ORTHOGONAL CUTTING STUDY OF WOOD AND KNOTS OF WHITE SPRUCE

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Abstract. Wood defects can cause important loss of raw material and tooling during wood machining. White spruce (*Picea glauca* [Moench] Voss) is a wood species widely used in Canada, which presents an important occurrence of knots. These knots provoke several problems during machining affecting the final surface quality. The main objective of this research was to evaluate the orthogonal cutting forces and surface quality of white spruce wood with and without the presence of knots. Wood pieces of 12% MC were machined at four rake angles (10°, 20°, 30°, and 40°). Cutting forces and roughness were measured on clear wood (90°-0° cutting direction), knot (90°-90° cutting direction), and surrounding knot areas (before and after knot). Wood density in matched pieces were analyzed by X-ray densitometry. The results showed that the density of knots was in average 2.4 times higher than the density of clear wood. However, cutting forces of knots were up to eight times higher than those of clear wood. For all cutting areas, the parallel force increased as rake angle decreased. However, the sensitivity of cutting forces to changes in rake angle was higher for knots than for clear wood. Furthermore, surface roughness was positively correlated with the cutting forces. The rake angle of 40° produced the smaller cutting forces and lower surface roughness for clear wood, knots, and surrounding knot areas.

Keywords: Cutting forces, knots, wood density, surface roughness.

INTRODUCTION

White spruce (*Picea glauca* [Moench] Voss) is a softwood widely used in eastern Canada for lumber, plywood, and pulp productions. It is also used in general millwork, interior finishing, boxes, and packing cases (Zhang and Koubaa 2008). Planing is an important machining process for the manufacture of these end products. Feed speed, rake angle, and depth of cut are the most important parameters affecting cutting forces and surface quality during planing (Stewart 1970, 1977; Koch 1972, 1985). In addition, knot size and distribution also have an important impact on wood product quality. Plantation-grown white spruce has numerous and small knots (average of 15.6 mm in diameter), a weak self-pruning mechanism, and is prone to forking (Tong et al 2013). These characteristics often generate problems during the machining processes.

Knots and grain deviation are the main growth characteristics significantly affecting lumber strength and quality of wood solid products (Cramer and

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McDonald 1989; Lemieux et al 2001). A knot appears when a branch is embedded in the tree stem as the tree grows in diameter (Tong et al 2013). This internal attachment deviates and distorts wood fibers (Lemieux et al 2001). Most technological processing steps and applications of lumber–veneer wood-based products consider knots as wood defects (Buksnowitz et al 2010). The extent of the knot influence depends on its size, location, shape, and soundness, the related local grain slope, and the type of stress to which the lumber is subjected (Tong et al 2013). Consequently, knots are a major cause of lower product volume and value recovery from logs (Zhou and Smith 1991; Duchesne 2006; Zhang et al 2006).

Moreover, Canadian industrial expertise in softwood planing indicates that the presence of knots is to some level involved in tool wear mechanisms. The size and distribution of knots in a wood piece negatively affect the tool edge geometry, causing chipping, gaping, or crumbling of the tool edge. Therefore, the tools can quickly become unusable (Ko et al 1999). This could be caused by the higher density and grain deviation of knots, which will result in the increase of the cutting forces. Kivimaa (1952) found a correspondence between measured cutting force and the change of tool edge. In addition, the constant density variation between clear wood and knot-wood that the knife encounters as it passes through a wood piece could accelerate the tool wear mechanism. There was a discernible effect of wood density variation between species on tool wear, which was reported by Konishi (1972). Therefore, the assessment of the knot areas during machining will contribute to a better understanding of the relationship between wood characteristics and tool wear.

Within this context, the goal of this study was to evaluate the effect of rake angle and cutting areas (clear wood, before-knot, knot-wood and after-knot) on orthogonal cutting forces and surface quality of white spruce wood pieces. The variation in density and grain deviation along the wood areas was considered.

MATERIALS AND METHODS

Twenty flat-sawn pieces of white spruce of 900 mm in length were stored in a conditioning room at 20°C and 60% RH, until they reached 12% EMC. One sound knot of at least 10 mm in minor diameter was selected from each wood piece. A sample of 25 mm (*T*, tangential) width, 50 mm (*R*, radial) thickness, and 120 mm in length was cut from the wood piece in which the selected knot was centered in the longitudinal–tangential plane of the sample. Four cutting areas were identified in the sample as shown in Fig 1.

Density Profiles

One strip of 1.57 mm thick was cut on the longitudinal-tangential plane of each sample. The strips were scanned with an X-ray densitometer on the tangential face, following the longitudinal direction. No extraction was made in the samples before scanning. The average wood density at 12% EMC was calculated for each cutting area, which was then associated with the average cutting forces.

