EFFECT OF CHIPPING EDGE INCLINATION ANGLE ON SIZE DISTRIBUTION OF PULP CHIPS PRODUCED BY A CHIPPER-CANTER

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Abstract. The effect of oblique cutting on the chipper-canter wood chipping mechanism was studied. A bent knife was modified to obtain inclination angles (IAs) of 30° and 50° between the chipping edge and the log feeding direction. The standard knife had an IA of 40°. These three knives were tested on 15 logs each, under frozen (−10°C) and unfrozen conditions. Chip dimensions were assessed by using thickness (Domtar distribution) and width/length (Williams distribution). Characteristics and physical properties of the log knots were also measured. Experiments revealed that IA had a significant effect on chip formation mechanism. The IA affected the chipping edge entering the log and the form of the wood slice that was transformed into chips. These changes provoked variations in chip size. An IA of 30° produced wider chips, mostly in the first half of the cut, shaped as an elongated parallelepiped that resulted from a tangential, oblique, and radial splitting in a single chip. The shape of chips obtained with IAs of 40° and 50° was more like an upright parallelepiped that was detached mostly by radial and oblique splittings. At the beginning and at the end of the cut, chips were produced by tangential splitting. As a result, for a same chip length of 23 mm, weighted mean chip thickness (WCT) decreased almost 1 mm when IA decreased from 50° to 30°. The knot ratio (total knot area/cant total area) affected both chip size distributions and WCT. Chipping frozen wood at −10°C reduced the chip thickness by 0.55 mm with respect to unfrozen wood. The amount of fines and pin chips also increased nearly two times compared with unfrozen wood. The amount of the Williams accepts chip class increased by 6% when IA decreased from 50° to 30° and by 8% when chipping unfrozen wood compared with frozen wood.

Keywords: Oblique cutting, chipper-canter, chipping edge inclination angle, chip formation, chip thickness.

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INTRODUCTION

In Canada, the forest industry contributed more than 23.1 billion $CAD (1.2%) to the nominal gross domestic product in 2016. The pulp and paper subsector accounted for approximately 36% of this contribution. Moreover, Canada remains the world's largest producer of newsprint and the largest producer of northern bleached softwood kraft pulp (NRCAN 2017). This industry has a major economic importance in the Quebec Province as well. It counted for six 116 million $CAD in exports in 2017, which represents 57% of total exports of the province's forest products (MFFP 2017a).

The raw material used for pulp manufacturing in Quebec consists mainly of wood chips produced by sawmills (70.4%), which are the principal byproducts of the lumber manufacturing industry. The revenue from chip production is estimated to be 10.6% of the total profit earned by sawmills in 2016 (MFFP 2017b). The price of the chips is directly influenced by their quality and their availability. The size, bulk density, MC, bark content, and wood species mixture are the main attributes of chip quality (Bergman 1985). Moreover, the uniformity and consistency of chip dimensions over time are key factors for any pulping process (Bjurulf 2005). The influence of chip size distribution on pulp characteristics has been widely studied for the available pulping technologies and different types of chippers. Most of the studies agreed that among chip dimensions, chip thickness is the most important parameter affecting pulp quality, including kraft pulping (Hatton and Keays 1973; Tikka et al 1993), mechanical pulping (Hoekstra et al 1983), chemimechanical pulping (Lönnberg and Robertsén 1986), and sulfite pulping (Feiner and Gallay 1962). In addition to a desired chip thickness, the homogeneity of the chip size distribution is very important for an optimal pulping process (Broderick et al 1998). Sawmills aim to limit the production of small particles (fines and pin chips) and the oversized fraction, thus narrowing the size distribution of wood chips. Reducing the undesirable fractions will result in chip quality improvement which gives sawmills a better chance to commercialize pulp chips (Smith and Javid 1992).

