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Effects of cutting parameters on cutting forces and surface quality of black spruce cants

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Abstract The effects of rake angle, cutting direction, and depth of cut on cutting forces and surface quality of black spruce were evaluated. Cutting forces were measured during cutting at four rake angles (35°, 45°, 55° and 65°), four cutting directions (0°–90°, 15°–75°, 30°–60°, and 45°–45°), and three depths of cut (1, 2, and 3 mm). Torn grain, waviness, and roughness were evaluated. The results showed that as rake angle increased, cutting forces, torn grain, waviness, and roughness decreased. The lowest cutting forces and the best surface quality were obtained with 65° of rake angle. At this angle, cutting forces and surface quality were more affected by depth of cut than by cutting direction variations. Thus, as depth of cut decreased, the effects of cutting orientation on the cutting forces and surface quality decreased. The application of these results to the canting work of a chipper-canter is analyzed.

Einfluss von Schneidparametern auf die Schnittkräfte und die Oberflächenqualität von Schwarzfichtenkantholz

Zusammenfassung Der Einfluss von Spanwinkel, Schnittrichtung und Schnitttiefe auf die Schnittkräfte und die Oberflächenqualität von Schwarzfichte wurden bestimmt. Gemessen wurden die Schnittkräfte beim Zerspanen bei vier Spanwinkeln (35°, 45°, 55°, und 65°), vier Schnittrichtungen (0°–90°, 15°–75°, 30°–60° und 45°–45°) und drei Schnitttiefen (1, 2 und 3 mm). Faserausriss, Welligkeit und Rauigkeit wurden bestimmt. Die Ergebnisse zeigten, dass mit zunehmendem Spanwinkel die Schnittkräfte, der Faserausriss, die Welligkeit und die Rauigkeit abnahmen. Bei einem Spanwinkel von 65° wurde die geringste Schnittkraft benötigt und die beste Oberflächenqualität erzielt. Bei diesem Winkel hatte die Schnitttiefe einen größeren Einfluss auf die Schnittkräfte und die Oberflächenqualität als Änderungen der Schnittrichtung. Somit nahm der Einfluss der Schnittrichtung auf die Schnittkräfte und die Oberflächenqualität mit abnehmender Schnitttiefe ab. Die Anwendung dieser Ergebnisse auf die Herstellung von Kantholz mit einem Profilzerspaner wird untersucht.

1 Introduction

Chipper-canters are usually used as primary breakdown machines for processing logs of small and medium diameter more efficiently. These machines mainly convert logs into cants with very low sawdust production. The chips obtained are normally destined to the pulp and paper industry. Cants are then processed to obtain studs and other members principally used for structural purposes. Although machining using a chipper-canter generates a quite satisfactory production, technical aspects remain to be improved in order to increase even more its performance. The increase in surface quality of cants and the reduction of the energy requirements are among the more important. The canting action of the chipper-canter is often associated with orthogonal cutting.

To remove chips from a piece of wood, the cutting tool must apply enough force to overcome the mechanical strength of wood. For analysis, this force is usually decomposed into two components; one parallel to the

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direction of tool movement and another normal to the machined surface (Kivimaa 1950). The forces applied by the tool are affected by several factors such as those related to feeding, cutting tool, and workpiece (Koch 1964). For instance, rake angle greatly affects the forces generated during orthogonal cutting. Thus, forces increase as the rake angle decreases (Kivimaa 1950; Woodson and Koch 1970; Koch 1985; Huang 1994; Jin and Cai 1996). Moreover, the arrangement of wood elements with respect to the cutting tool edge and cutting direction affects the mechanical properties of wood, and consequently, the required cutting forces (Kivimaa 1950; Koch 1985; Hoadley 2000). In addition, using large rake angles, the forces required are lower when cutting across the grain than following the grain (Stewart 1970). According to Jodin (1994), the depth of cut is also a factor affecting the orthogonal cutting forces. Thus, the parallel force increases as depth of cut increases (Woodson 1979; Huang 1994; de Moura and Hernández 2007).

The quality of wood surfaces is often evaluated by the presence of defects and by their topography. One of the defects affecting more the surface is the torn grain, which is produced when wood particles break off below the surface. Too large rake angles and depths of cut as well as very dry or very wet wood may promote the production of this defect (Stewart 1980). The topography of a surface represents a superposition of irregularities having different wavelengths. Thus, the roughness contains irregularities with low wavelength while waviness describes the irregularities with higher wavelength (Khazaeian 2006).