Machining Treatment

The cutting treatments were performed with a tool accessory system mounted on the column of a milling machine, which allowed to set the cutting tool at different rake angles (Fig 2). A freshly sharpened tool having 5 mm of width (kerf), 41° of tool angle, and 4° of side clearance angle was used (Fig 2). The width of the tool was set according to the knot mean diameter found in the samples (Fig 1), assuring that the cut passed within the knot. Each sample was cut following the longitudinal direction at 4.7 mm/s feed speed and 1.0 mm of cutting depth using four rake angles: 10°, 20°, 30°, and 40°. The top back clearance angles were 39°, 29°, 19°, and 9°, respectively. The tool cut through the following cutting areas: clear wood (90°-0° cutting direction, according to McKenzie (1960) notation of orthogonal cutting), before-knot (with the grain), knot-wood (nearly 90°-90° cutting direction), and after-knot (against the grain) (Fig 1).

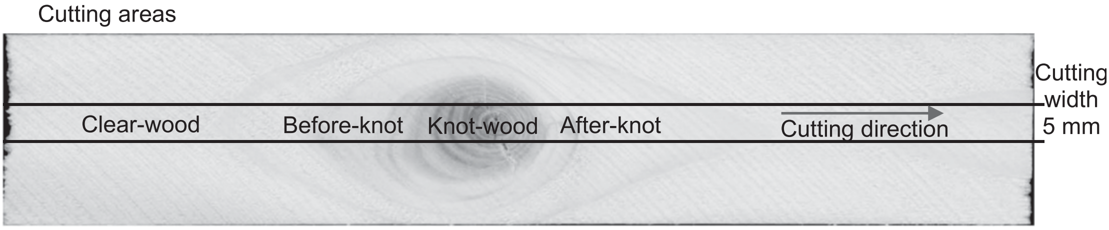

Figure 1. Four wood areas in the longitudinal–tangential plane of the sample showed on the tool cutting path.

The first number in the McKenzie notation corresponds to the angle formed between the knife-edge and the wood grain. The second number corresponds to the angle formed between the cutting direction and the wood grain. Previous smooth cuts were carried out to level samples before each cutting. The same parameters were used to cut a matched sample following the 90°-90° cutting direction in clear wood.

Force Measurements

During cutting treatments, the wood samples were fastened to a Kistler 9257B quartz three-component dynamometer, which was fixed to the feed table of the milling machine (Fig 2). The parallel (F_P), normal (F_N), and lateral (F_L) components of the cutting forces were recorded with a computer and a data acquisition card, set at 100 readings per second. The forces for each treatment were measured in the four areas previously described within each wood sample. The average F_P, F_N, and F_L forces for each rake angle and cutting area were determined from these data. The specific parallel force (SF_P) was also calculated as the ratio between F_P and wood density. This "specific" property represents the parallel force normalized with respect to the density found in each cutting area (90°-90° clear wood, before-knot, knot-wood, and after-knot).

Surface Topography

Three-dimensional measurements of surface roughness were obtained by a Stil MicroMeasure profilometry system. A surface of 10 (x-axis) by

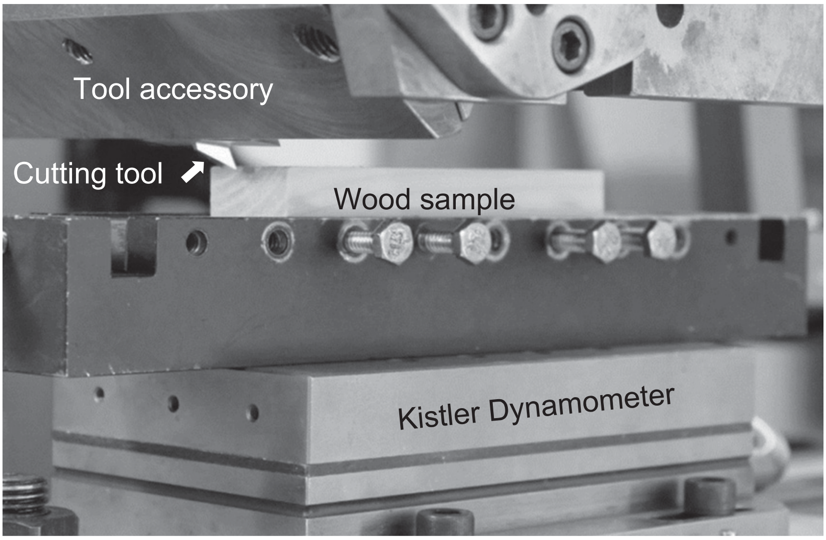

Figure 2. Orthogonal cutting system used in this study.

3 (*y*-axis) mm on longitudinal and tangential directions, respectively, was measured by Surface Map 2.4.13 software (Stil - Aix-en-Provence, France) for the four cutting areas in each sample. Measurement steps were 20 and 30 μm in *x* and *y* axes, respectively. The acquisition frequency of 100 Hz and a scanning rate of 2 mm/s were used. Roughness profiles were extracted from the measured surfaces by MountainsMap® software (DigitalSurf - Besançon, France), which analyzes the surface texture from scanned samples by Surface Map. The amplitude parameters of arithmetical mean deviation of the profiles (R_a), root mean square deviation of the profiles (R_q), maximum profile peak height (R_p), maximum profile valley depth (R_v), maximum height of profile (R_z), and total height of profile (R_t), were determined using a cutoff length of 0.8 mm combined with a robust Gaussian filter (ISO 16610-31 2010). The functional parameters of core roughness depth (R_k), reduced peak height (R_{pk}), and reduced valley depth (R_{vk}) were calculated from the Abbott curve according to ISO 13565-2 (1996).

