EFFECT OF CUTTING WIDTH AND CUTTING HEIGHT ON THE SURFACE QUALITY OF BLACK SPRUCE CANTS PRODUCED BY A CHIPPER-CANTER

*Roger E. Hernández**†

Professor

Svetka Kuljich

MSc Student
Centre de Recherche sur le Bois
Département des Sciences du Bois et de la Forêt
Université Laval, G1V 0A6
Québec, Canada

Ahmed Koubaa†

Professor
Centre de Recherche sur le Bois
Université du Québec en Abitibi-Témiscamingue, J9X 5E4
Québec, Canada

(Received September 2009)

Abstract. The effects of the cutting height and cutting width on the surface quality of black spruce cants produced by a chipper-canter were evaluated. Three diameter classes (102, 152, and 203 mm dia as measured at the small end of the log) were studied, each processed using two cutting widths (12.5 and 25 mm). The rotation and feed speeds, kept constant at 783 rpm and 197 m/min, respectively, yielded a nominal feed per knife (chip length) of 31.5 mm. Twelve logs for each cutting condition were processed under frozen and unfrozen wood temperatures (winter and summer). The surface quality was analyzed using roughness and waviness standard parameters. Torn grain was evaluated by means of its maximum depth. The results showed that surface quality was affected by cutting height, cutting width, and temperature of logs. In general, surface quality was better when processing unfrozen logs at lower cutting width and height. Surface quality also varied within the cant, being generally better at the small end of the log and at the upper part of the cant. The results give useful information to improve the performance of the chipper-canter in terms of surface quality.

Keywords: Chipper-canter, surface quality, black spruce.

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. In fact, 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). Traditional methods to measure surface quality include visual and tactile approaches. Both methods are effective but are also highly subjective. Today, there are a variety of different surface texture instruments available to measure wood surface geometry, including stylus profilometers, optical profilometers, ultrasonic optical light sectioning, and image analysis using video cameras (Hendarto et al 2006).

The surface geometry of wood can be considered as a superposition of various subgeometries related to various bases (Sandak and Negri 2005). Profile data from a nominally flat surface contain form errors, waviness, and roughness.

* Corresponding author: Roger.Hernandez@sbf.ulaval.ca
† SWST member

Form errors are the long-wavelength deviations of the surface from the corresponding nominal surface that usually results from an inaccurate alignment of the workpiece or uneven wear in machining equipment (Hendarto et al 2006). Surface roughness is described as texture effects from the wood structure (anatomical roughness) and the effects produced by cutting the wood with a knife edge (processing roughness). Surface waviness is defined as the intermediate wavelength components produced by the machining process, including any deviations from the ideal waviness profile. According to Brown et al (2002), in the rotary timber machining process, waviness can result from machine vibrations, cutterhead imbalance, and flexure of the machine frame. The quality of a given surface is influenced by the type and condition of the wood workpiece, type and condition of the cutter equipment used, machine configuration, method of machine operation, and the engineering quality of the machine (Jackson et al 2002).

Once the surface profile is obtained with any profilometer, filtering is applied to remove form errors and separate the waviness and roughness profiles. The cutoff length of the filter is the value that separates the wavelength that is within the range of interest for a particular feature from those that are not (ISO 11562 1996). The evaluation of the surface quality is a numerical characterization with parameters contained in general standards. These parameters permit comparisons between different surface textures. One of the most commonly used parameters is the arithmetical mean deviation of the assessed profile, R_a, defined in ISO 4287 (1997). According to Khazaeian (2006), this parameter, along with R_q, the root-mean-square deviation of the assessed profile (ISO 4287 1997), could give a good evaluation of the topography of wood surfaces. However, R_a does not differentiate between peaks and valleys (Mummery 1992; Zani 2003). Similarly, W_z, the maximum height of the profile (ISO 4287 1997), can be calculated. Lemaster and Taylor (1999) noted that R_q and W_z are able to detect fuzzy and torn grain on wood surfaces, respectively. However, several authors state that there is not yet a definitive set of parameters for a complete assessment of wood surfaces (Funck et al 1993; Krisch and Csiha 1999; Fujiwara et al 2003; Sandak and Tanaka 2003; Gurău et al 2005; Sandak and Negri 2005).

A wood surface of good quality is desirable even in primary breakdown. In fact, the improvement of the surface from the first phase of wood processing contributes to minimize production costs, material losses from oversizing wood pieces, losses in lumber grading, and expenses during secondary breakdown operations. In Quebec province, chipper-canters are the most common primary breakdown machine being installed in sawmills. This machine has been designed primarily to convert small-diameter logs into cants with very low sawdust production. However, the cants produced often have poor surface quality. Improving the surface of the cants produced by this machine is certainly desirable.

The purpose of this study was to examine the effect of cutting width and height on the surface quality of the cants produced by a chipper-canter in processing black spruce logs. Three log diameter classes were processed using two equal cutting widths. These transformations were made under frozen (winter) and unfrozen (summer) wood conditions.

MATERIALS AND METHODS

A total of 144 stems of black spruce [*Picea mariana* (Mill) B.S.P.] were selected for this study. The stems were crosscut into 2.44-m logs and freshly debarked with a draw knife. The crosscutting position of the stem was chosen to yield logs with three specific small-end diameters. The mean diameter and log taper values for each season and cutting condition are presented in Table 1. The logs were without crook or visible decay, had a minimum of knots, and had straight grain and concentric growth rings.

