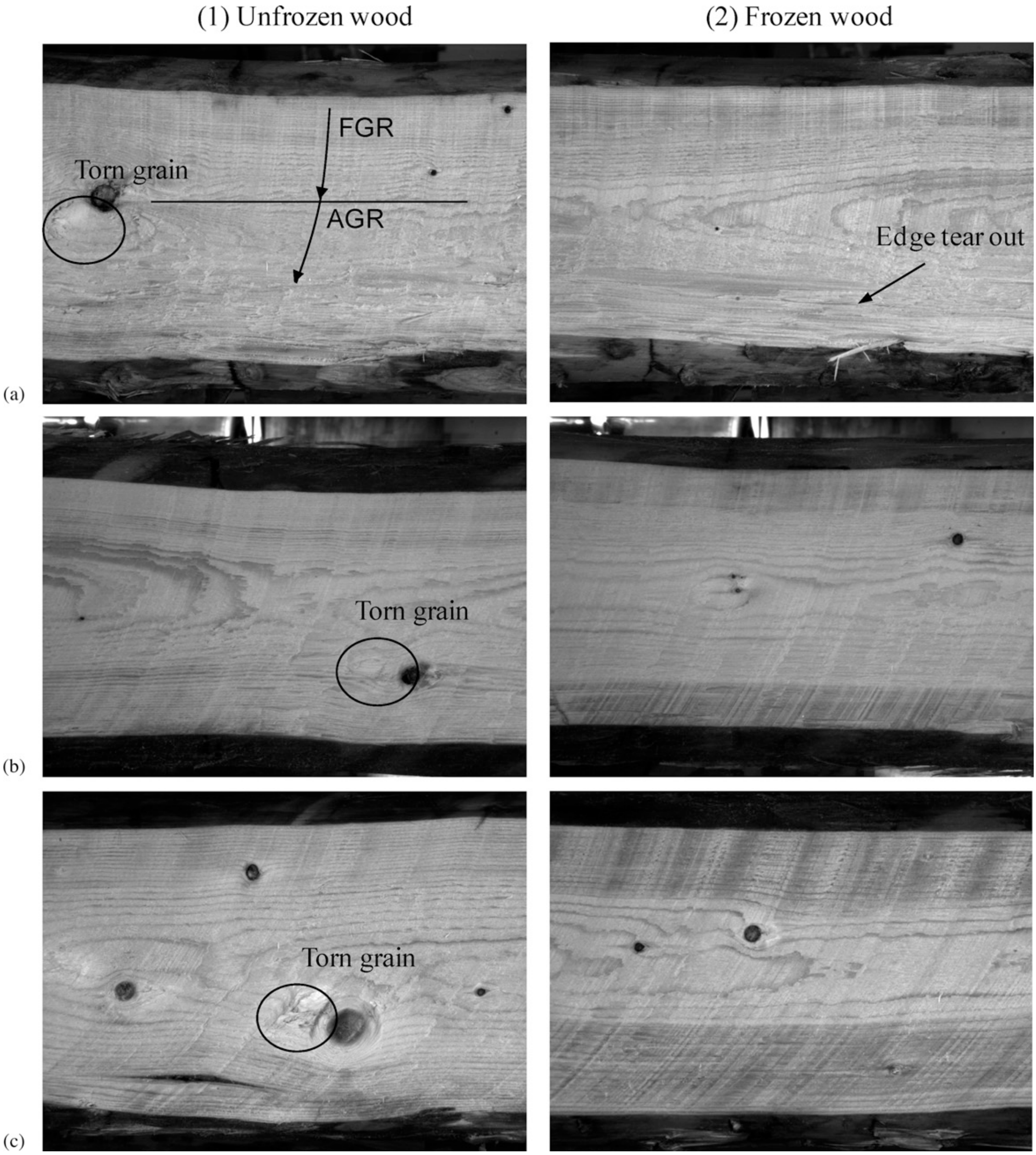

Figure 4. Surfaces produced while processing (1) unfrozen and (2) frozen logs with the larger cutterhead diameter (ø 661.5 mm) at the three infeed positions: (a) 178 mm, (b) 232 mm, and (c) 280 mm. Generally, frozen logs produced smoother surfaces compared with unfrozen logs; surfaces were coarser at the cant bottom half; and defects like torn grain were produced near the knots. At 178 mm of infeed position, angle between the canting edge and wood grain at the point of exit of the log was quite low (5°) producing an important tear out along the cant edge.

Table 4. *F* values obtained from the ANOVAs for waviness and roughness.