Statistical Analyses

Data were analyzed using the Statistical Analysis System (SAS) 9.4 software (SAS Institute 2014, Cary, NC). Raw data were first evaluated with the Box–Cox method showing the more fitted transformation if required. The F_P, SF_P, and all roughness parameters were transformed using a logarithmic function. Given the number of surface parameters studied, a principal component analysis (PCA) was then applied to roughness data to regroup them in common factors and facilitate 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. A nonparametric analysis of variance was used to evaluate the variation in F_N. A univariate analysis of variance was performed to assess surface quality (PCA results), F_P, and SF_P. The data structure followed a split-plot design with the cutting area in the main plot and the rake angle in the subplot. Means comparison tests were used to determine significant differences at 5% probability level when required. Finally, the normality was verified with Shapiro–Wilk test and the homogeneity of variance was verified with the graphical analysis of residuals.

RESULTS AND DISCUSSION

The analysis of variance showed that parallel and normal cutting forces, SF_P, and roughness were statistically affected by variations in cutting area and rake angle. The interaction between these two variables was also significant (Table 1). The lateral component of the cutting force was very low (0.25 N/mm) and was not affected by the rake angle and wood areas. Therefore, this component was not considered in the ulterior analyses.

Force Assessment

To illustrate the effect of the interaction on the cutting forces, Figs 3 and 4 show the parallel and

Table 1. *F* values obtained from the analysis of variances for cutting forces, specific parallel force (SF_P), and surface quality.

				Surface quality
	Cutting force			Roughness
	Parallel force	Normal force	SF_P	Factor 1
Source of variation	*F* value			
Cutting area	515.3**	52.3**	131.7**	280.3**
Rake angle	120.9**	980.0**	141.2**	28.3**
Cutting area * Rake angle	3.8**	48.2**	4.6**	2.1*

* Statistically significant at 0.05 probability level, ** statistically significant at 0.01 probability level.

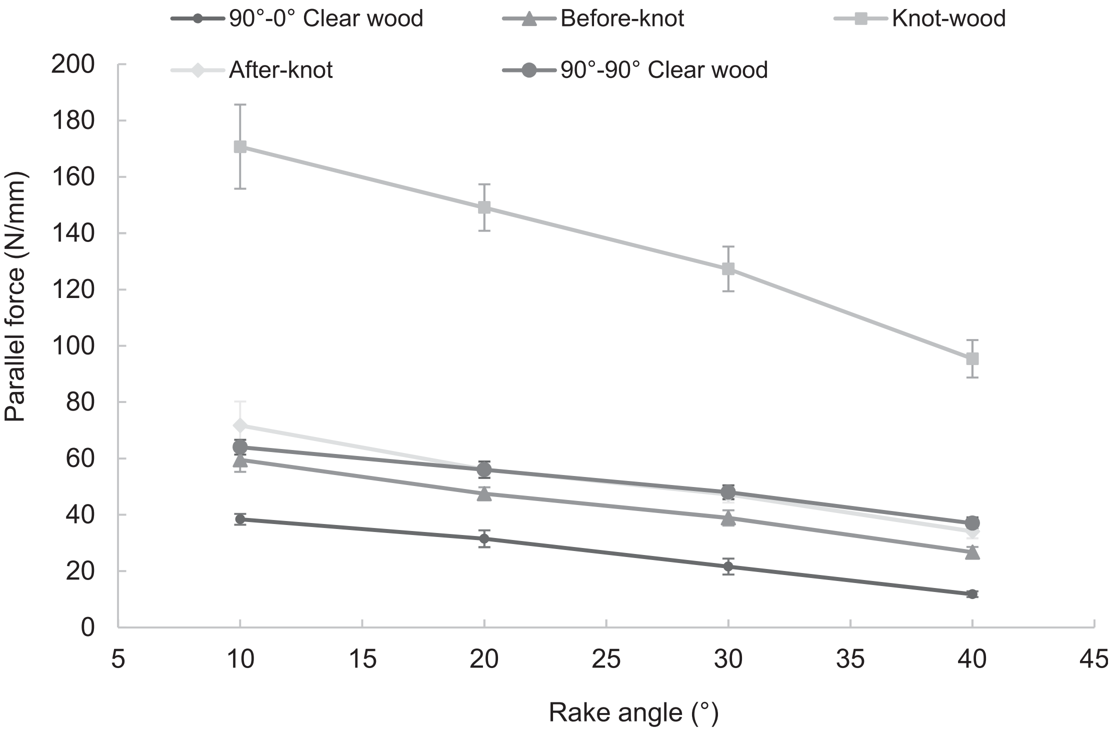

Figure 3. Parallel force mean as a function of the rake angle for all cutting areas (bars correspond to the standard error).