Log processing was done with a Swecan™ chipper-canter with two side-opposed end-milling cutterheads that have the shape of shallow truncated cones (Fig 1). Each cutterhead

Table 1. Description of logs used in the experiments.

		Nominal diameter					
		101.6 mm		152.4 mm		203.2 mm	
Cutting width	Diameter and taper	Winter	Summer	Winter	Summer	Winter	Summer
	Small end (mm)	101.6	103.6	150.2	156.1	203.9	207.0
12.5 mm	Large end (mm)	124.5	120.7	169.5	175.1	228.8	237.1
	Taper (mm/m)	9.4	7.0	7.9	7.8	10.2	12.4
	Small end (mm)	101.7	104.5	149.9	154.6	203.2	206.9
25 mm	Large end (mm)	124.1	123.2	174.1	173.8	227.0	226.2
	Taper (mm/m)	9.2	7.7	9.9	7.9	9.8	7.9

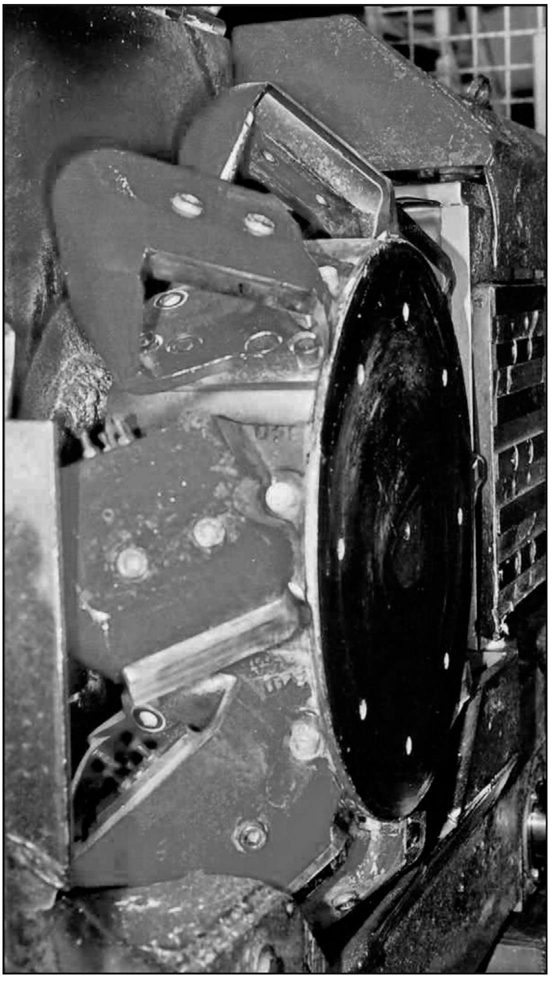

Figure 1. View of the end-milling cutterhead (left side) of the Swecan chipper-canter showing some knife holders.

is 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; the longer edge severs a slice to make chips and the shorter edge smoothes the cant. Basically, the shorter edge of the knife cuts nearly across the grain at the point of entry on the log and more obliquely to the grain as the knife exits.

The experiment consisted of processing three diameter classes of logs, each using two cutting widths (12.5 and 25 mm measured at the small-end diameter). The six profiles produced are shown in Fig 2. In addition, the seasonal effect on log processes was evaluated by conducting the experiment during winter and summer. Twelve logs were used for each cutting condition, making a total of 72 logs for each season.

Sawmill Experiments

The 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. During processing, the log was always fed with the small end first. The feed system of the chipper-canter includes a rugged steel frame with an automatic self-centering belt mechanism. The log was machined flat on only two sides to produce a cant whose cross-section depended on the cutting width and diameter to be studied (Fig 2). The cant obtained was immediately weighed, painted on both ends, and wrapped in polyethylene to maintain its initial moisture content until measurement. The knife angle of the shorter edge of the knife (finishing knife) was set constant at 28° with a rake angle of 60°. Feed speed was 197 m/min and rotation speed was 783 rpm, which gave a calculated feed per knife (or chip length) of 31.5 mm. The knives were

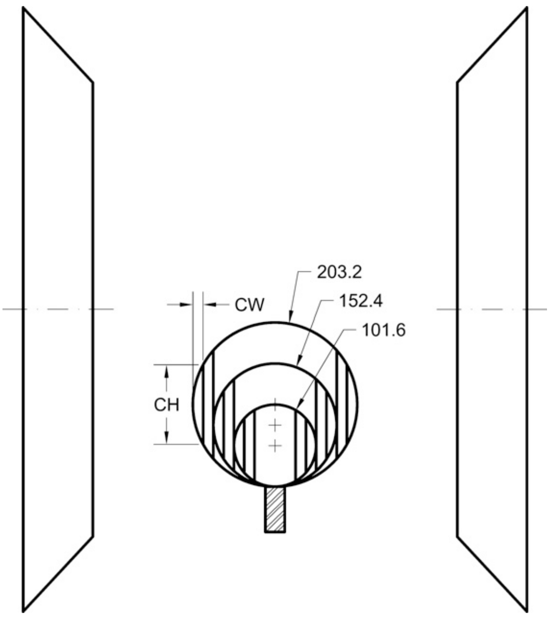

Figure 2. Diagram showing the relative position for the small log end for each diameter class (in mm) on the chipper-canter: CW = cutting width; CH = cutting height. Note that because the lower bedplate is fixed, the relative position through which the knife edge enters the wood will change with log diameter and taper.

freshly sharpened before the experiment to minimize the effect of tool wear on surface quality. The processing was done from –14 to –4°C in the winter and 20-26°C in the summer.