Source of variation	*F* Value	
	Waviness	Roughness
Cutterhead diameter	21.83**	50.94**
Infeed position (diameter)	17.17**	4.76n.s.
Temperature condition	6.85**	0.07n.s.
Diameter* temperature condition	0.84n.s.	0.48n.s.
Infeed position* diameter* temperature condition	1.42n.s.	1.5n.s.

ANOVAs, analysis of variances.

**Statistically significant at the 1% probability level; n.s not statistically significant.

increased waviness. When cutting frozen logs, the increased strength of earlywood due to the presence of frozen water compensates the strength differences between bands. Thus, smother surfaces were produced.

- Finally, surfaces produced with the larger cutterhead (661.5 mm in diameter) at 178 mm of infeed position were of lower quality at the bottom edge of the boards. At this particular cutting condition, AC at the point of exit of the log was quite low (5°, see Fig 2c). This low AC produced an important tear out along the cant edge (Fig 4). Lower exit angles increase the unit shear stress component across the grain along the edge of the log (Stewart 1985). In contrast, as the exit angle increases, only one point of the canting edge crosses the exit edge at a time, which should generate a cleaner cut. Thus, the AC at the exit point of the log should be at least higher than 11°.

On the other hand, the PCA showed that 97% of the variance of topography scaled data was explained by two common factors (or components). The first factor represents surface waviness having high factor loadings for W_a (0.92), W_q (0.91), W_p (0.89), W_v (0.84), W_z (0.84), and W_t (0.84). The second stands for surface roughness. It had high factor loadings for R_a (0.87), R_q (0.87), R_p (0.89), R_v (0.91), R_z (0.91), and R_t (0.81). Each of the two factors explained 48.5% of the total variance.

Surface quality was therefore assessed by means of waviness and roughness (factors 1 and 2, respectively, in PCA). The ANOVA showed

Table 5. Averages of W_a (arithmetic mean deviation of the waviness profile) and R_a (arithmetic mean deviation of the roughness profile) of black spruce cants.

Cutterhead diameter (mm)	Infeed position (mm)	W_a	R_a
		μm	
345.2	135	29[a] (2)[b] a[c]	20.5 (0.7) a
	147	29 (2) a	20.7 (1.2) a
	160	29 (1) a	21.4 (1.0) a
	Mean	29 (1) A	20.9 (0.4) A
448.7	148	33 (2) c	19.5 (0.9) a
	174	28 (2) b	19.6 (0.9) a
	199	26 (2) a	20.6 (0.6) a
	Mean	29 (1) A	19.9 (0.4) A
661.5	178	46 (3) b	28.7 (1.2) a
	232	35 (2) b	24.9 (1.1) a
	280	33 (2) a	25.0 (0.9) a
	Mean	38 (1) B	26.2 (0.4) B

[a] Means of 28 replicates.

[b] Standard error of means in parenthesis.

[c] Means within a column followed by the same letter are not significantly different at the 5% probability level. Uppercase letters are for comparison of means among cutterhead diameters (means). Lowercase letters are for the comparison of means among infeed positions, for each cutterhead separately.

that surface quality was, in general, significantly affected by the cutterhead diameter, infeed position, and temperature condition (frozen and unfrozen wood) (Table 4). Thus, waviness was affected by the three sources of variation, whereas roughness was only affected by the cutterhead diameter. Means of W_a and R_a (two of the 12 parameters included in the PCA) are shown in Table 5.

Effect of Cutterhead Diameter

Waviness and roughness were greater when processing logs with the larger cutterhead diameter (661.5 mm in diameter) compared with the other two (448.7 and 345.2 mm in diameter) (Table 5). This can be explained by a combination of factors that could have increased the vibration on the larger cutterhead. First, taking into account the perimeter of the cutterhead, the number of knives was six for the smaller and medium cutterheads (345.2 and 448.7 mm in diameter, respectively), and eight for 661.5-mm-diameter cutterhead. Thus, the smaller and medium cutterheads could have been more balanced that the larger one. Even small errors in balance can produce surface quality problems due to vibration. Second, the distance between successive knives within the cutting circle was 181, 235, and 260 mm for the 345.2, 448.7, and 661.5 mm cutterheads, respectively. Knowing that one knife cut at a time, the period between the end of cut of a knife and the beginning of the next one was longer for the larger cutterhead. Higher periods of nonwood cutting could have destabilized the cutterhead and increased vibration. Any misalignment of the cutterhead could also have produced lateral vibration, which could be higher as the size of the cutterhead increased. Several works have demonstrated the high relationships between lateral or normal vibrations and surface roughness and waviness (Lemaster et al 2000; Jackson et al 2007; Iskra and Hernández 2012).