normal forces, respectively, as a function of the rake angle and cutting areas. Figure 3 also shows the parallel force at 90°-90° cutting direction for clear wood, as a function of the rake angle. The parallel force decreased as the rake angle increased, regardless of the cutting area. However, this effect was more noticeable for the knot, where F_P decreased at a rate of 25 N/mm for each 10° of augmentation in rake angle. This rate was in average 11 N/mm for the other cutting areas (Table 2). These results are in agreement with previous works (Woodson 1979; Huang 1994; Jin and Cai 1996; Hernández et al 2014) which reported a negative relationship between F_P and rake angle. On the other hand, F_N initially decreased, changed of action direction (from pushing to pulling out), and finally increased as rake angle increased (Fig 4). Again, knot-wood was more sensitive to changes in rake angle than the other cutting areas.

Moreover, the F_P significantly varied among cutting areas. As the tool cut through a sample, F_P lowest value was obtained when cutting clear wood, it then increased before the knot, attained its maximum within the knot, and finally it decreased after the knot. The same pattern was followed by the wood density profile (Table 2). The correspondence between wood density and F_P patterns is shown in Fig 5. The F_P increase was more important between knot and clear wood areas (Fig 3). The significant increase in forces can be partially explained by the 2.4 wood density ratio between these two cutting areas (Table 2). The important effect of wood density on cutting forces has been largely reported by various authors (Kivimaa 1950; Koch 1964; Eyma et al 2004; Porankiewicz et al 2011). However, an important part of the force increment could be related to the orientation of knot within the wood piece. The knot is the base of a branch inserted in the bole with an inclination angle. Therefore, as the tool cut through the sample, the cutting direction went from 90°-0° in clear wood to nearly 90°-90° in knot-wood.

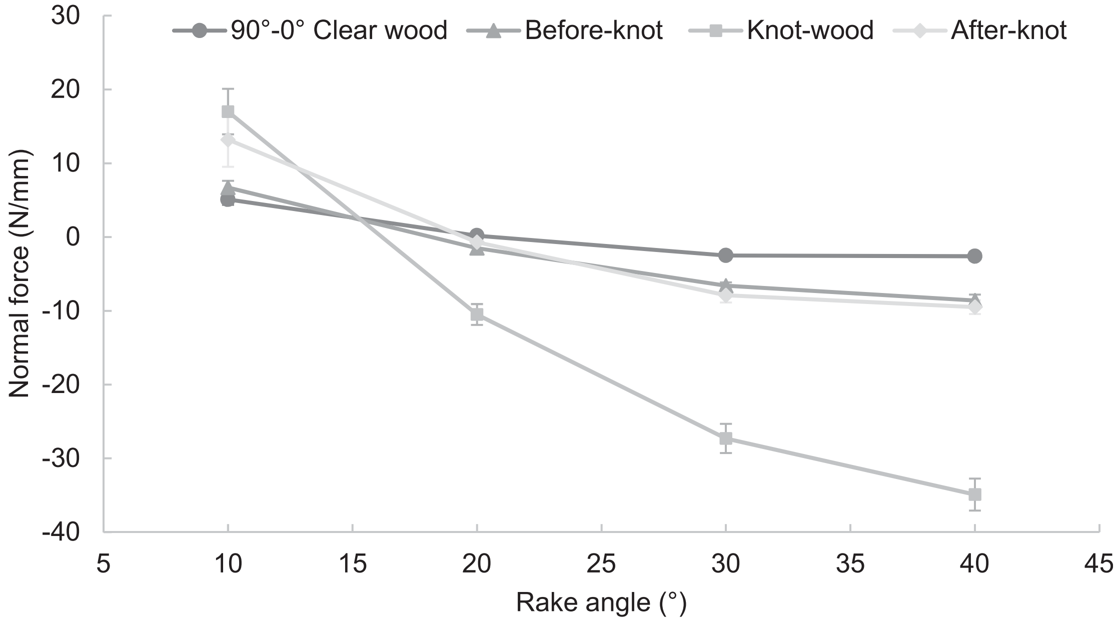

Figure 4. Normal force mean as a function of the rake angle for all cutting areas (bars correspond to the standard error).

Cutting forces in 90°-90° direction are greater than in 90°-0° (Kivimaa 1950; McKenzie 1960; Woodson and Koch 1970). Parallel forces obtained in 90°-90° clear wood were in average 2.2 times higher than the ones obtained at 90°-0° clear wood (Table 2). Thus, the association between higher density and grain deviation (90°-90°) in knot-wood could better explain the increase of F_P. However, the increase in F_P was not equal between rake angles. The F_P ratio between clear wood and knot-wood wood increased with rake angle. This ratio went from 4.4 at 10°, to 4.7 at 20°, to 5.9 at 30°, and to 8.1 at 40° (Table 2). Therefore, higher rake angles were more F_P sensitive to the changes in the cutting areas but produced smaller F_P values.