Laboratory Experiments

The cants were used to prepare boards for wood surface quality tests and specimens for physical property tests. Two 840-mm-long boards were cut from each side of the cant (one from the small end and one from the large end of the log). The boards from the two ends permitted evaluation of the effect of the log taper on wood surface quality. In addition, a line dividing the board into two parts (upper and lower) was drawn following the grain. This line corresponded to the longitudinal axis of the log and helped analyze surface quality from the effect of the finishing knife edge orientation with respect to the wood grain.

The round edge or waney part of the cant was used to assess the mean specific gravity as well as the moisture content of both sapwood and heartwood. A total of 864 sapwood and heartwood samples were obtained from three uniformly spaced points on each log. All samples were 25 mm wide and 150 mm long. The thickness of samples from heartwood was maintained at 25 mm; thickness of sapwood samples varied depending on the sapwood thickness of the individual logs. The specific gravity is reported as oven-dry weight and green volume.

Surface Topography Evaluation

Roughness and waviness of the cants were measured using an MTI Microtrack system 7000 provided with two MT-250 laser sensor heads. The data were collected with LabView™ software using an acquisition frequency of 50 Hz and a scanning speed of 15 mm/s. Roughness and waviness of the cant were assessed in two directions, along and across the grain.

For along the grain evaluation, two profiles in the upper part and two in the lower part of the board were assessed. These profiles were 252 mm long and corresponded to the second complete rotation of the cutterhead (boards coming from the small end of the log) or the next to last revolution of the cutterhead (boards coming from the large end of the log).

For the assessment across the grain, eight profiles (one per knife) corresponding to one rotation of the cutterhead and following the cutting direction were taken per board. The length of the profiles varied among the machining conditions and corresponded to the width of each board. This assessment covered the same surface (cutterhead rotation) used for the evaluation along the grain (at the small and large ends of the log).

For along and across the grain evaluation, 12 surface quality parameters (ISO 4287 1997) were determined using task software developed with LabView software (Table 2). A cutoff length of

Table 2. Quality surface assessment parameters used in the surface quality evaluation.

Parameter name	Profile	
	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 within a sampling length	R_p	W_p
Maximum profile valley depth within a sampling length	R_v	W_v
Maximum height of the profile within a sampling length	R_z	W_z
Total height of the profile on the evaluation length	R_t	W_t

2.5 mm and the robust Gaussian filter (ISO/DTS 16610-31 2007) were applied for calculations.

The maximum depth of the torn grain in each board was measured with a Micromeasure confocal microscope. Such depth represents the distance between the cant surface and the lowest point at the bottom of the defect. This measurement was made within the same region (corresponding to the same cutterhead rotation) used for roughness and waviness evaluation. The data were collected with Surface Map 2.4.13 software using an acquisition frequency of 300 Hz and a scanning speed of 12.5 mm/s. In general, torn grain was produced near the knots in the boards. Thus, four diameters of the knots were measured (vertical, horizontal, largest, and smallest diameter). These measurements were used to evaluate torn grain incidence from grain deviation associated with knots.

Statistical Analyses

Statistical analysis was performed by means of the SAS package version 9.2 (SAS Institute 2007). The raw data were first transformed using the Box and Cox method. In general, two types of transformation were used depending on the parameter studied. Given the number of surface parameters studied, a principal component analysis (PCA) was then applied to data to regroup them in common factors and facilitate their analysis.

A split-plot analysis of variance was used to evaluate the variation in the surface quality of the processed cants (mixed procedure of SAS Institute). Season, cutting height, and cutting width were the sources of variation as principal plots and the log end was the source of variation as a subplot. For the assessment along the grain and for torn grain, the position (upper and lower part of the cant) was added as a source of variation as a subplot. The normality of the data was verified using Shapiro-Wilk, Kolmogorov-Smirnov, and Cramer-von Mises tests (SAS Institute 2007).

Correlation analyses among surface topography, torn grain, and wood physical properties were performed with a mixed procedure from the SAS package. When required, means were compared with the least squares means statement from SAS GLM procedure at a 95% confidence level (SAS Institute 2007).

RESULTS AND DISCUSSION

The mean specific gravity was 0.430 for sapwood and 0.438 for heartwood; the difference was not statistically significant at the 0.05 probability level. However, the difference between moisture content of sapwood (127%) and heartwood (40%) was statistically significant at the 0.05 probability level. The mean thickness of sapwood was 15 mm.

Data analysis shows that the surface quality was affected by all factors studied (season, cutting height, cutting width, and within-cant variation). In general, surface quality was better when cutting unfrozen logs at lower cutting width and cutting height. The surface was also smoother at the small end of the log and at the upper part of the cant.