A large part of the sawmill chips in Canada are produced by chipper-canters. These machines are used for the primary breakdown of small- to medium-diameter softwood logs. Their advantages are high processing speed, low sawdust production, and obtaining cants and chips in one single operation. The most common chipper-canter used in eastern Canada has a truncated conical-shaped cutterhead fitted with uniformly distributed knife holders, each with a bent knife and a knife clamp. The bent knife has two cutting edges that are joined at an angle: a longer or chipping edge and a shorter or canting edge. The cutting work is performed by the simultaneous action of both cutting edges. The chipping edge severs a slice to produce chips, and the canting edge smooths the cant surface. The influence of some chipper-canter machining parameters on chip size distribution have been previously studied, namely cutting speed (Hernández and Boulanger 1997), cutting width (Hernández and Lessard 1997; Cáceres et al 2015, 2016, 2017), knife clamp geometry (Hernández and Quirion 1993; 1995), log infeed position (or attack angle [AA]), and cutterhead diameter (Kuljich et al 2017). Other experiments revealed that log characteristics also have a noticeable effect on chip size distribution, such as wood provenance (Cáceres et al 2015) and log position in the stem (Cáceres et al 2016, 2017). More precisely, the wood properties including wood density, growth ring characteristics, bending properties (Cáceres et al 2015, 2016), and the number and size of knots (Cáceres et al 2016, 2017) significantly influenced the chip size. The temperature condition (TC) of wood (frozen and unfrozen) also has a considerable effect over chip dimensions. The differences between frozen and unfrozen conditions depend on wood temperature and wood MC (MC) variations. Because of the effects of these two factors on mechanical properties of wood, frozen logs produce more fines and pin chips and reduce chip thickness during chipping (Hernández and Quirion 1993, 1995; Hernández and Boulanger 1997; Hernández and Lessard 1997; Kuljich et al 2017).

Quality fluctuation in sawmill chips supply is a continuous concern of pulp mills. Thus, sawmills are required to regularly control the chip size distribution produced by the chipper-canter. The improvement of chip quality in terms of chip dimensions can be achieved with a better understanding of the mechanism of chip formation. This chip production can then be modified by setting the machine parameters. Among them, some attributes of the knife geometry remain to be studied. In wood machining, oblique cutting was introduced as a method to improve cutting steadiness and processing quality and to reduce cutting forces and noise. McKenzie and Franz (1964) studied oblique cutting and observed a reduction in cutting forces due to the inclination of the cutting edge when cutting across the fibers. Similarly, Ozaki and Kimura (1989) reported that an increase in the inclination angle (IA) of the cutting edge decreased the depth of the split along the grain. The chipper-canter cutterhead has the shape of a shallow truncated cone which is defined by an oblique angle. The effect of this angle on chipping characteristics has been poorly documented. Thus, a study of oblique cutting could be a promising alternative to improve the chipping process with this machine. In this context, the objective of this work was to understand the influence of the chipping edge IA on the formation mechanism and chip size distribution. These effects were evaluated by machining black spruce logs under frozen and unfrozen wood conditions.

MATERIALS AND METHODS

Testing Material

Tests were carried out on 45 logs of black spruce (*Picea mariana* [Mill.] B.S.P.) from the region of Mauricie in the Quebec Province. This species is one of the most important boreal species in eastern Canada and is part of the spruce-pine-fir wood group, which is widely used for construction applications and in the pulp and paper industry (Zhang and Koubaa 2008). Logs were debarked, crosscut to 2.45 m length, wrapped in plastic films, and stored under −19°C to limit MC loss until the day of transformation. Logs were without excessive crook or visible decay.

All logs were assessed by their main physical characteristics. First, the form of the log was evaluated to choose the best two opposite sides for fragmentation (frozen and unfrozen sides). One 25-mm-thick disk from each end of the log was cut to prepare specimens to measure physical properties. The thickness of sapwood was measured at three positions in each side of the disk along the radial direction. Afterward, one cube of 25-mm side was obtained from each side of the disc. The cubes were then divided between sapwood and heartwood for separate measurements of MC and basic density using ASTM D4442-15 and ASTM D2395-14, respectively. Length, top and bottom diameters, and taper of each log were also measured. Knots bigger than 10 mm in diameter located in the areas corresponding to fragmentation were counted. All log characteristics were analyzed to separate the logs into three equivalent groups of 15 logs (Table 1), which assured a homogeneous distribution of the raw material properties in each group. Basic densities of sapwood and heartwood were similar, and thus, only their mean value was used to assess the separated log groups.