Moreover, the increase of the F_P before and after the knot respect to clear wood can also be related to the increase of density in these cutting areas. Areas surrounding the knot were 128 kg/m^3 denser than clear wood (Table 2). However, the increase in F_P was more important in the wood after the knot compared with before the knot (Fig 3). These results are explained by the fact that cutting forces are lower when the tool cuts with the grain (before the knot) than against the grain (after the knot) (Stewart 1969). The SF_P

Table 2. Mean values of wood density and parallel and normal forces by cutting area and rake angle.

		Parallel force (N/mm)								Normal force (N/mm)							
		Rake angle								Rake angle							
Cutting area	Wood density (kg/m^3)	10°		20°		30°		40°		10°		20°		30°		40°	
90°-0° clear wood	393	38[a]	Ca[b]	32	Cb	22	Dc	12	Dd	5.1	Ba	0.2	Ab	−2.5	Ac	−2.6	Ac
Before-knot	520	60	Ba	48	Bb	39	Cc	27	Cd	6.7	Ba	−1.5	Bb	−6.6	Bc	−8.6	Bd
Knot-wood	943	171	Aa	149	Aab	127	Ab	95	Ac	17.0	Aa	−11	Cb	−27	Cc	−35	Cc
After-knot	522	72	Ba	56	Ba	47	Bb	34	Bc	13.2	ABa	−0.7	ABb	−7.9	Bc	−9.5	Bd
90°-90° clear wood	393	64	a	56	ab	48	b	37	c	10.8	a	3.2	b	−1.8	c	−3.4	c

[a] Mean of 20 replicates.

[b] Means within a row or a column followed by the same letter are not significantly different at 5% probability level. Upper case letters are for cutting area comparison (column) and lower case letters are for rake angle comparison (row) for parallel force and normal force separately. In 90°-90° clear wood condition, lower case letters are for rake angle comparison (row) for parallel and normal forces separately.

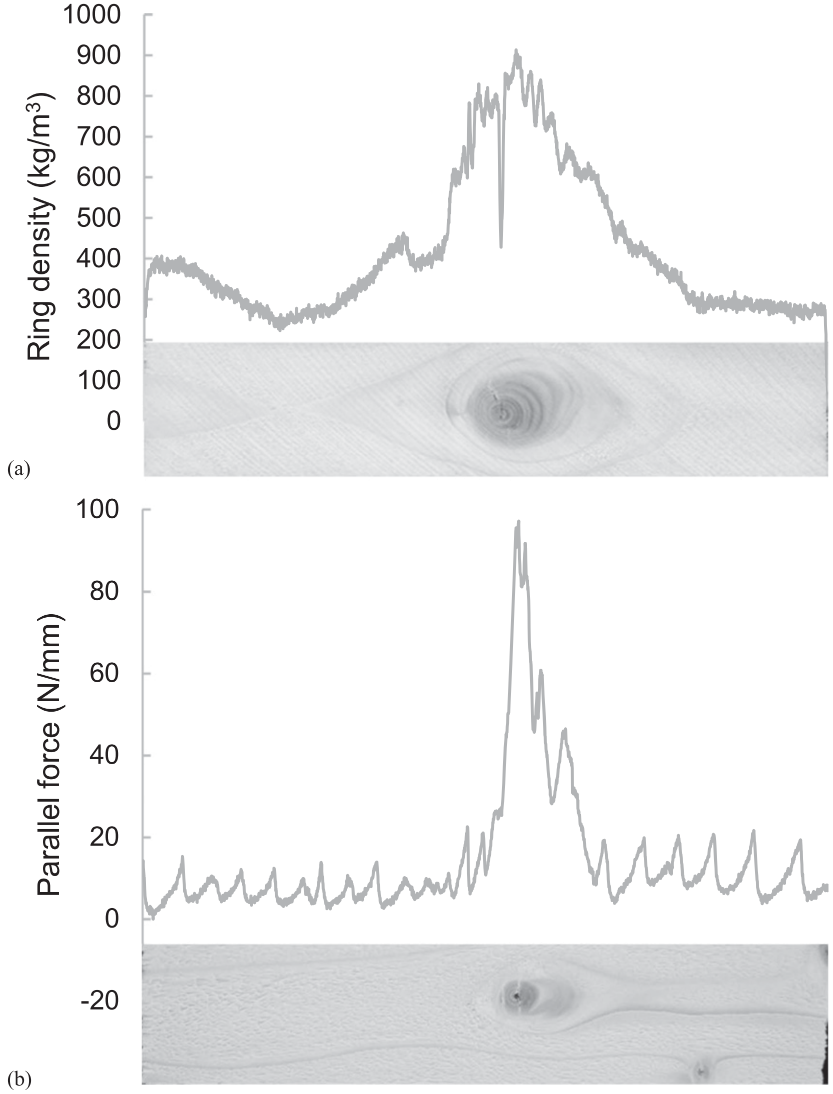

Figure 5. (a) Wood density profile (b) parallel force at 40° of rake angle of one sample of 120 mm of length.

allowed removing the effect of the density variation during the cut and thus more effectively evaluates the effect attributed to the grain deviation. Once the density effect was eliminated, multiple comparisons tests showed that there is still a significant difference between cutting areas for all rake angles (Table 3). Therefore, as the tool cut through the wood piece (clear wood, before-knot, knot-wood, and after-knot), as if there was no density variation, parallel force would vary with the grain orientation changes between cutting areas (Fig 6). Moreover, knot-wood and 90°-90° clear wood are not significantly different (Table 3), which reflects that the density correction was consistent.