The surface can be quantitatively assessed according to roughness (R) and waviness (W) parameters contained in ISO 4287 (1997). One of the most used is the arithmetical mean deviation of the assessed profile (R_a and W_a). The root mean square deviation of the assessed profile (R_q and W_q), compared with R_a and W_a, increases the sensitivity to the extreme values of the profile. The maximum height of the profile (R_z and W_z) represents the average of the amplitudes between the peaks and valleys. Similarly, R_p and W_p consider the maximum height of peaks and R_v and W_v compute the maximum depth of valleys (ISO 4287 1997; Mummery 1992). Lemaster and Taylor (1999) noted that R_q and W_z are able to detect fuzzy and torn grains in wood surfaces, respectively. However, there is not a definitive set of parameters for a complete assessment of wood surfaces (Fujiwara et al. 2003; Sandak and Tanaka 2003; Sandak and Negri 2005; Gurau et al. 2005).

In orthogonal cutting, the rake angle affects the type of chip produced and, hence, the quality of the surface. When planing across the grain, surface quality increases as the rake angle increases (Stewart 1975, 1979; Stewart and Parks 1980). Low rake angles, combined with inadequate clearance angles, produce defects such as subsurface crushing, fuzzy or raised grain, and glazing (Stewart 1991). When planing across the grain, the transverse orientation of the grain with respect to the cutting direction prevents that failure generated by cleavage ahead of the tool extends below the surface of the workpiece. This generates a more uniform and smooth surface with thinner knife marks and slighter torn grain (Stewart 1970, 1971; Stewart and Parks 1980). In addition, in orthogonal cutting across the grain, the transverse compression is significantly reduced when using thin sections. The mechanical stresses required to separate the fibers are therefore lower, which makes cutting more stable and ensures that wood is less crushed. The quality of surface improves as depth of cut decreases (Stewart 1979).

Chipper-canters, commonly used in Eastern Canada, have conical-shaped cutter heads fitted with uniformly distributed knives on its periphery. In some cases, bent knives are used, which have 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. In other cases, the bent knife is replaced by a dual-knife set. The shorter edge cuts nearly across the grain at the point of entry on the log and more obliquely to the grain as the knife exits. Therefore, the cutting orientation of the finishing knife edge with respect to the grain varies along with its path on the log (Fig. 1). Hernández et al. (2010) found that surface quality of black spruce cant decreased as the angle between the cutting edge and wood grain becomes more oblique. This situation will be more critical for smaller cutter heads, where the orientation of the finishing knife with respect to the grain will vary more than in larger cutter-heads. The cutting orientation of the finishing knife edge will also depend on the position of log entry or vertical distance with respect to the cutter head rotation axis. Logs are usually fed over a bedplate that is fixed respect to the cutter heads rotation axis.

The objective of this work was to evaluate the effects of rake angle, cutting direction with respect to the grain, and depth of cut on cutting forces and surface quality produced when machining black spruce wood [*Picea mariana* (Mill.) B.S.P.]. These cutting variables were analyzed considering their application to the machining processes performed by a chipper-canter.

2 Materials and methods

2.1 Testing material

Ten logs 2.44 m long of black spruce [*Picea mariana* (Mill) B.S.P.] were selected for this study. This tree is one of the most important boreal species in Canada and takes part of the SPF (spruce-pine-fir) wood group, which are