Surface Topography Evaluation

Principal component analysis. The purpose of a factor analysis is to determine the number of common factors and their factor loading (Tabachnick 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 value of 0.60 was selected as the lowest level to consider a given factor as significant. The number of factors was defined according to the principal components initial factor method with an eigenvalue greater than one (Table 3). In addition, a varimax rotation was needed for the along the grain measurements.

The PCA of the profiles measured along the grain showed that 91.5% of the variance of the scaled data was explained by two factors (Table 3). The first represents surface roughness having high factor loadings for R_a (0.89), R_q (0.92), R_p (0.89), R_v (0.92), R_z (0.92), and R_t (0.81) and explained 80.1% of the total variance. The second factor accounted for 11.4% of the total variance and represents the surface waviness. It had high factor loadings for W_a (0.93), W_q (0.93), W_p (0.74), W_v (0.73), W_z (0.74), and W_t (0.86).

The PCA of the profiles measured across the grain revealed a different structure underlying the variables. The surface parameters were grouped into one principal factor, which explained 86.2% of the total variance. This factor adequately represents the roughness and waviness of the wood surface. The factor loadings were 0.97 for W_p, W_v, and W_z; 0.95 for R_q, R_v, and R_z; 0.92 for R_a and R_p; 0.89 for W_t; 0.88 for W_q; 0.87 for W_a; and –0.89 for W_t.

Table 3. Factor analysis scores for all surface quality parameters following principal components initial factor method (factor loadings >0.6 are shown in bold).

Variable	Along the grain analysis: Factor 1	Along the grain analysis: Factor 2	Across the grain analysis: Factor 1
R_a	**0.89**[bd]	0.33	**0.92**[a]
R_q	**0.92**[bd]	0.37	**0.95**[a]
R_p	**0.89**[bd]	0.39	**0.92**[a]
R_v	**0.92**[bd]	0.36	**0.95**[a]
R_z	**0.92**[bd]	0.37	**0.95**[a]
R_t	**0.80**[bd]	0.36	**–0.89**[bc]
W_a	0.26	**0.93**[bc]	**0.87**[a]
W_q	0.27	**0.93**[bc]	**0.88**[a]
W_p	0.59	**0.74**[bc]	**0.97**[a]
W_v	0.59	**0.73**[bc]	**0.97**[a]
W_z	0.59	**0.74**[bc]	**0.97**[a]
W_t	0.41	**0.86**[bc]	**0.88**[a]
Eigenvalue	9.6	1.4	10.3
Percent of variance	80.1	11.4	86.2
Cumulative percent	80.1	91.5	86.2

[a] Logarithmic transformation.
[b] Exponential transformation: [c] –0.5, [d] –1.5.

Along the grain assessment. The variance of the assessment along the grain was explained by two factors as mentioned in the PCA. The first factor represents the roughness and the second the waviness of the wood surface. Both factors were affected by a statistically significant interaction between cutting height and position (Table 4). However, the effects of cutting height on surface factors were the opposite. As the cutting height increased, surface roughness increased (Fig 3a) but waviness decreased (Fig 3b). Furthermore, for roughness, this effect was more evident at the lower part of the cant; conversely, for waviness, it was more evident at the upper part of the cant. The feeding system of the chipper-canter appeared to be more stable for larger logs. As the small-end diameter of the log decreased 203-102 mm, the knife cutting period decreased during one revolution. This could have generated greater vibration if smaller logs are not properly fed. The lower weight of the smaller logs could also have a negative incidence. Consequently, waviness could be greater for smaller logs. Roughness also presented greater values at the upper position of the cant, this difference being evident only for the smaller logs (102 mm). As expected, the larger logs (152 and 203 mm dia) showed a greater surface waviness at the lower part of the cant. Previous work on orthogonal cutting showed that surfaces produced across the grain (0°-90°) are of good quality (Stewart 1969). In the case of the chipper-canter, the finishing knife cuts the log nearly across the grain at the point of the entry and more obliquely to the grain as the knife exits from the log. As the angle between the cutting edge and the grain becomes more oblique, the surface quality will decrease. For example, for a 203-mm dia and 25-mm cutting width, the angle of the finishing knife increased from about 10° (orientation 10°-80°) at the entrance to 39° (orientation 39°-51°) at the

Table 4. Results of the variance analysis for measurements along and across the grain and for torn grain depth (simple effects and interaction statistically significant at the 0.01 probability level that were analyzed are shown in bold).