Fragmentation Process

Logs were processed with a laboratory chipper-canter equipped with one experimental cutterhead manufactured by DK-Spec (Quebec, Canada). The cutterhead was fitted with two bent knives placed at opposite positions of the cutting diameter (Fig 1). The knife angle of the chipping edge was 35°, with a rake angle of 51° and a clearance angle of 4°. This type of knife does not use a knife clamp as for other models of bent knives used in previous experiments (Hernández and Quirion 1993, 1995; Hernández and Boulanger 1997; Hernández and Lessard 1997; Kuljich et al 2017). The cutterhead position (vertical distance from the cutterhead axis to the bedplate) was fixed at 170 mm to obtain a 75° mean attack angle (AA; angle between the chipping rake face with respect to the grain, Fig 1). According to Kuljich et al (2017), this AA should produce chips with about 5 mm thickness

Table 1. Characteristics of black spruce logs.

Log characteristics		Group 1 (IA 30°)		Group 2 (IA 40°)		Group 3 (IA 50°)	
		Frozen	Unfrozen	Frozen	Unfrozen	Frozen	Unfrozen
Number of knots per side		7 (1)[a]	7 (1)	7 (1)	8 (1)	6 (1)	7 (1)
Sapwood thickness (mm)		15.4 (0.8)	15.4 (0.7)	14.9 (0.7)	14.6 (0.8)	15.3 (0.7)	15.4 (0.6)
MC (%)	Sapwood	131 (4)	132 (3)	125 (4)	135 (5)	126 (4)	127 (3)
	Heartwood	39 (3)	40 (2)	40 (2)	49 (4)	43 (3)	37 (2)
Basic density (kg/m^3)		436 (6)	438 (6)	434 (5)	433 (6)	436 (7)	443 (6)
Taper (mm/m)		7.9 (0.6)		7.8 (0.6)		7.8 (0.6)	
Diameter (mm)	Small end	148 (2)		145 (1)		147 (2)	
	Large end	168 (2)		166 (2)		168 (3)	

IA, chipping edge inclination angle.
[a] Numbers in parentheses are the standard errors.

under frozen conditions. The chipper-canter was equipped with a hydraulic feed carriage that held the log fixed during fragmentation.

To study the effect of the edge IA on chipping, three pairs of knives manufactured by DK-spec were used. The knives were designed to obtain three different IAs of the chipping edge but with the same rake angle, AA, and clearance angle. However, because the cutting width was always kept constant, knife length differed among the three pairs of knives. A standard knife with an IA of 40° was used as a reference for this experiment. This knife was modified to obtain an IA of 30° and 50° (Fig 2). The IA was measured between the chipping edge and a plane coincident to the canting knife clearance face (Fig 1). The 30°-IA knife had a 15-mm longer canting edge than the other knives, which resulted in a higher cutting diameter. Consequently, the feed speed and cutterhead rotation speed were adjusted to maintain the same cutting speed and nominal chip length. All knives were freshly ground before the experiment to minimize the effect of tool wear on chip size.

The cutting width was held constant at 25.4 mm (along the log) to reduce the effects of the log