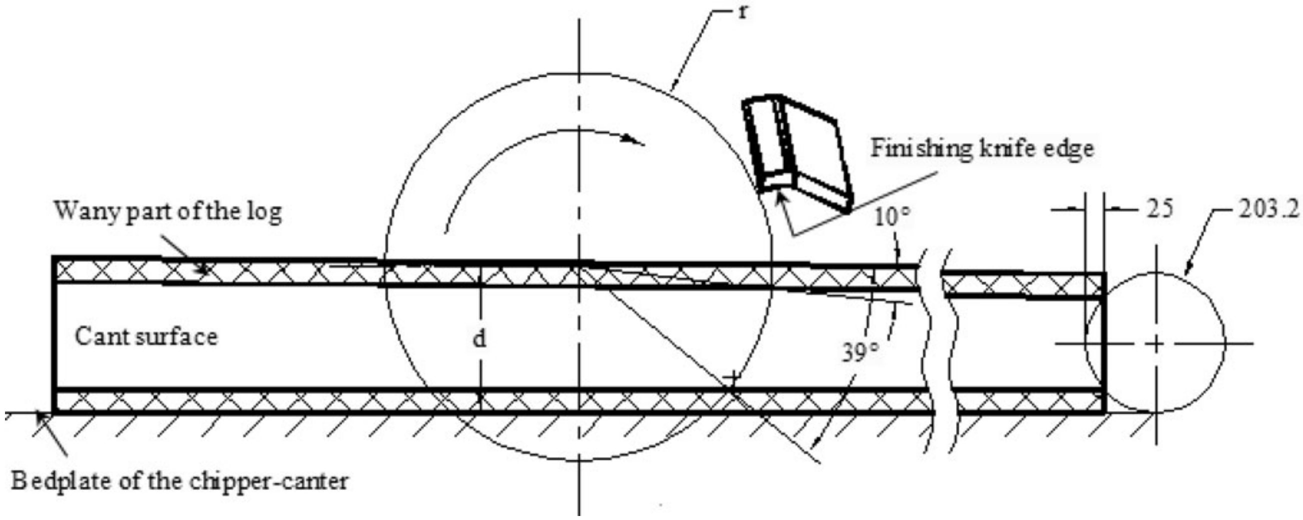

Fig. 1 Example of changes in the orientation of a finishing knife edge of a chipper-canter during its path on a log. The angle of the finishing knife edge respect to the wood grain can increase from about 10° (10°–80° cutting situation) at the point of entrance to 39° (39°–51° cutting situation) at the point of exit of the log (203 mm of log diameter and 25 mm of cutting width; 283 mm of radius of the cutting circle (r); d = distance from the bedplate of the machine to center of the cutting circle of the cutterhead) (adapted from Hernández et al. 2010)

Abb. 1 Beispiel für Richtungsänderungen der Schneidkante eines Profilzerspaners beim Zerspanen eines Stammabschnittes. Der Winkel der Schneidkante zur Faserrichtung kann von 10° (10°–80° Schnittrichtung) beim Eintritt der Schneide auf 39° (39°–51° Schnittrichtung) beim Austritt der Schneide aus dem Stammabschnitt ansteigen (203 mm Stammdurchmesser und 25 mm Schnittbreite, 283 mm Schneidradius (r); d = Abstand zwischen dem Aufleger des Stammes und der Mitte des Schneidkreises des Messerkopfes) (nach Hernández et al. 2010)

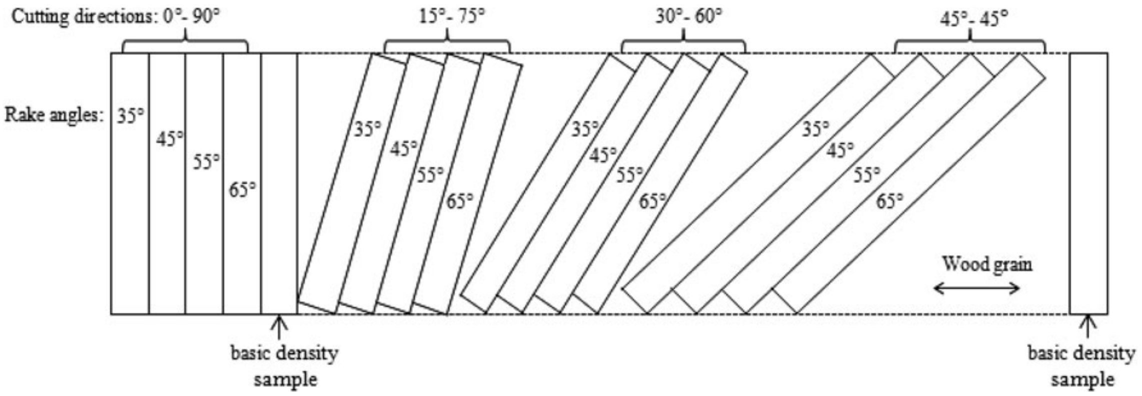

Fig. 2 Diagram showing the sample distribution on each board (16 samples for the machining treatments and two samples for the basic density measurement). The cutting direction is represented by two numbers, the first one is the angle between the cutting edge and the wood grain, and the second one is the angle between the tool direction and the wood grain

Abb. 2 Entnahme der Prüfkörper aus jedem Brett (16 Prüfkörper für die Zerspanung und 2 Prüfkörper für die Raumdichtebestimmung). Die Schnittrichtung wird durch zwei Zahlen beschrieben, die erste Zahl gibt den Winkel zwischen Schneidkante und Faserrichtung an und die zweite Zahl ist der Winkel zwischen Werkzeug- und Faserrichtung

widely used in pulp and paper industry and in construction applications (Zhang and Koubaa 2008). Two opposite slabs of 25-mm maximum thickness were initially cut with a portable band saw from each log. These slabs should correspond to the part of the log normally transformed into chips by a chipper-canter. Two flat-sawn boards of 39-mm of thickness and variable widths were then obtained from the remaining part of the log. Thus, the external tangential face of the flat-sawn board would coincide with a typical position of the log where cant surfaces are produced by this machine.

From each flat-sawn board, 16 samples of 30-mm width were machined in groups of four. The first four samples were cut following a grain orientation of 0° with respect to the grain. The second four samples were cut following a grain orientation of 15°, the next four samples following a grain orientation of 30°, and the last ones following a grain orientation of 45° (Fig. 2). By taking one sample from each board, 16 matched groups were formed. Thus, each group had twenty samples with a specific grain orientation (0°, 15°, 30°, or 45°) making a total of 320 samples. For basic density measurements (oven-dry weight to green volume ratio), two samples were also machined from each board (Fig. 2). All samples were without knots and crook or visible decay.