	Along the grain		Across the grain	
	Factor 1	Factor 2	Factor 1	Torn grain depth
Source of variation	Value-F	Value-F	Value-F	Value-F
Season	60.19*	**49.38***	31.06*	1.46
CH[a]	16.58*	3.09	3.93	1.94
Season × CH	**6.49***	3.26	0.09	1.25
CW[b]	4.24	1.79	71.40*	**13.24***
Season × CW	0.46	0.19	0.40	0.15
CH × CW	4.47	0.72	0.35	0.71
Season × CH × CW	1.41	0.81	1.42	0.40
End	1.41	**35.36***	71.72*	0.00
Season × end	**12.76***	1.50	30.75*	1.25
CH × end	1.37	0.61	2.45	0.53
Season × CH × end	0.22	0.71	4.54	0.03
CW × end	1.39	5.37	0.07	0.26
Season × CW × end	0.08	0.35	**8.25***	0.85
CH × CW × end	1.75	0.98	0.05	0.44
Season × CH × CW × end	1.95	0.17	0.82	0.56
Position	31.45*	65.26*	—	4.66
Season × position	0.05	4.47	—	2.29
CH × position	**12.85***	**10.67***	—	1.10
Season × CH × position	2.23	2.76	—	1.09
CW × position	1.32	4.70	—	0.01
Season × CW × position	0.00	1.33	—	1.23
CH × CW × position	1.52	1.43	—	0.50
Season × CH × CW × position	1.44	0.05	—	0.49
End × position	2.15	0.00	—	0.11
Season × end × position	0.89	0.11	—	0.35
CH × end × position	2.44	2.51	—	0.29
Season × CH × end × position	0.58	0.23	—	0.67
CW × end × position	0.16	0.67	—	0.06
Season × CW × end × position	1.35	0.27	—	0.43
CH × CW × end × position	0.30	0.48	—	1.30
Season × CH × CW × end × position	1.04	1.01	—	1.96

* Significant at the 0.01 probability level.
[a] CH = cutting height.
[b] CW = cutting width.

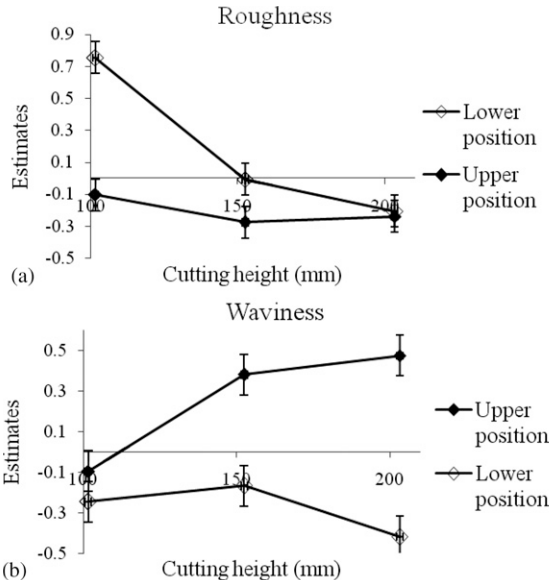

Figure 3. Effect of cutting height and position in the cant on roughness (a) and waviness (b) along the grain. Filled and open symbols correspond to the upper and lower position in the cant, respectively. The figure was made with the estimates of surface parameters that have been transformed ($R_a^{-1.5}$ and $W_a^{-0.5}$). Consequently, an inverse interpretation is required.

exit (Fig 4). This explains why the surface is smoother at the upper part of the cant compared with its lower part (observed for logs of 152 and 203 mm dia). From a practical point of view, this means that the diameter of the cutterhead (or diameter of the cutting circle) will directly affect the surface quality of the cant. This surface will be more uniform when processed with a large-diameter cutterhead than with a small cutterhead. For a given log, orientation of the knives will vary less in larger cutterheads than in smaller cutterheads. Furthermore, logs should be fed into the machine such that knives can cut more across the grain than obliquely (see Fig 4, upper cutting situation). The opposite effect observed for the 102-mm logs could be explained by the fact that the feeding system was less efficient for smaller logs.

In addition, the effect of the interaction between season and cutting height on roughness was statistically significant (Table 4). As the cutting height increased, the surface roughness increased, which was more evident under summer conditions. Furthermore, greater roughness values were found when processing frozen logs (Table 5). However, for 203-mm-dia logs, the effect of

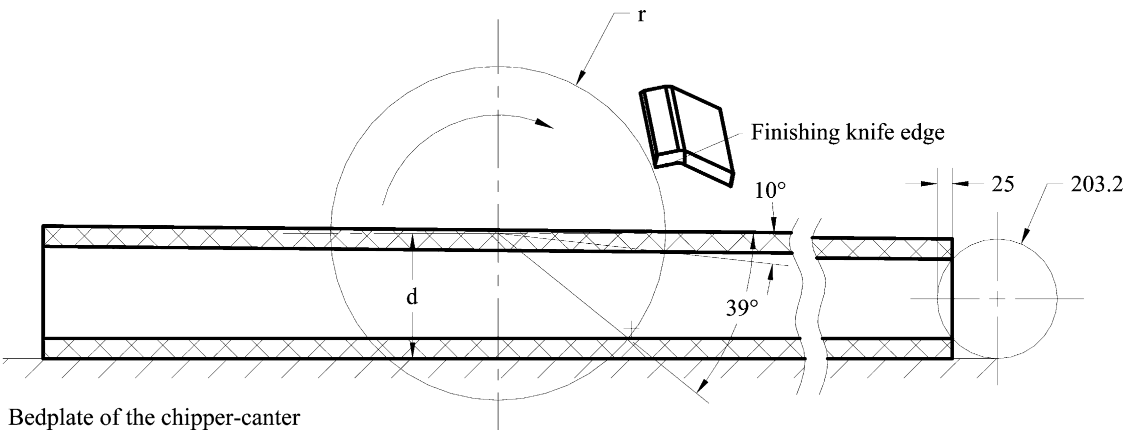

Figure 4. Diagram showing the variation in the orientation of the finishing knife edge along the path on the log (203-mm log diameter and 25-mm cutting width). The angle of the finishing knife edge increases from about 10° (orientation 10°-80°) at the point of entrance to 39° (orientation 39°-51°) at the point of exit of the log. r = radius of the cutting circle (283 mm); d = distance from the bedplate of the machine to the center of the cutting circle.