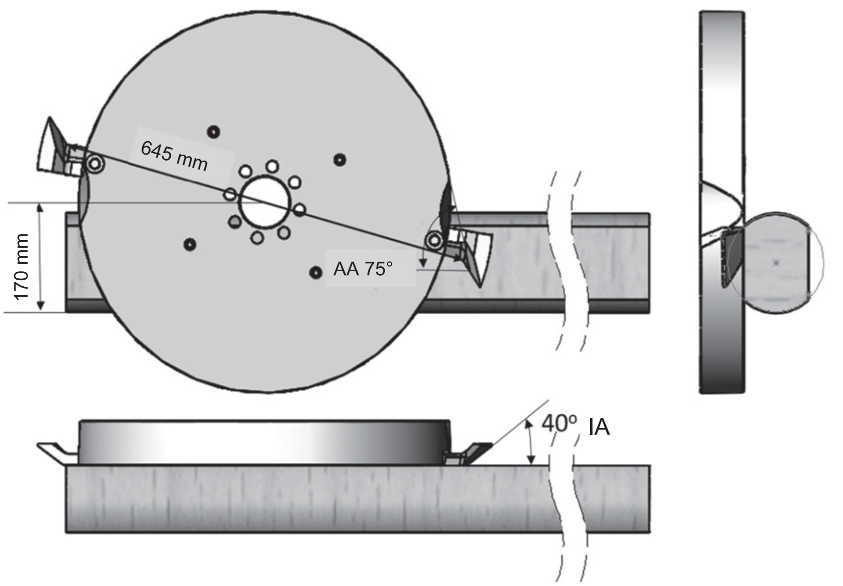

Figure 1. CAD view of the cutterhead and knife assembly used for the tests including log positioning, attack angle (AA) values, and inclination angle (IA).

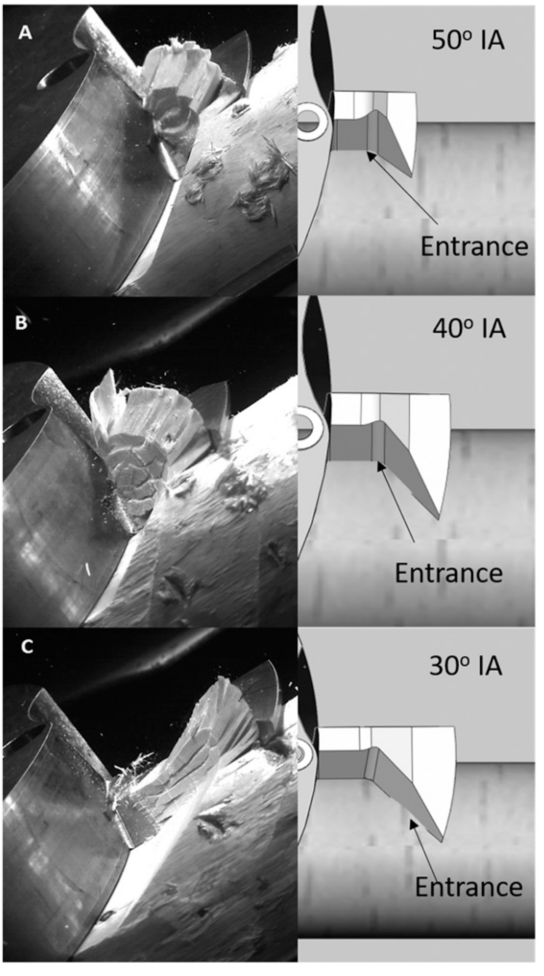

Figure 2. Left: Chip formation at the beginning of cut for a chipping edge IA of 50° (a), 40° (b), and 30° (c). Right: Entrance position of the cutting edge into the log surface.

taper and cutting height on wood fragmentation. Five clamps in the carriage held the log firmly in place to minimize vibration during the log fragmentation. The linear cutting speed was set at 23.6 m/s and calculated at the junction point between the chipping and canting edges of the knife. Rotation and feed speeds were calculated to obtain a nominal chip length of 23 mm. The cutting parameters for all studied conditions are shown in Table 2.

The study was carried out in two steps to simulate seasonal temperature differences during log transformation (frozen and unfrozen wood conditions). The same log was machined on one side under frozen condition and on the opposite side in an unfrozen one. The temperature of the log was measured at the two ends of the log at a depth of 25 mm with a digital thermometer to the nearest 0.1°C. The log was always fed with the small end first, and next, it was machined flat on one side under the frozen condition (−10°C). Logs that were transformed under frozen condition on one working day were left overnight in an indoor laboratory and were processed the next day at an average temperature of 9.8°C (unfrozen side). Cants were then wrapped with a plastic film and stored in a −18°C freezer. As soon as each log was transformed, all chips produced were collected in plastic bags and stored for subsequent analysis.