2.2 Machining treatments

The cutting treatments were performed with a fixed-knife mounted on the column of a milling machine. Sixteen groups of samples were used to machine at four cutting directions with respect to the grain (0°–90°, 15°–75°, 30°–60°, and 45°–45°) and with one of four nominal rake angles (35°, 45°, 55°, and 65°). Within each group, each sample was machined three times at three different cutting depths (1, 2, and 3 mm). To avoid the cutting effect of the previous treatment, the tangential face of the sample was resurfaced after each treatment. The machining was always performed with a freshly sharpened knife, having an angle of 20° and at a feed speed of 7.6 mm/s. Although feed speed used could be considered slow, previous research showed that the effect of feed speed on cutting forces and surface quality was insignificant (Kivimaa 1950; Franz 1958; McKenzie 1960). All cutting parameters are summarized in Table 1.

2.3 Force measurements

During machining, wood samples were fastened to a Kistler 9257B quartz three component dynamometer, which was fixed to the feeding table of the milling machine. A charge amplifier Kistler type 5010B equipped with 180 kHz analog low-pass filter was used to amplify and condition the input data. A long time constant was chosen to make quasistatic measurements. Normal (F_N) and parallel (F_P) components of cutting forces were recorded with a computer and a data acquisition card set at 100 readings per second. No additional filtering was performed on the original data. The average forces for each treatment were determined with Dynoware software.

Table 1 Cutting conditions
Tab. 1 Schnittbedingungen

Factor	Condition
Number of knives	1
Knife angle	20°
Rake angle	35°, 45°, 55°, 65°
Cutting direction with respect to the grain	0°–90°, 15°–75°, 30°–60°, 45°–45°
Cutting depth	1, 2, 3 mm
Workpiece dimension	Section 30 × 30 mm, variable lengths
Feed speed	7.6 mm/s

2.4 Surface topography measurements

Roughness and waviness measurements were carried out with a Micromeasure confocal microscope equipped with a 24 mm optical pen. Three profiles of variable lengths (corresponding to the width of each initial board), spaced 7.5 mm of another, were assessed. Data was collected with the Surface Map 2.4.13 software using an acquisition frequency of 30 Hz and a scanning speed of 2.5 mm/s. The ISO 4287 (1997) roughness (R) and waviness (W) parameters [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), and maximum height of profile (R_z and W_z)] were determined using Mountains Map Topography XT 4.1. A cut-off length of 2.5 mm combined with a robust Gaussian filter (ISO DTS 16610-31 2002) were used for calculations. The depth of torn grain was also assessed as the maximum valley depth within the total length of the profile.

2.5 Statistical analyses

Statistical analyses were performed by means of the SAS package version 9.2 (SAS Institute 2007). The raw data was first transformed using the Box and Cox method. Two types of transformation (logarithmic for parallel force data and exponential for torn grain data) were employed. A principal component analysis (PCA) was then applied to regroup the ten surface quality parameters into common factors in order to simplify their analysis. Thus, these parameters were regrouped into two factors; a first representing waviness and a second describing roughness. Two analyses of variance were applied to evaluate the variation in cutting forces and surface quality on black spruce samples (mixed procedure of SAS Institute). The first analysis, in split–split-plot (having cutting direction, rake angle and depth of cut as sources of variation, respectively) revealed that, regardless of cutting direction and depth of cut, a rake angle of 65° produced the lowest cutting forces and the best surface quality. Therefore, a second analysis was made by considering only data obtained with this rake angle (split-plot design). All analyses were made at 0.05 and 0.01 significance levels. The normality of data was verified using the Shapiro–Wilk test. Correlation analyses among cutting forces, surface parameters, torn grain, and basic density were performed with a mixed procedure from SAS package.

3 Results and discussion

Specimens from the ten logs of black spruce had a mean basic density of 405 kg/m^3 with a coefficient of variation of 8 %. Thus, the specimens covered the mean value of the natural distribution of wood density of this species, whose mean is 406 kg/m^3 with a coefficient of variation of 9.4 % (Jessome 2000).

The first analysis of variance showed that cutting forces (parallel and normal components) and surface quality (depth of torn grain, waviness, and roughness) were affected by a statistically significant interaction between cutting direction, rake angle, and depth of cut (not shown). This triple interaction indicated that changes in one of the independent variables affected behavior of the other two variables and, therefore, behavior of the dependent variables. However, in all cases, F-value for the triple interaction was low compared with F-values from the simple effects. Thus, F-values indicate that depth of cut was the principal parameter that affected the parallel force, torn grain, and waviness. In addition, the rake angle was the variable that most affected the normal force and roughness.