Table 5. Averages of R_a (arithmetic mean deviation of the roughness profile) and W_a (arithmetic mean deviation of the waviness profile) for analysis along the grain.

	Cutting width (CW)		12.5 mm				25 mm					
			Small end		Large end		Small end		Large end			
Parameter	Season	Diameter (mm)	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Average	Overall average
R_a (μm)	Summer	101.6	19	15	14	14	14	14	16	15	15.1	
		152.4	15	15	16	17	21	16	18	17	16.8	16.3
		203.2	16	16	16	17	18	19	15	19	17.0	
	Winter	101.6	20	22	19	17	22	17	21	17	19.5	
		152.4	17	19	17	19	22	22	24	20	20.2	20.2
		203.2	26	18	20	19	22	22	18	21	20.9	
	Average		Upper position		18.7		Lower position		17.8			
			CW 12.5 mm		17.7		CW 25 mm		18.8			
W_a (μm)	Summer	101.6	172	150	168	172	143	146	171	156	159.8	
		152.4	119	139	140	159	146	171	142	161	147.1	150.1
		203.2	133	141	127	180	116	169	109	173	143.4	
	Winter	101.6	195	219	225	191	190	199	205	172	199.4	
		152.4	159	181	192	204	174	208	179	205	188.0	196.9
		203.2	202	180	179	219	175	245	188	239	203.3	
	Average		Upper position		164.6		Lower position		182.4			
			CW 12.5 mm		172.7		CW 25 mm		174.3			

season was not apparent. It was expected that cutting forces would increase as more material is transformed, which happens when cutting height increases. As a result, vibration during cutting increases leading to greater roughness. The differences in surface quality between seasons can be explained by the effect of temperature and moisture content on mechanical properties of wood (Gerhards 1982). Because temperatures in winter decreased below 0°C, the wood strength increased, causing more brittle fracture behavior, resulting in a decrease in surface quality. A similar effect of log temperature on size distribution of chips produced by the chipper-canter has been previously reported (Hernández and Quirion 1993).

Finally, the effects of season and log end were significant on waviness, whereas the interaction between season and end showed significant effects on roughness (Table 4). In general, roughness and waviness had greater values in winter than summer. This behavior is shown in Table 5 for R_a and W_a, 2 of the 12 parameters included in the PCA. Moreover, waviness increased as the cutting advanced toward the large end of the log (the logs were always fed with the small end first). This probably happens given that cutting height and width are greater at the large than the small end because of log taper. Waviness will increase from the increase of cutting forces. However, the logs processed in winter were slightly rougher at their small end. This could be explained by the role played by the ice located in greater proportion in the sapwood than in the heartwood of black spruce. The proportion of sapwood in the cutting zones was higher in the small end of the log than in its large end. The effect of the temperature could be slightly greater for the smaller cutting width (12.5 mm) because the mean thickness of the sapwood was 15 mm.

Across the grain assessment. As mentioned in the PCA, the variance for the across the grain analysis was explained by one principal factor. This factor adequately represents the roughness and waviness observed on cant surfaces. A statistically significant triple interaction was found among season, cutting width, and log end. As the cutting width increased 12.5-25 mm, roughness and waviness across the grain increased. This behavior is shown in Table 6 for R_a and W_a, 2 of the 12 parameters included in the PCA. Furthermore, similar to roughness and waviness along the grain, these increased across the grain as cutting advanced toward the large end of the log (Table 6). It is expected that cutting forces will increase as more material is processed, because cutting height and/or cutting width increases. However, the difference between the small and large ends of the log was not evident in winter for the smaller cutting width (12.5 mm). This could be explained by the role played by the ice located in the sapwood of black spruce. As mentioned previously, the effect of temperature could be greater for the smaller cutting width (12.5 mm). Also, the proportion of sapwood in the cutting zones was greater in the small end of the log than its large end. Consequently, the small end of the log could have lower surface quality and be comparable to the quality of the large end. Finally, roughness and waviness across the grain had greater values when cutting in winter, this effect being more obvious at the small end of the log. It is known

Table 6. Averages 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.

	Cutting width		12.5 mm		25 mm			
Parameter	Season	Diameter (mm)	Small end	Large end	Small end	Large end	Average	Overall average
R_a (μm)	Summer	101.6	29	31	36	38	33.4	
		152.4	26	37	34	42	34.9	35.3
		203.2	32	39	37	43	37.6	
	Winter	101.6	37	40	39	45	40.3	
		152.4	32	36	42	48	39.8	41.1
		203.2	37	37	48	51	43.2	
	Average		34.5		41.9			
W_a (μm)	Summer	101.6	64	95	126	154	109.9	
		152.4	60	108	103	167	109.2	112.6
		203.2	75	121	122	156	118.7	
	Winter	101.6	86	97	127	138	111.8	
		152.4	87	85	115	132	104.9	113.9
		203.2	130	104	132	135	125.1	
	Average		92.7		133.8			

that cutting forces increase as the wood temperature decreases below 0°C. Therefore, vibration during cutting will increase, resulting in greater roughness and waviness.