Surface Quality Assessment

Surface quality was assessed using nine roughness parameters. The PCA results showed that one common factor grouped all the roughness

Table 3. Mean values of the specific parallel force (SF_P) by cutting area and rake angle.

	SF_P							
	Rake angle							
Cutting area	10°		20°		30°		40°	
90°-0° clear wood	0.099[a]	Ca[b]	0.081	Cb	0.055	Dc	0.031	Dd
Before-knot	0.116	BCa	0.093	BCb	0.076	Cc	0.052	Cd
Knot-wood	0.182	Aa	0.160	Aab	0.136	Ab	0.100	Ac
After-knot	0.138	Ba	0.110	Bb	0.091	Bc	0.064	Bd
90°-90° clear wood	0.167	Aa	0.145	Aab	0.123	Ab	0.096	Ac

[a] Mean of 20 replicates.

[b] Means within a row or a column followed by the same letter are not significantly different at 5% probability level. Upper case letters are for cutting area comparison (column) and lower case letters are for rake angle comparison (row) for parallel force and normal force separately. In 90°-90° clear wood condition, lower case letters are for rake angle comparison (row) for parallel and normal forces separately.

parameters. This factor explained 82.7% of the total variance. The factor loadings were 0.96 for R_a; 0.97 for R_q; 0.87 for R_p; 0.97 for R_v, R_t, and R_z; 0.62 for R_k; 0.85 for R_{pk}; and 0.93 for R_{vk}.

Multiple comparisons results for R_a by cutting area and rake angle are shown in Table 4. During the cutting path, the tool cut following the grain in first place. It passed through the clear wood and then the before-knot wood, which both showed low surface roughness. Then, the tool passed through the knot-wood, increasing the roughness to a maximum due to the knot grain deviation (90°-90°). This type of cutting produces a very poor surface quality (McKenzie 1960). Finally, the tool cut against the grain as it passed through after-knot wood, which decreased roughness (Table 4). Thus, the difference in roughness between before-knot and after-knot wood cutting was related to their grain orientation with respect to the cutting direction, namely with and against

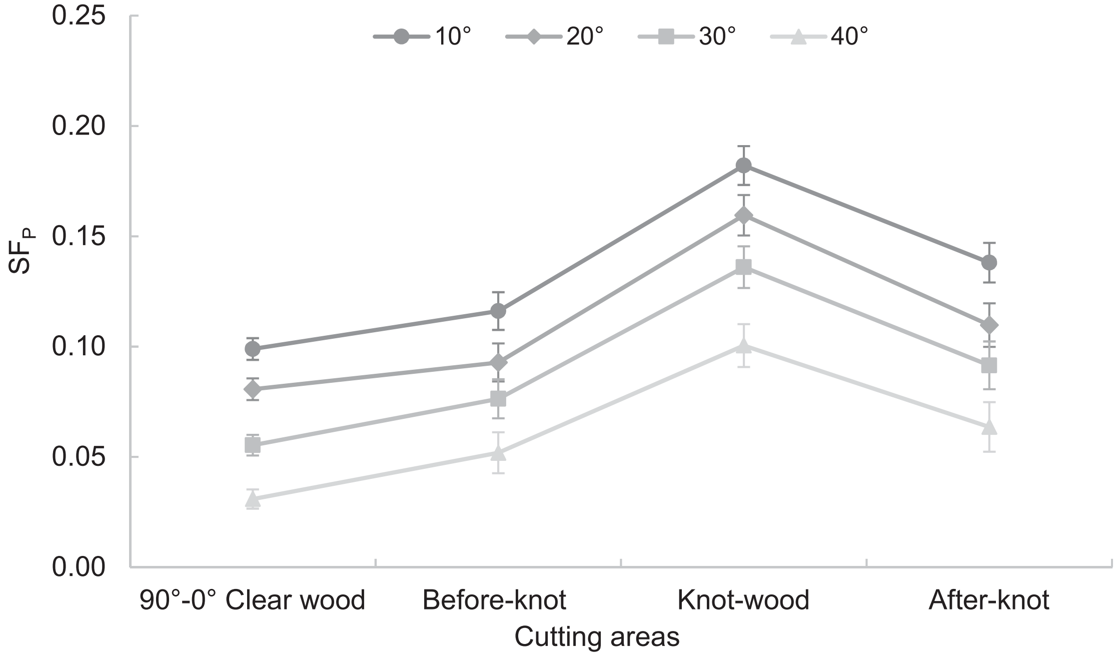

Figure 6. Specific parallel force mean as a function of the cutting area for all rake angles (bars correspond to the standard error).