To illustrate the effect of the triple interaction, Fig. 3 shows the parallel force as a function of cutting direction, rake angle, and depth of cut. The effect of cutting direction on this force component depended on the rake angle involved. This variable effect of the cutting direction was more noticeable when comparing the extreme values of the rake angle used (35° and 65°). This could be explained by the different mechanisms of chip formation occurring for these two angles. According to Stewart (1979), when machining wood across the grain (0°–90°) at low rake angles (30°–40°) a chip type B is formed. In this case, the cutting tool causes compression perpendicular to the grain, resulting in shearing failures in wood at and ahead of the tool edge. It is known that compression is greater along than perpendicular to the grain. This could explain why parallel force increases when cutting progresses from 0°–90° to 45°–45° direction, when cutting with a rake angle of 35° (Fig. 3a). In contrast, as rake angle increases a chip type A is formed, where wood splits ahead of the tool by cleavage followed by shear failures at the tool edge until failure in bending occurs (Stewart 1979). Compression perpendicular to the grain is substantially decreased, especially at shallow cuts. The parallel force obtained at 65° of rake angle was then lower and less variable as cutting changes from 0°–90° to 45°–45° direction (Fig. 3b).

Moreover, Fig. 3 shows that parallel force decreased as rake angle increased regardless of the cutting direction and depth of cut. The negative relationship between parallel force and rake angle has been reported previously (Kivimaa 1950; Woodson and Koch 1970; Stewart 1979; Woodson 1979; Huang 1994; Jin and Cai 1996). The decrease of parallel forces resulted in lower values of torn grain (Fig. 4), waviness, and roughness (not shown). In fact, a statistically significant positive correlation was found between parallel force and two surface quality factors [torn grain (R = 0.37) and waviness (R = 0.52), Table 6]. Furthermore, as it was shown for the parallel

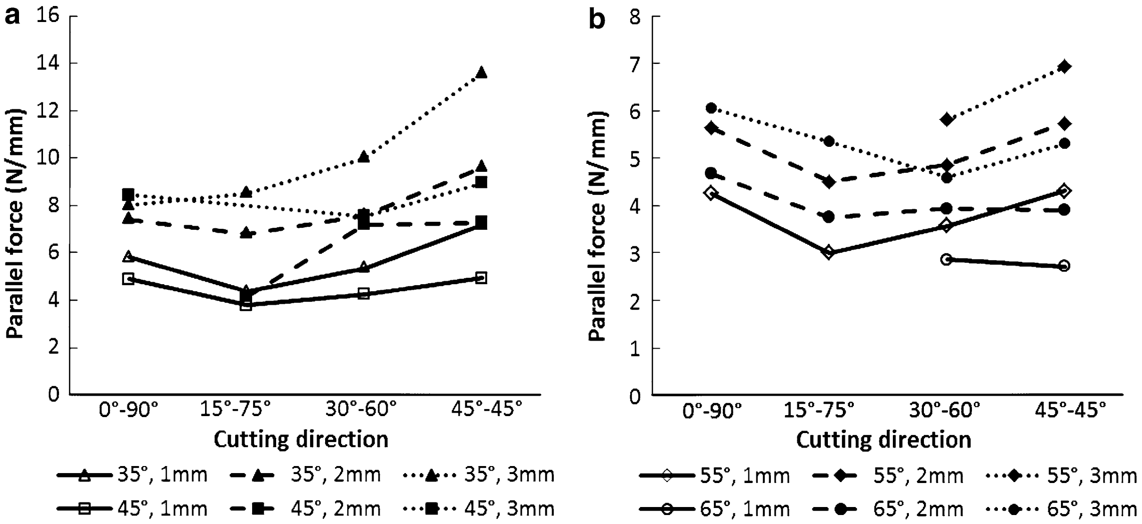

Fig. 3 Parallel force (N/mm) as a function of cutting direction, rake angle, and cutting depth obtained when cutting black spruce wood with a rake angle of, **a** 35° and 45° and **b** 55° and 65°. Each point represents a mean of 20 replicates

Abb. 3 Schnittkraft (N/mm) in Abhängigkeit der Schnittrichtung, des Spanwinkels und der Schnitttiefe beim Zerspanen von Schwarzfichtenholz mit einem Spanwinkel von a) 35° und 45°, b) 55° und 65°. Jeder Punkt entspricht dem Mittelwert aus 20 Versuchen