High-Speed Photography

High-speed photography was used to evaluate the effect of oblique cutting on the chip formation mechanisms. A MotionPro Y4-S3 high-speed camera (IDT, Tallahassee, FL) equipped with a 35-mm/f 1.4 lens (Kowa, Nagoya, Japan), installed below the cutterhead, was used. The field of view was approximately 35 × 35 cm. The view was focused on the chipping edge rake face at a midposition between the point of entry and the point of exit of the knife into the wood. Videos were taken with an acquisition frequency of 2500 Hz and an exposure time of 22 μs by means of Motion Studio software (IDT). The images were acquired at maximum resolution (1024 × 1024 pixels) with a pixel depth of 10 bit (monochrome). The cutting action of knives was recorded during fragmentation of one log per treatment under frozen and unfrozen conditions.

Knot Characterization

Knots were assessed on the cant surfaces obtained after log fragmentation. Images were obtained from each surface using a portable scanner GoScan 50 (Creaform, Lévis, Canada). The scanner is based on triangulation of fascicles of white light to capture the color and form of the

Table 2. Cutting parameters of the chipper-canter during fragmentation.

Chipping edge inclination angle (°)	Cutting diameter (mm)	Cutting speed (m/s)	Rotation speed (rpm)	Feed speed (m/min)	Nominal chip length (mm)	Nominal cutting width (mm)	Mean attack angle (°)
30	660	23.6	685	31.8	23	25.4	75
40	645		700	32.4			
50	645		700	32.4			

surface. Knot information was then retrieved using an image segmentation algorithm developed in Matlab. The algorithm was based on an RGB (red, green, blue) thresh holding and knot shape recognition. Knots with diameters less than 10 mm were disregarded in this algorithm. The elliptical form of the knot (maximum and minimum diameters) was taken into account. Knot parameters obtained with the algorithm included knot mean diameter, total knot number on the cant surface (every knot of at least 10 mm of diameter), total knot area (TKA) (sum of the area of each knot on the cant surface), knot ratio (TKA/cant total area), and knot eccentricity (ratio between maximum and minimum knot diameter).

Chip Screening

Chips were air-dried indoors for 2 wk to facilitate their separation. An average of 2.2 kg from each plastic bag was obtained using a Domtar (Montreal, Canada) chip separator. The chips were then screened using a Domtar chip classifier, which separates chips according to both thickness and length (Lapointe 1979). The Domtar classifier retained the following chip classes: fines (material that passed a 4.5-mm-diameter screen hole), fragile chips (chips less than 2 mm thickness, minus fines), accepts chips (chips from 2 to 4, 4 to 6, and 6 to 8 mm thickness), over-thick chips (chips greater than 8 mm thickness by 2 mm classes up to 18 mm), and oversize chips (the fraction retained by the 45-mm-diameter screen hole).

Chips were also screened with a LabTech (Tampa, FL) classifier (similar to the Williams classifier), which sorts chips by width and length and is more efficient in separating the smallest chip classes. The LabTech classifier retained the following chip classes: fines (material that passed a 4.8-mm-diameter screen hole), pin chips (material retained in a 4.8-mm-diameter screen hole), 9.5-mm chips (chips retained in a 9.5-mm-diameter screen hole), accepts chips (chips retained in screens of 15.9, 22.2, and 28.6 mm of hole diameter), and oversize chips (the fraction retained by the 45-mm-diameter screen hole). All chip classes were expressed as percent weight of the total chips.

The chip thickness distribution has a form similar to the normal curve, and it can be described by a weighted mean chip thickness (WCT) statistic. This factor takes into account all 2-mm-thick groups, and it is a useful tool to describe changes in the chip size distribution as a whole. WCT was calculated for each cutting condition by using the median value for each 2-mm thickness class (from 0 to 18 mm). The desired mean chip thickness was 5 mm, which is the median value of the accepts class, established between 2 and 8 mm. Size distribution of chips was also described by the kurtosis statistic, which is a measure of the concentration of a distribution around its mean.