On the other hand, Jackson et al (2002) have reported that structural vibration is one of the major causes of machine-induced waviness defects and, as such, is an indicator of the machine structural quality. They have also mentioned that larger machinery can often conceal structural weaknesses. Thus, the increase in vibration (because of factors mentioned earlier) as the cutterhead diameter increased, could have decreased the surface quality of cants produced by the larger cutterhead (661.5 mm)

Effect of Infeed Position

Waviness of cants generally decreased as the distance from the cutterhead axis to the bedplate increased. This was true for logs processed with the medium and larger cutterheads (448.7 and 661.5 mm in diameter, respectively). However, the infeed position had a negligible effect on surface quality produced by the smaller cutterhead (345.2 mm in diameter). The effect of the infeed position on surface quality was probably due to an influence of the global cutting action of the bent knife on the canting edge. According to Kuljich et al (2015), the cutting work of a chipper-canter is in fact performed by the simultaneous action of both cutting edges. The chipping edge severs a slice to produce chips, and the canting edge smoothes the cant. The feed per knife ensures the thickness of the slice and the length of the chips. The chips are mainly produced by splitting or shear failure parallel to the grain. Therefore, the energy required for cutting is a sum of contributions of different actions. Cutting the slice of wood by the chipping edge is probably the action that demands the most energy. As mentioned previously, the chipping edge severs a slice of wood by cutting the log across the end-grain. Rupture occurs in that case by cross-cutting the fibers by shearing perpendicular to the grain. The canting edge smoothed the cant surface by cutting nearly across the side-grain, where rupture occurs by shearing or splitting oblique to the grain (Table 1). The shear strength perpendicular to the grain is higher than shearing oblique to the grain. Thus, the forces generated at the chipping edge should be greater than the ones generated at the canting edge. This could have introduced some vibration into the canting edge.

The vibration would be lower as the distance from the cutterhead axis to the bedplate increases due to a higher mean AA (Fig 2b). Kuljich et al (2017) reported that as mean attack angle increased, chip fragmentation occurred more by splitting parallel to the grain. In contrast, as the log infeed position approached the cutterhead axis, mean AA decreased. Smaller AA increased the parallel to the grain compression component (compressive stresses that are induced in the wood area in contact with the chipping rake face), which led to a failure by shear parallel to the grain. Because splitting strength is lower than shear strength, stresses would decrease as the distance bedplate is moved away from the cutterhead axis (or as mean AA increased). Therefore, vibration induced into the canting edge due to the cutting action of the chipping edge also decreased as the distance from the cutterhead axis to the bedplate increased. Finally, waviness decreased as the distance from the cutterhead axis to the bedplate increased when processing with the medium and larger cutterheads (448.7 and 661.5 mm in diameter, respectively). The insignificant effect found for the smaller cutterhead (345.2 mm in diameter) was probably due to the lower variation in mean AA between infeed positions (10°, compared with 16° or 20° for the medium and larger cutterheads, respectively) (Table 1).

Surface Quality for Frozen and Unfrozen Wood Conditions

Frozen cants showed lower waviness compared with unfrozen cants (Table 4). Wood strength increases as temperature decreases below 0°C at higher moisture contents (Gerhards 1982; Hernández et al 2014b) causing more brittle fracture behavior (Lunstrum 1985). Therefore, frozen wood can be cut cleaner than unfrozen wood, which improved surface quality. Similar results were reported by Ghosh et al (2015). Other studies on surface quality of cants produced by this machine found the opposite behavior. Unfrozen logs produced smoother surfaces than frozen logs (Hernández et al 2010, 2013). The latter results were attributed to a lower efficiency of feeding systems in industrial sawmill conditions, which became critical for frozen logs. Vibration during cutting increased due to the increase of cutting forces as wood temperature decreased below 0°C.

Effect of the Angle between the Canting Edge and the Grain Direction

A split-split-plot ANOVA (not shown) was applied to determine the effect of AC on waviness (factor 1 of the PCA). This analysis showed that the effect of AC on waviness depended on the cutterhead diameter, infeed position, and temperature condition. Regression analyses were then applied to explain the influence of AC on W_a for each cutting condition. W_a was selected for these analyses because it showed the higher factor loading (0.92) for waviness in the PCA. In general, the best model representing the relationship between AC and waviness was a linear function. However, some conditions were best fitted with a quadratic function (Fig 5). The coefficients, overall significance (F value), R^2, and standard error (SE) of each function are shown in Table 6. SE indicates how close the observed data are to the function-predicted values. Thus, lower values indicate better fit. The F values were statistically significant for almost all cutting conditions. Thus, the relationship between AC and waviness is statistically significant and the observed R^2 are statistically reliable. R^2 were in general high, which means that AC is in some degree responsible for the waviness variation of cants produced by the chipper-canter.