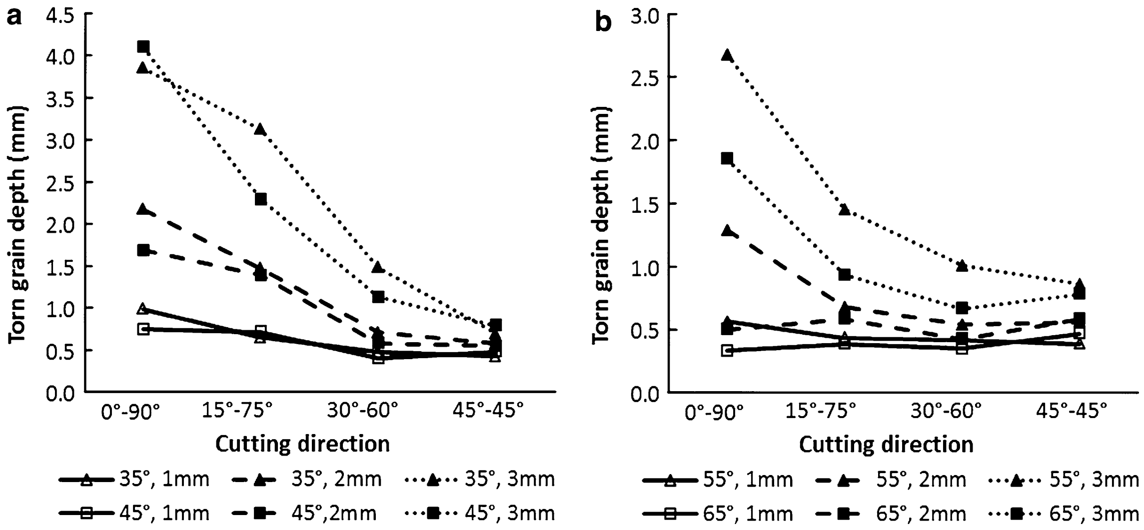

Fig. 4 Torn grain depth as a function of cutting direction, rake angle, and cutting depth obtained when cutting black spruce wood with a rake angle of, **a** 35° and 45° and **b** 55° and 65°. Each point represents a mean of 20 replicates

Abb. 4 Faserausrisstiefe in Abhängigkeit der Schnittrichtung, des Spanwinkels und der Schnitttiefe beim Zerspanen von Schwarzfichtenholz mit einem Spanwinkel von a) 35° und 45°, b) 55° und 65°. Jeder Punkt entspricht dem Mittelwert aus 20 Versuchen

force, the effect of cutting direction on surface quality depended on the rake angle used. For example, as rake angle increased from 35° to 65°, the influence of cutting direction on depth of torn grain was less important (Fig. 4). The influence of depth of cut on torn grain also decreased as rake angle increased from 35° to 65°. Previous works have reported that the effect of depth of cut on cutting forces depend on the rake angle used (Woodson and Koch 1970; Axelsson et al. 1993).

Therefore, the use of a rake angle of 65° for machining the cant surface with a chipper-canter should be advantageous. In this machine, the orientation of finishing knife edge with respect to the grain varies along the cutting path on the log (Fig. 1). At the point of entry, the knife cuts nearly across the grain and more obliquely to the grain as the knife exits from the log (Hernández et al. 2010). For a given cutting height, this fact will be more critical for smaller cutter-heads than for larger cutter-heads. The selection of a high rake angle is hence very important while assuring that knives will have good resistance to wear.

Since machining at 65° of rake angle produced the best conditions for cutting forces and surface quality, the subsequent analyses were only performed with the data produced when machining with this rake angle.

3.1 Cutting forces analysis

At 65° rake angle, the parallel and normal components of cutting forces were statistically affected by an interaction between cutting direction and depth of cut (Table 2). It is known that cutting forces are lower when cutting at 0°–90° than at 90°–0° mode (Kivimaa 1950; Woodson and Koch 1970; Woodson 1979; Koch 1985; Jin and Cai 1996). Therefore, an increase in the cutting forces as the cutting changes from 0°–90° to 45°–45° direction was expected. However, parallel and normal forces had different behaviors throughout the changes on cutting modes. As explained previously, this could be explained by the different mechanisms of chip formation occurring at low and high rake angles. Table 3 shows that parallel force was higher when machining at 0°–90° cutting direction, then decreased and kept constant at 15°–75°, 30°–60°, and 45°–45° cutting directions.

Furthermore, the ANOVA in Table 2 shows that depth of cut had a greater influence on parallel force (F-value = 445.4) compared to that associated with the cutting direction (F-value = 12.4). The parallel force increased as depth of cut increased from 1 to 3 mm, regardless of cutting direction (Table 3). In contrast, the normal force was more affected by the cutting direction (F-value = 69.0) than by the depth of cut variations (F-value = 39.8). This force component was always negative, which indicates that the workpiece tried to push away the cutting tool. The normal force slightly increased as the cutting changed from 0°–90° to 45°–45° direction (not shown).

3.2 Surface quality analysis

A principal component analysis (PCA) was performed to simplify the statistical analysis of surface quality. PCA produces, mathematically, several linear combinations of observed variables, each linear combination being a component. Variables that are correlated with one another but

Table 2 Analysis of variance (F values) of cutting forces and surface quality assessments when machining black spruce boards at 65° of rake angle

Tab. 2 Varianzanalyse (F-Werte) der Schnittkräfte und der Oberflächenqualität beim Zerspanen von Schwarzfichtenbrettern mit einem Spanwinkel von 65°

Source of variation	Cutting force		Surface quality		
	Parallel force F-value	Normal force	Torn grain depth	Waviness (factor 1)	Roughness (factor 2)
Cutting direction (CD)	12.4**	69.0**	2.6[n.s.]	9.6**	2.4[n.s.]
Depth of cut (DoC)	445.4**	32.8**	229.0**	270.8**	12.0**
CD*DoC	17.1**	82.0**	9.0**	9.5**	1.4[n.s.]