Statistical Analysis

Data were analyzed using Statistical Analysis System (SAS) 9.3 software (SAS Institute Inc., Cary, NC). A multivariate analysis of variance (MANOVA) was performed to examine if log characteristics were comparable between the three groups of logs used. Data structure followed a split-plot design with IA as the main plot and wood TC in the subplot. Raw data were first evaluated with the Box–Cox method showing the more fitted transformation if required. A mixed model of analysis of covariance (ANCOVA) was used to evaluate the variation in WCT and kurtosis. A multivariate analysis of covariance

(MANCOVA) was performed using the Aitchison approach of compositional data (Aitchison 1982) for the Domtar and Williams chip class distributions. For both analyses, knot characteristics and physical properties were used as covariates, keeping only the ones that were significant for each model. Aitchison approach uses one of the chip classes as a reference and works with the proportion of each of the other classes as a function of the reference. Hence, compositional data analysis takes into account the existing dependence among the classes as they function as a whole, and therefore, when one class increases, another has to decrease to maintain the same whole. However, compositional data analysis does not allow comparison of the real values of each class because it works with proportions. Consequently, an ANCOVA of each class was performed individually. Finally, the normality was verified with Shapiro–Wilk's test, and the homogeneity of variance was verified with the graphical analysis of residuals.

RESULTS AND DISCUSSION

Mechanism of Chip Formation

Chip formation with a chipper-canter involved two simultaneous phases. In the first phase, the chipping edge compressed the wood perpendicularly. It penetrated the wood surface severing a slice by shearing perpendicular to the grain. The feed per knife determines the thickness of the slice, which, after fragmentation, will correspond to the length of chips. In the second phase, the slice of wood underwent stresses parallel to the grain because of the compression induced by the chipping edge rake face, which resulted in fragmentation. Chips could be produced by splitting or shear failure parallel to the grain (Fig 2).

Motion analysis performed with Solidworks 2017 simulations of the cutting tools revealed that the IA influenced the way the chipping edge entered the wood surface, which was different for the three tested knives. For 50° and 40° IAs of chipping edge, the first contact of the edge with the wood was at the joining area of the chipping and canting edges. Moreover, it appeared that for 50° IA, the entry point was further toward the canting edge, whereas for 40° IA, it was further toward the chipping edge (Fig 2(a) and (b)). In the case of 30° IA of the chipping edge, the entry point was almost at the middle of the chipping edge (Fig 2(c)). It can be observed that fragmentation was different in each case. Therefore, the knife cutting path and relative entry position of the chipping edge were very important in the chip formation mechanism. In this regard, our results showed that the chipping edge must be the first in contact with the wood surface to allow the resultant compressive force of the rake face to send the slice of wood to an optimal direction for chip detachment. As the cut continued, at 30° IA, solely the chipping edge was engaged into the wood until the middle of the cutting path. On the second half of the cut, the chipping edge was progressively exiting wood. At the end of the cut, chipping was finished by the joining zone of the two edges but further toward the canting edge. This resulted in visible reduction in the chip width from the beginning to the end of the cut (Fig 3(a)). In the cases of 40° and 50° IA of the chipping edge, the chip width also decreased along the cut, but it was less noticeable (Fig 3(b) and (c)). In addition, the assessment of chip formation based on wood TC confirmed previous results that reported a more regular chip fragmentation in frozen wood (Hernández and Boulanger 1997; Kuljich et al 2017). Consequently, the chips were thinner when fragmented under frozen condition than when fragmented under the unfrozen one (Fig 3).