Tables 5 and 6 show mean values of R_a and W_a for along and across the grain, respectively. The R_a along the grain was 16.3 μm in summer and 20.2 μm in winter. R_a across the grain showed greater values: 35.3 μm in summer and 41.1 μm in winter. In contrast, waviness had greater values along than across the grain (150 μm compared with 113 μm in summer and 197 μm compared with 114 μm in winter). In other words, roughness was two times greater across than along the grain, whereas waviness was either 1.3 times greater (in summer) or 1.7 times greater (in winter) along than across the grain. This opposite behavior could be explained in that waviness along the grain was affected by the variation in the projection of the eight knives mounted on the cutterhead. Moreover, the profiles along the grain could be more affected by the area of the torn grain, which was longer along than across the grain. Thus, it is deduced that quality control of the knife projections on the cutterhead plays an important role on the quality of surfaces produced by the chipper-canter.

Torn grain evaluation. A higher incidence of torn grain was observed at the lower part of the cant. Eighty percent of the boards had the deepest torn grain at the lower part in contrast with 20% at the upper part of the cant. As mentioned previously, the finishing knife edge orientation with respect to the grain became more oblique as the knife exited the log. This condition could increase the incidence of torn grain at the lower part of the cant. Again, processing logs with larger cutterheads and being fed immediately below the center of the cutting circle is recommended.

The mean of the maximum depth of torn grain for all the cutting conditions is presented in Table 7. The maximum depth of torn grain ranged 0.8-2.6 mm depending on the cutting conditions. Given the magnitude of the torn grain, this parameter needs to be carefully controlled to improve surface quality. The maximum depth of the torn grain showed a statistically simple effect of the cutting width (Table 4). The other sources of variation were not significant. The maximum depth of torn grain increased as the cutting width increased 12.5-25 mm at the small end of the log. The depth of torn grain was 1.4 times greater for 25-mm than 12.5-mm cutting width. An increase of the cutting width will increase the cutting forces during the cut. As a result, the depth of the torn grain was greater at the larger cutting width.

Correlation Analysis

A correlation analysis was made between the maximum depth of torn grain and roughness and waviness parameters along and across the grain. The factors of the PCA of both assessments were used in the calculation given that the individual parameters have a strong correlation between them, as shown in Table 3. The PCA revealed two principal factors for along the grain assessment. These factors showed a statistically significant correlation with the maximum depth of torn grain. The corresponding regression model explained 37.8% of the variation in torn grain.

$$ln(depth\,of\,torn\,grain) = 0.27 - 0.19\,factor\,1 - 0.22\,factor\,2$$

Similarly, a correlation analysis was performed between the maximum depth of torn grain and the principal factor of the across the grain assessment. A significant correlation was also found; as the principal factor (roughness and waviness across the grain) increases, the torn grain will be deeper. The corresponding regression model explained 58.8% of the variation in torn grain.

$$\ln(depth\,of\,torn\,grain) = 0.32 + 0.27\,factor$$

Therefore, waviness and roughness across the grain more satisfactorily explained the variation in the maximum depth of torn grain.

A second correlation analysis was performed between torn grain occurring near the knots and five variables: the knot diameters (vertical, horizontal, largest, and smallest) and the distance of

Table 7. Averages of torn grain depth.

	Cutting width (CW)		12.5 mm				25 mm					
			Small end		Large end		Small end		Large end			
	Season	Diameter (mm)	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Average	Overall average
Torn grain depth (mm)	Summer	101.6	1.1	1.2	1.1	1.4	1.3	1.5	1.7	1.5	1.4	1.5
		152.4	1.0	1.0	1.3	1.3	2.3	1.5	2.4	1.5	1.5	
		203.2	1.6	0.9	2.4	1.2	2.3	1.3	1.5	1.6	1.6	
	Winter	101.6	1.6	1.6	1.2	1.6	1.8	1.9	1.4	1.7	1.6	1.8
		152.4	0.8	1.6	1.3	1.7	2.6	1.8	1.9	1.7	1.7	
		203.2	1.9	1.4	1.3	2.1	2.5	2.3	2.4	2.0	2.0	
	Average		Upper position		1.7		Lower position		1.6			
			CW 12.5 mm		1.4		CW 25 mm		1.9			

torn grain from the log axis. This distance was positive if the torn grain was located at the upper part of the cant and negative if it were at the lower part. The analysis revealed a significant correlation between the maximum depth of torn grain and two variables: the horizontal diameter of the knot and the distance of torn grain from the log axis.

$$\sqrt{depth} \text{ of torn grain } = 0.7 - 0.0068 \text{ distance of torn grain from log axis} + 0.038 \text{ knot horizontal diameter}$$

Torn grain increased as the horizontal diameter of the knot increased and as the knife was advancing in its path. This supports the observation that there was more incidence of torn grain at the lower part of the cant. However, this model explained just 20.4% of the variation in torn grain. The remainder of variables did not present any significant correlation with the maximum depth of torn grain.