* Statistically significant at 0.05 probability level

** Statistically significant at 0.01 probability level

[n.s.] Not statistically significant at 0.05 probability level

Table 3 Parallel force (N/mm) as a function of cutting direction and depth of cut when machining black spruce boards at 65° of rake angle

Tab. 3 Schnittkraft (N/mm) in Abhängigkeit der Schnittrichtung und der Schnitttiefe beim Zerspanen von Schwarzfichtenbrettern mit einem Spanwinkel von 65°

Depth of cut (mm)	Cutting direction							
	0°–90°		15°–75°		30°–60°		45°–45°	
1	n.a.[a]		n.a.		2.9	Aa	2.7	Aa
2	4.7[b]	Ba[c]	3.8	Aa	3.9	ABb	3.9	ABb
3	6.1	Bb	5.3	ABb	4.6	Ab	5.3	ABc

[a] Not available (data missing because some problems with the data acquisition system occurred)

[b] Mean of 20 replicates

[c] Means within a row or a column followed by the same letter are not significantly different at 1 % probability level. Upper letters are for cutting direction comparison (row) and lower letters are for depth of cut comparison (column)

Table 4 Mean waviness [W_a (μm)] as a function of cutting direction and depth of cut when machining black spruce boards at 65° of rake angle

Tab. 4 Mittlere Welligkeit [Wa (μm)] in Abhängigkeit der Schnittrichtung und der Schnitttiefe beim Zerspanen von Schwarzfichtenbrettern mit einem Spanwinkel von 65°

Depth of cut (mm)	Cutting direction							
	0°–90°		15°–75°		30°–60°		45°–45°	
1	39.0[a]	Aa[b]	48.7	Aa	35.4	Aa	67.5	Aa
2	87.7	Aa	98.8	Aab	58.3	Aa	99.4	Aa
3	396.8	Bb	173.2	Ab	104.7	Aa	143.2	Aa

[a] Mean of 20 replicates

[b] Means within a row or a column followed by the same letter are not significantly different at 1 % probability level. Upper letters are for cutting direction comparison (row) and lower letters are for depth of cut comparison (column)

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.

PCA showed that 96.3 % of the variance of scaled data was explained by two factors. The first factor represents surface waviness having high factor loadings for W_a (0.94), W_q (0.94), W_p (0.84), W_v (0.88), and W_z (0.88) and accounted for 49.6 % of the explained variance. The second factor accounted for 46.7 % of the explained variance and represents surface roughness. It had high factor loadings for R_a (0.80), R_q (0.83), R_p (0.93), R_v (0.90), and R_z (0.94).

Surface quality was hence assessed by means of waviness and roughness (factor 1 and factor 2, respectively, in the PCA), and depth of torn grain (Table 2). As it was noted for cutting forces, surface quality was affected by the cutting direction and depth of cut. While torn grain depth and waviness were affected by an interaction between these two sources of variation, roughness was only affected by the depth of cut variation. Thus, waviness was similar as cutting direction changed from 0°–90° to 45°–45°, for 1 and 2 mm of cutting depth. This behavior is shown in Table 4 for W_a, one of the waviness parameters included in the PCA.

For 3 mm of depth of cut, even though the parallel force was quite similar for 0°–90° and 45°–45° cutting directions (Table 3), waviness was considerably higher for the former than for the latter cutting direction (Table 4). This occurred because when cutting across the grain (0°–90°), the cutting edge was oriented parallel to the grain and often parallel to the earlywood/latewood bands. The knife slid easily when cutting softer zones and hardly when reached denser zones. This situation led to a discontinuous cutting, which increased waviness. In contrast, as cutting direction changes from 15°–75° to 45°–45° mode, the angle between the cutting edge and earlywood/latewood bands increased. The knife traveled through soft/dense wood bands, leading to a

Table 5 Torn grain depth (mm) as a function of cutting direction and depth of cut when machining black spruce boards at 65° of rake angle
Tab. 5 Faserausrisstiefe in Abhängigkeit der Schnittrichtung und der Schnitttiefe beim Zerspanen von Schwarzfichtenbrettern mit einem Spanwinkel von 65°

Depth of cut (mm)	Cutting direction							
	0°–90°		15°–75°		30°–60°		45°–45°	
1	0.33[a]	Aa[b]	0.39	Aa	0.35	Aa	0.47	Aa
2	0.50	Ab	0.58	Ab	0.43	Aa	0.58	Aa
3	1.85	Cc	0.94	Bc	0.67	Ab	0.78	ABb

[a] Mean of 20 replicates

[b] Means within a row or a column followed by the same letter are not significantly different at 1 % probability level. Upper letters are for cutting direction comparison (row) and lower letters are for depth of cut comparison (column)

more continuous and cleaner cut. This explains why waviness was higher when cutting at 0°–90° direction compared to the other modes.