The regression analysis confirmed what was noted by the visual examination of cants. Waviness generally increased as the bent knife exited the log or at the cant bottom half for all cutting conditions (Fig 5). Waviness was greater when cutting against the growth rings compared with following the growth ring orientation even though AC had the same value. In addition, this effect was more evident for unfrozen compared with frozen cants. Therefore, the effect of AC

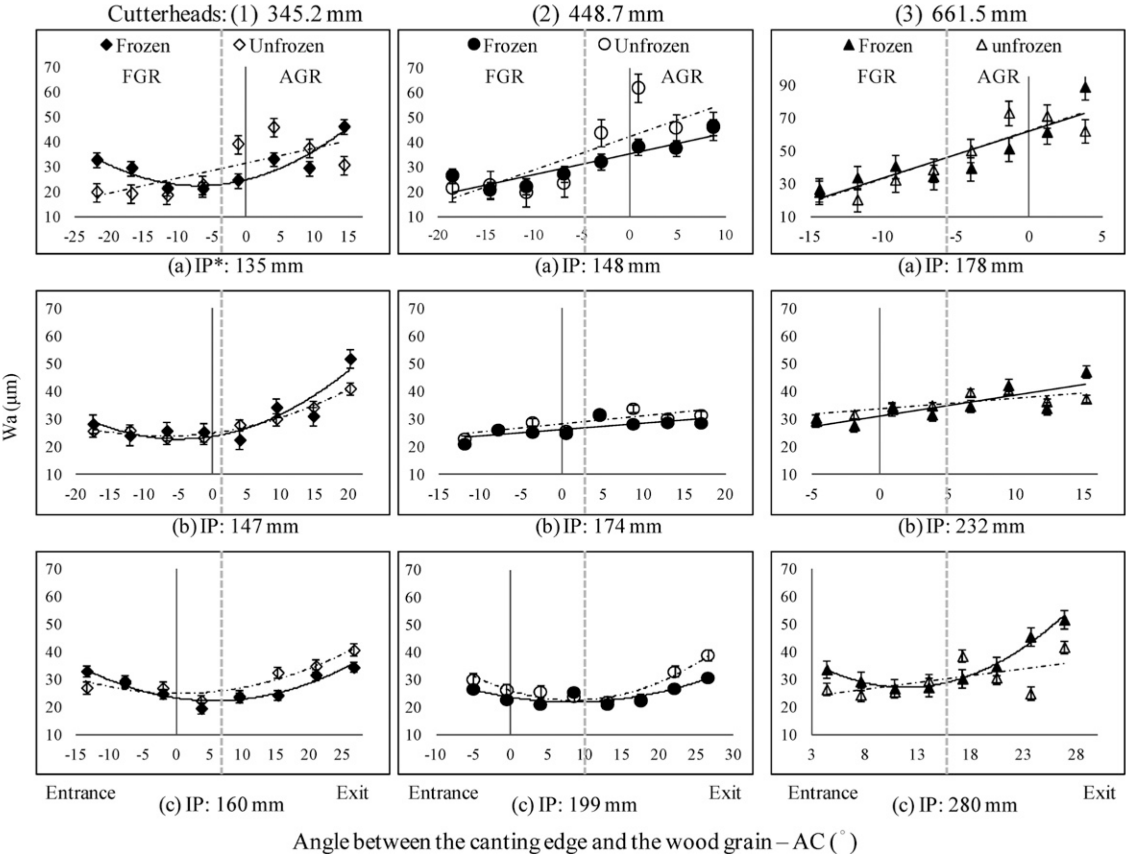

Figure 5. Effect of the angle between the canting edge and wood grain (AC) on W_a for all cutting conditions studied. The variation of AC through the cutting path is represented on the x-coordinate. Each angle corresponds to an average of a segment of 14 mm of the nominal cutting height of the cant (112 mm). The canting edge enters the log following the orientation of the growth rings (FGR) until it reaches the center of the cant (discontinued gray line). From this point, the canting edge cuts against the orientation of the growth rings (AGR). IP, infeed position.

on waviness depends on the orientation of the growth rings and whether wood is frozen or unfrozen. As previously discussed, the fact that AC reached 0° just before the bent knife passed the first half of the boards had a very harmful impact on unfrozen surfaces. Figures 5.1a and 5.2a show an important increase in W_a around 0° (AC) when cutting against the growth rings at unfrozen conditions. In contrast, W_a remained similar around 0° (AC) when cutting following the growth rings (for both temperature conditions) as shown in Figs 5.1c and 5.2c. Figure 5 shows that as the distance from the cutterhead axis to the bedplate decreases, AC would reach 0° when cutting against the growth rings. Therefore, decreasing log infeed positions should be avoided to avoid this undesirable cutting situation.