High-speed images allowed observation of the influence of the IA angle on the slice projection during fragmentation. At 30° IA, the fragmented slice was sent away from the cutterhead, whereas at 50° IA, it was directed toward the cutterhead (Fig 3). Thus, the slice projection might have affected the chip size. The high-speed images also confirmed that the IA affected the form of the slice that was transformed into chips and, thus, the chip geometry as well. We can deduce from Figs 3 and 4 that the slice obtained with an IA of 30° was wider than those obtained with IAs of

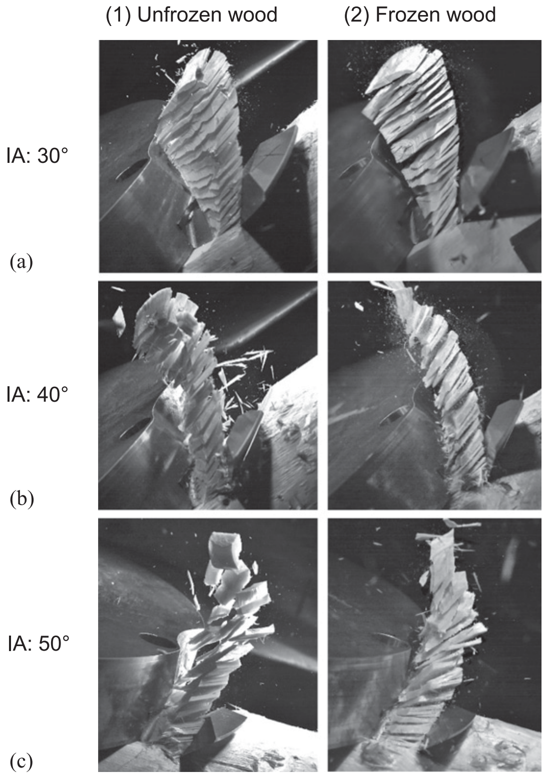

Figure 3. Chip formation with three chipping edge IA (a-c) and under unfrozen (1) and frozen (2) wood conditions.

40° and 50°. Therefore, chips obtained with 30° IA were wider, mostly in the first half of the cut, and as the slice projection did not produce any impact on cutterhead, the chips did not break into narrower fractions. In this case, the chip shape was an elongated parallelepiped. Fragmentation with 40° and 50° IAs resulted in chips shaped more as an upright parallelepiped (Fig 4). As the chip geometry changed with the IA, the anatomical arrangement within the chip was also different. IAs of 40° and 50° produced two considerable proportions of chips. One chip fraction had growth rings oriented parallel to chip thickness, which means that chips were detached by radial (RL plane) splitting (Fig 4(a)). Another chip fraction had growth rings oriented in a diagonal direction with respect to chip thickness. Accordingly, chip separation could be identified as oblique splitting (Fig 4(b)). In the case of 30° IA, an important fraction of chips, more precisely, wider chips formed in the first half of the cut, showed a combination of ruptures in a single chip. Thus, chip formation was a result of tangential, oblique, and radial splittings (Fig 4(c)). In all cases, there was a small fraction of chips produced exclusively by tangential splitting. This type of rupture was generally observed at the beginning and at the end of the cut (one or two chips) because of the orientation of the annual rings within the log. Kuljich et al (2017) previously reported this last chip formation mechanism.

Weighted Mean Chip Thickness, Kurtosis, and Chip Size Distributions

The first MANOVA (not shown) revealed that the three groups of logs used for the cutting conditions studied were equivalent in terms of log characteristics (Table 1). ANCOVAs showed that WCT and kurtosis were strongly

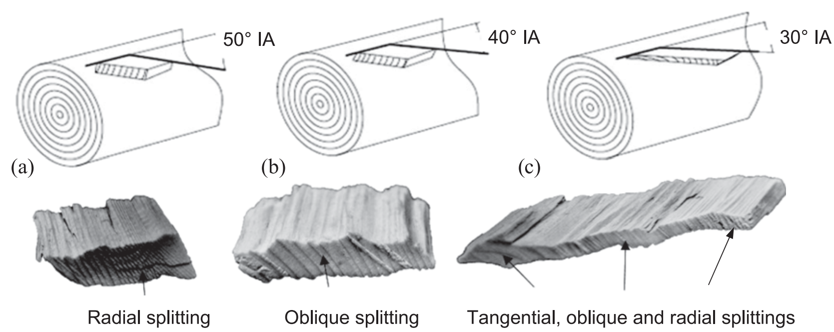

Figure 4. Chip geometry and growth ring orientation as a function of chipping edge IA.