Torn grain also worsened as cutting direction changed from 0°–90° to 45°–45°, being this effect only statistically significant when cutting at 3 mm of depth of cut (Table 5). This can be explained by the same fact why waviness was higher at 0°–90° cutting mode. Within a perspective of working with a chipper-canter, cutting at 0°–90° direction should therefore be avoided with heterogeneous wood species. Furthermore, the ANOVA (Table 2) shows that depth of cut was the most important source of variation affecting the three surface quality parameters. In addition, it is clear that the relative importance of cutting direction decreases as the depth of cut decreases (Fig. 3). This agrees with findings by Stewart (1979), who reported that surface quality improved as depth of cut decreased, especially at high rake angles.

On the other hand, surface roughness was only affected by the depth of cut variation (Table 2). Thus, roughness increased as the cutting changed from 1 to 3 mm of cutting depth. The effect of the cutting direction on roughness was not statistically significant.

Results of this study made on orthogonal cutting trials show that surface quality of black spruce wood improved as the cutting mode changed from 0°–90° to 45°–45°. However, Hernández et al. (2010) reported different results when chipper-canting black spruce logs under industrial conditions. The quality of cants was lower at the bottom area compared to the upper area of cants. Such cants were machined at about 58° of rake angle. Figure 3b shows that, excluding 0°–90°, cutting forces increase from 15°–75° to 45°–45° for 55° and 65° rake angles. Higher cutting forces should increase vibration in the feeding systems during industrial cutting, which could contribute to decreased surface quality.

Table 6 Spearman correlation analysis among surface quality factors, cutting forces, and basic density data when machining black spruce boards at 65° of rake angle
Tab. 6 Spearman Korrelationskoeffizienten zwischen Faktoren der Oberflächenqualität, Schnittkräften und Raumdichte beim Zerspanen von Schwarzfichtenbrettern mit einem Spanwinkel von 65°

Variables		R
Torn grain depth	Parallel force	0.37**
	Normal force	−0.23**
	Basic density	0.04[ns]
	Waviness	0.83**
	Roughness	0.41**
Waviness (factor 1)	Parallel force	0.52**
	Normal force	−0.21**
	Basic density	0.10[ns]
	Roughness	−0.02[ns]
Roughness (factor 2)	Parallel force	−0.20**
	Normal force	0.10[ns]
	Basic density	−0.16*

[ns] Not significant

* Statistically significant at 0.05 probability level

** Statistically significant at 0.01 probability level

3.3 Correlation analysis

A correlation analysis was performed to examine the degree of linear association between cutting forces (parallel and normal) at 65° rake angle and surface quality (torn grain depth, waviness, and roughness), and between these variables and basic density (Table 6). Parallel force showed statistically significant correlations with the three components of surface quality [torn grain depth (R = 0.37)], waviness (R = 0.52), and roughness (R = −0.20). Normal force was also correlated with torn grain (R = −0.23) and waviness (R = −0.21) but at a lower degree. Similarly, higher correlations were found between torn grain and waviness (R = 0.83), and between torn grain and roughness (R = 0.41) (Table 6). These results show that waviness and torn grain increased as parallel cutting force increased. Because of its higher magnitude, torn grain should be favored as a good predictor of surface quality. Thus, any optimization of the cutting conditions for decreasing torn grain depth should also lower the level of waviness and roughness. On the other hand, basic density only appeared to weakly affect surface roughness (R = −0.16). It is known that denser wood gives normally lower values of roughness.

4 Conclusion and recommendation

This study showed that, at low cutting speed, rake angle, cutting direction with respect to the grain, and depth of cut affected significantly the cutting forces and surface quality produced when canting black spruce wood. As rake angle increased from 35° to 65°, parallel force, torn grain, waviness, and roughness decreased while the normal forces, always with negative values, generally increased. Moreover, as rake angle increased, the relative importance of cutting direction and depth of cut on cutting forces and surface quality decreased. When all studied cutting directions and depths of cut were pooled, machining with 65° rake angle produced the lowest cutting forces and the best surface quality. Thus, a chipper-canter with finishing knives working with this rake angle should produce a better surface quality at a lower energy cost.

The results obtained at 65° rake angle have shown that the effects of depth of cut on the cutting forces and surface quality factors were higher than those associated with the cutting direction. Thus, as depth of cut increased the effects of cutting direction on the cutting forces and surface quality increased largely, especially at 3 mm of depth of cut. Within a perspective of using a chipper-canter, if the diameter of the cutter-head is small, it should be possible to minimize the potential effect of cutting direction on the surface quality by using a suitable rake angle (in this case 65° or probably above) with thin cuts. Also, the 0°–90° cutting situation should be avoided when chipper-canting this wood species.

Finally, the correlation analyses indicated that any reduction of torn grain will also have a positive impact on the roughness and waviness of the cant surfaces.

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