Table 4. Mean values of the arithmetic mean deviation (R_a) by cutting area and rake angle.

	Roughness—R_a (μm)							
	Rake angle							
Cutting area	10°		20°		30°		40°	
90°-0° clear wood	33[a]	Ca[b]	29	Bab	28	Bab	26	Bb
Before-knot	59	Ba	37	Bb	26	Bbc	17	Bc
Knot-wood	201	Aa	198	Aa	120	Ab	98	Ab
After-knot	125	Aa	103	Aa	56	Ab	50	Ab

[a] Mean of 20 replicates.

[b] Means within a row or a column followed by the same letter are not significantly different at 5% probability level. Upper case letters are for cutting area comparison (column) and lower case letters are for rake angle comparison (row).

the grain. Several authors have reported that surface quality was poorer when cutting against the grain compared to cutting with the grain (Stewart 1969; Iskra and Tanaka 2005; Iskra and Hernández 2009). Rake angles of 10° and 20° produced comparable surface roughness, which significantly decreased toward higher rake angles, producing similar surface quality between 30° and 40° rake angles (Table 4).

Among all roughness parameters, Fig 7 shows maximum profile valley depth (R_v) as a function of rake angle for each cutting area. This parameter showed the highest sensitivity to the variation of the studied variables. R_v was significantly higher in knot-wood and after-knot wood compared with before-knot and clear wood and it decreased as rake angle increased. This behavior was more noticeable in after-knot wood (Fig 7), which can

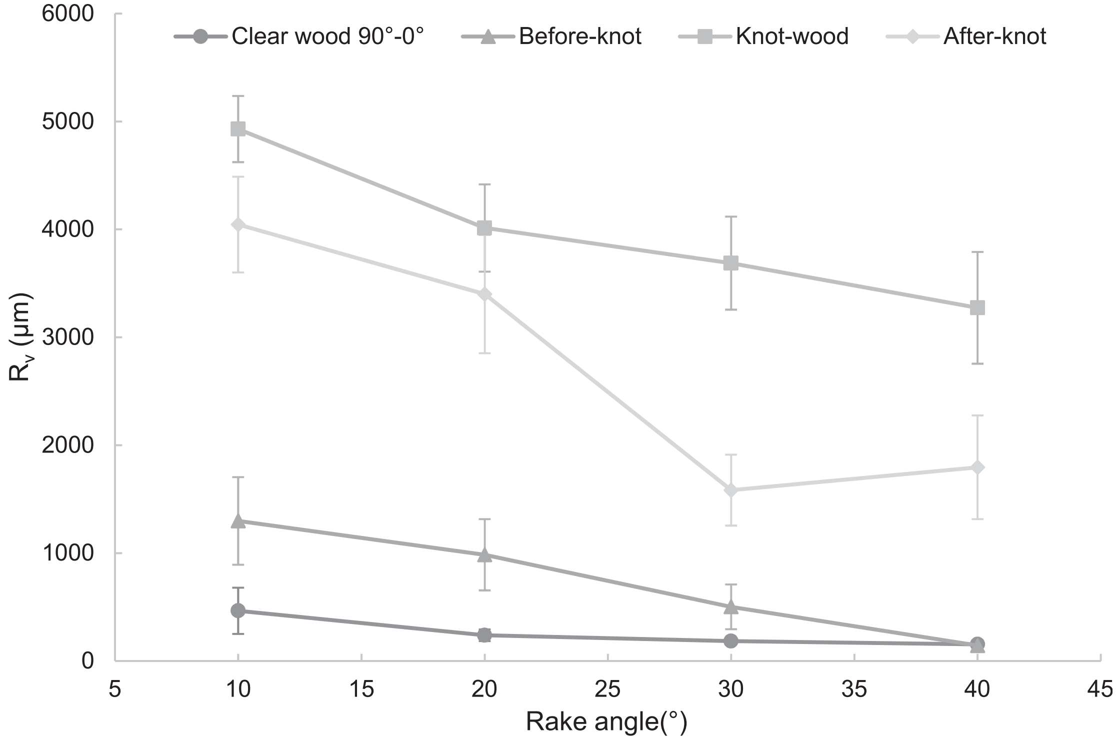

Figure 7. Arithmetic mean deviation (R_v) as a function of rake angle for all cutting areas (bars correspond to the standard error).

be directly related to the formation of torn grain when cutting against the grain. In general, surface quality was poorer when cutting with a rake angle of 10° and it was better with a rake angle of 40°.

Overall, the critical point during cutting was reached when passing through the knot. Among tested rake angles, 40° gave the better results, producing the lowest forces and surface roughness. However, industrial-scale trials need to be done to validate these results. In addition, the knot influence on the tool edge chipping should be further studied.