This experiment was part of a comprehensive study, which was aimed to improve conical chipper-canters performance. Energy requirements, size distribution of chips, and surface quality of cants produced by this machine were studied as a function of the cutterhead diameter, infeed position, and attack angle. Results showed that as cutterhead diameter increased its energy requirements decreased (Kuljich et al 2015). As for chip quality, as attack angle (or the distance from the cutterhead axis to the

Table 6. Regression equations applied to evaluate the effect of AC on surface waviness (W_a). Data were obtained at eight levels of AC.

Cutterhead diameter (mm)	Infeed position (mm)	Temperature condition	β_0	β_1	β_2	F value	R^2	SE
345.2	135	Frozen	25^{**}	$0\ 7^{**}$	0.05^{**}	13.7^{**}	0.85	3.8
		Unfrozen	31^{**}	0.6^{**}	—	6.8^{*}	0.53	7.8
	147	Frozen	24^{**}	0.4^{*}	0.04^{*}	12.6^{*}	0.83	4.6
		Unfrozen	24.9^{**}	0.33^{**}	0.023^{**}	94.1^{**}	0.97	1.2
	160	Frozen	23.3^{**}	-0.35^{**}	0.031^{**}	24.8^{**}	0.91	1.9
		Unfrozen	25^{**}	$-0.01^{\text{n.s.}}$	0.023^{*}	13.6^{**}	0.84	2.8
448.7	148	Frozen	35^{**}	0.8^{**}	—	28.9^{**}	0.83	4.0
		Unfrozen	42^{**}	1.3^{*}	—	$^{*}11.3^{*}$	0.65	10.0
	174	Frozen	26.2^{**}	0.23^{*}	—	7.7^{*}	0.56	2.3
		Unfrozen	28.1^{**}	0.29^{*}	—	11.1^{*}	0.65	2.4
	199	Frozen	24^{**}	$-0.4^{\text{n.s.}}$	0.026^{*}	7.3^{*}	0.74	2.0
		Unfrozen	26^{**}	-0.8^{**}	0.049^{**}	19.3^{*}	0.89	2.3
661.5	178	Frozen	62^{**}	$2\ 9^{**}$	—	23.5^{**}	0.80	9.9
		Unfrozen	62^{**}	2.9^{**}	—	28.4^{**}	0.83	9.2
	232	Frozen	31^{**}	0.8^{*}	—	12.8^{*}	0.68	4.0
		Unfrozen	34^{**}	0.4^{*}	—	9.4^{*}	0.61	2.4
	280	Frozen	43^{**}	-2.8^{**}	0.116^{**}	162.5^{**}	0.98	1.3
		Unfrozen	23^{**}	$0.5^{\text{n.s.}}$	—	$3.3^{\text{n.s.}}$	0.36	5.7

AC, angle of the canting edge respect to the grain.

**Statistically significant at the 1% probability level; *statistically significant at the 5% probability level; $^{\text{n.s.}}$not statistically significant.

bedplate) increased, the variation in the chip size distribution and chip thickness decreased (Kuljich et al 2017). Similarly, smoother cants surfaces were produced as distance from the cutterhead axis to the bedplate increased. An accurate balance process is very important to limit vibrations, especially for larger cutterhead diameters. Therefore, larger cutterhead diameters combined with a higher vertical distance from the cutterhead axis to bedplate (or greater attack angle) could be suitable to produce pulp chips and surface cants of good quality with less energy requirements.

CONCLUSIONS

This experiment showed that the cutterhead diameter, log infeed position, and wood temperature condition affected the surface quality of black spruce cants produced by a conical chipper-canter. Surface quality improved as the vertical distance from the cutterhead axis to the bedplate increased. Thus, waviness decreased as the infeed position was set away from the cutterhead axis. The influence of the AA on the canting edge could explain the variation in surface quality among infeed positions. The chipping action introduced some vibration into the canting edge, which was lower for greater attack angles (or as the vertical distance from the cutterhead axis to the bedplate increased). Moreover, frozen logs produced smoother surfaces compared with unfrozen logs.

The effect of the angle of the canting edge respect to the wood grain (AC) on surface quality depended on the orientation of growth rings and whether wood is frozen or unfrozen. An AC of 0° when cutting against the growth rings should be avoided for heterogeneous species. Low AC at the exiting point of the log should also be avoided.

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