Finally, a correlation analysis was performed between the maximum depth of torn grain and two physical properties of wood: specific gravity and moisture content. Only the former presented a statistically significant correlation with the maximum depth of torn grain. As the specific gravity decreased, the maximum depth of torn grain increased. However, variation in specific gravity only explained 12.3% of the variation in torn grain. In conclusion, highest positive correlations were found between roughness and waviness across the grain and torn grain. Any optimization of the cutting conditions for improving roughness and waviness will also reduce the occurrence of torn grain.

CONCLUSIONS AND RECOMMENDATIONS

This study has shown that cutting height, cutting width, and temperature of logs affect the surface quality of black spruce cants produced by a chipper-canter. Cutting height affected roughness and waviness measured along the grain. As the cutting height increased, roughness increased but waviness decreased. Furthermore, cutting width affected roughness and waviness across the grain and depth of torn grain. As cutting width increased 12.5-25 mm at the small log end, surface quality decreased (rougher and wavier surfaces and deeper torn grain). Moreover, roughness and waviness over both directions of wood (along and across the grain) were less when processing unfrozen than frozen logs. This work also showed that roughness and waviness, along and across the grain, increase at the large log end because of the constant increase in cutting width and cutting height. Finally, the surface quality of the cants was generally lower at the lower part of the cut from the change of the finishing knife orientation with respect to the wood grain. The correlation analyses showed that roughness and waviness across the grain positively explained the variation of the maximum depth of torn grain with an R^2 of 58.8%. Any reduction of torn grain will have also a positive impact on the roughness and waviness of the cant surfaces. Finally, results indicate the advantage of feeding the logs into the machine just below the center of the cutting circle as well as by using cutterheads of larger diameter.

ACKNOWLEDGMENTS

We thank Piotr Iskra, Research Assistant, for technical support during testing. This research was supported by the Fonds Québécois de la Recherche sur la Nature et les Technologies (FQRNT) and by FPInnovations, Forintek Division, Eastern Region.

REFERENCES

Brown N, Parkin RM, Jackson MR (2002) Simulation of a modified rotary timber machining process to improve surface form. Mechatronics 12:489-502.

Fujiwara Y, Fujii Y, Okumura S (2003) Effect of removal of deep valleys on the evaluation of machined surfaces of wood. Forest Prod J 53(2):58-62.

Funck JW, Forrer JB, Butler DA, Brunner CC, Maristany AG (1993) Measuring surface roughness on wood: A comparison of laser scatter and stylus tracing approaches. *In* Proc SPIE, Boston, MA. 1821:173-184.

Gerhards CC (1982) Effect of moisture content and temperature on the mechanical properties of wood: An analysis of immediate effects. Wood Fiber Sci 14(1):4-36.

Gurău L, Mansfield-Williams H, Irle M (2005) Processing roughness of sanded wood surfaces. Holz Roh Werkst 63(1):43-52.

Hendarto B, Shayan E, Ozarska B, Carr R (2006) Analysis of roughness of a sanded wood surface. Int J Adv Manuf Technol 28(7/8):775-780.

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

ISO 11562 (1996) Geometrical product specifications (GPS)—Surface texture: Profile method. Metrological characteristics of phase correct filters. British Standards Institute, London, UK.

ISO 4287 (1997) Geometrical product specifications (GPS) Surface texture: Profile method—Terms, definitions and surface texture parameters. British Standards Institute, London, UK.

ISO/DTS 16610-31 (2007) Geometrical product specifications (GPS)—Filtration. Part 31: Robust profile filters. Gaussian regression filters. International Standards Organization, Geneva, Switzerland.

Jackson M, Parkin R, Brown N (2002) Waves on wood. *In* Proc of the Institution of Mechanical Engineers. Part B: Journal of Engineering Manufacture 216(4): 475-497.

Khazaeian A (2006) 3D characterization of wood surface quality: Strategies of meausrement—Influence of the parameters related to species and machining [in French]. PhD thesis, École Nationale du Génie Rural, des Eaux et des Forêts, France. 241 pp.

Krisch J, Csiha C (1999) Analyzing wood surface roughness using an S3P perthometer and computer based data processing. *In* Proc XIII Sesja Naukowa 'Badania dla Meblarstwa,' Poland.

Lemaster RL, Taylor JB (1999) High speed assessment of wood and wood-based composites. *In* Proc 14th International Wood Machining Seminar, Paris, Epinal, and Cluny, France. Pages 479-488.

Mummery L (1992) Surface texture analysis; The Handbook. Hommelwerke, GmbH, Germany, 106 pp.

Sandak J, Negri M (2005) Wood surface roughness—What is it? Pages 242-250 *in* Proc 17th International Wood Machining Seminar, Rosenheim, Germany.

Sandak J, Tanaka C (2003) Evaluation of surface smoothness by laser displacement sensor 1: Effect of wood species. J Wood Sci 49(4):305-311.

SAS Institute (2007) SAS/Stat User's Guide, release 9.2 ed. SAS Institute Inc, Cary, NC.

Stewart H (1969) Effect of cutting direction with respect to grain angle on the quality of machined surface, tool force components, and cutting friction coefficient. Forest Prod J 19(3):43-46.

Tabachnick BG, Fidell LS (2007) Using multivariate statistics. 5th ed. Pearson, Allyn and Bacon, Boston, MA. 980 pp.

Zani M (2003) Measure of roughness? Some standards. . .and several tens of parameters [in French]. Mesures mécaniques. 758:59-63.