CONCLUSIONS

White spruce parallel and normal forces were highly affected by the rake angle. For all cutting areas, F_P decreased as rake angle increased. F_N decreased up to 0 N/mm and then increased as rake angle increased. Knot-wood was more force sensitive to rake angle variation compared with clear, after-knot, and before-knot wood. The cutting direction and higher density of knots were the main causes of their highest cutting forces. In general, surface quality improved as rake angle increased. This effect was more noticeable in knot and after-knot wood areas. F_P and surface roughness were lower when cutting before-knot wood than after-knot wood, which was attributed to cutting with the grain in the former and against the grain in the latter. Overall, a rake angle of 40° produced lower cutting forces and better surface quality.

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REFERENCES

Buksnowitz C, Hackspiel C, Hofstetter K, Muller U, Gindl W, Teischinger A, Konnerth J (2010) Knots in trees: Strain distribution in a naturally optimised structure. Wood Sci Technol 44(3):389-398.

Cramer SM, McDonald KA (1989) Predicting lumber tensile stiffness and strength with local grain angle measurements and failure analysis. Wood Fiber Sci 21(4):393-410.

Duchesne I (2006) Effect of rotation age on lumber grade yield, bending strength and stiffness in jack pine (*Pinus banksiana* Lamb.) natural stands. Wood Fiber Sci 38(1): 84-94.

Eyma F, Meausoone PJ, Martin P (2004) Study of the properties of thirteen tropical wood species to improve the prediction of cutting forces in mode B. Ann Sci 61(1):55-64.

Hernández RE, Llavé AM, Koubaa A (2014) Effects of cutting parameters on cutting forces and surface quality of black spruce cants. Eur J Wood Wood Prod 72(1):107-116.

Huang YS (1994) Cutting force components in orthogonal cutting parallel to the grain (90-0) I. Effects of rake angles. Mokuzai Gakkaishi 40(10):1134-1140.

Iskra P, Hernández RE (2009) The influence of cutting parameters on the surface quality of routed paper birch and surface roughness prediction modeling. Wood Fiber Sci 41(1):28-37.

Iskra P, Tanaka C (2005) The influence of wood fiber direction, feed rate, and cutting width on sound intensity during routing. Holz Als Roh-und Werkst 63(3):167-172.

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

Kivimaa E (1950) Cutting force in woodworking. Valtion Teknillinen Tutkimuslaitoksen Julkaisuja, Helsinki, Finland, 18.

Kivimaa E (1952) Blunting of wood-working tools. Holz Roh Werkst 10(11):425-428.

Ko PL, Hawthorne HM, Andiappan J (1999) Tribology in secondary wood machining. Pages 101-117 *in* S Bahadur, J Magee, eds. Wear processes in manufacturing. American Society for Testing Materials, West Conshohocken, PA.

Koch P (1964) Wood machining processes. Ronald Press Co., New York, NY.

Koch P (1972) Utilization of the southern pines, Vol. 2: Processing. US Department of Agriculture-Forest Service, Washington, DC.

Koch P (1985) Utilization of hardwoods growing on southern pine sites, Vol. 2: Processing. US Department of Agriculture-Forest Service, Washington, DC.

Konishi C (1972) Cutting ability of knife with planer. I. Relationship between condition of wood and cutting force. Mokuzai Gakkaishi 18(5):223-229.

Lemieux H, Beaudoin M, Zhang SY (2001) Characterization and modeling of knots in black spruce (*Picea mariana*) logs. Wood Fiber Sci 33(3):465-475.

McKenzie WM (1960) Fundamental aspects of the wood-cutting process. Forest Prod J 10(9):447-456.

Porankiewicz B, Axelsson B, Grönlund A, Marklund B (2011) Main and normal cutting forces by machining wood of *Pinus sylvestris*. BioResources 6(4):3687-3713.

Stewart HA (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.

Stewart HA (1970) Cross-grain knife planing hard maple produces high-quality surfaces and flakes. Forest Prod J 20(10):39-42.

Stewart HA (1977) Optimum rake angle related to selected strength properties of wood. Forest Prod J 27(1):51-53.

Tabachnick BG, Fidell LS (2007) Using multivariate statistics. Pearson/Allyn & Bacon, Boston, MA.

Tong QJ, Duchesne I, Belley D, Beaudoin M, Swift E (2013) Characterization of knots in plantation white spruce. Wood Fiber Sci 45(1):84-97.

Woodson GE (1979) Tool forces and chip types in orthogonal cutting of southern hardwoods. USDA Forest Service, New Orleans, LA.

Woodson GE, Koch P (1970) Tool forces and chip formation in orthogonal cutting of loblolly pine. USDA Forest Service, New Orleans, LA.

Zhang SY, Chauret G, Swift DE, Duchesne I (2006) Effects of precommercial thinning on tree growth and lumber quality in a jack pine stand in New Brunswick, Canada. Can J Res 36(4):945-952.

Zhang SY, Koubaa A (2008) Softwoods of eastern Canada: Their silvics, characteristics, manufacturing and end-uses. FPInnovations, Quebec, Canada.

Zhou H, Smith I (1991) Factors influencing bending properties of white spruce lumber. Wood Fiber Sci 23(4): 483-500.