affected by the chipping edge IA and the TC of wood (Table 3). WCT increased as IA increased, regardless of the wood TC (Table 4). A linear relationship between WCT and IA can be observed in frozen and unfrozen chippings (Fig 5). As explained earlier, for a small IA, the chip formation mechanism resulted in more elongated thinner chips. Conversely, a higher IA produced thicker chips. An increase in IA from 30° to 40° to 50° increased the mean chip thickness from 4.77 to 5.37 to 5.76 mm, respectively (Table 4). Moreover, WCT decreased when processing frozen wood. Frozen chips (at −10°C) were on average 0.55 mm thinner than unfrozen chips (Table 4). This is consistent with the results of previous studies, which established the importance of wood temperature on chip thickness (Hernández and Lessard 1997; Hernández and Boulanger 1997; Kuljich et al 2017). These results could help sawmill operators to choose the set of knives with the more appropriate IA that should be installed on the cutterhead, depending on the wood TC and desired mean chip thickness. The covariates that significantly affected WCT were, in order of importance (*F*-values), knot ratio and basic density (Table 3). The knot ratio had a positive effect over WCT; therefore, when the area of the knots covers a larger area of the cant face, the knot ratio will be higher and the mean chip thickness will be increased. Previous studies had already established the importance of knot characteristics on chip dimensions (Cáceres et al 2016, 2017). Basic density negatively affected chip thickness. This is in agreement with previous findings that established that denser black spruce wood produced thinner chips (Cáceres et al 2015, 2016).

Table 3. *F*-values obtained from the ANCOVAs for weighted mean chip thickness and kurtosis.

Source of variation	WCT	Kurtosis
Knot ratio	31.3**	ni
Basic density	9.8*	4.4*
IA	53.1**	51.0**
TC	128.5**	128.1**
IA*TC	0.4 ns	0.9 ns

IA, inclination angle; WCT, weighted mean chip thickness; TC, temperature condition; ns, not significant; ni, not included in the ANCOVA.
** Significant at the 0.01 probability level; * significant at the 0.05 probability level.

Table 4. Weighted mean chip thickness and kurtosis values by chipping edge IA and temperature condition (TC).

		WCT (mm)	Kurtosis
IA (°)	30	4.76 C[a]	2.7 A
	40	5.38 B	1.4 B
	50	5.74 A	0.7 C
TC	Frozen	5.02 B	0.9 B
	Unfrozen	5.57 A	2.3 A

WCT, weighted mean chip thickness; IA, chipping edge inclination angle; TC, temperature condition.
[a] Means within a column followed by the same letter are not significantly different at the 5% probability level for IA and TC separately.

Kurtosis increased as the IA decreased, regardless of the wood TC (Table 4). In all cases, the distributions had positive kurtosis. Distribution with positive kurtosis (leptokurtic) has heavier tails and higher peaks than the normal, whereas a distribution with negative kurtosis has lighter tails and is flatter than the normal distribution (DeCarlo 1997). This indicates that chip size distribution tends to be more homogenous and concentrated toward an acceptable class as the IA decreased, regardless of frozen or unfrozen wood. However, this behavior was more noticeable under unfrozen wood condition (Fig 6).

The MANCOVA for the Domtar chip class distribution showed that the IA and the wood condition (frozen or unfrozen wood), and their interaction significantly affected the chip size. In the case of Williams distribution, only the main effects were significant (Table 5). These analyses took into account the existing dependence among the chip classes and showed that these classes are affected differently by the IA and wood temperature. The compositional data analysis does not allow comparison of the real values of each class because it deals with proportions. Therefore, an ANCOVA for each chip class was performed separately for comparison purposes (Table 6). The knot ratio significantly affected the chip thickness distribution (Domtar) as well as the width/length chip class distribution (Williams). However, its relevance was more important in the Domtar distribution (Table 5). Moreover, Williams chip distribution was also affected by the TKA.

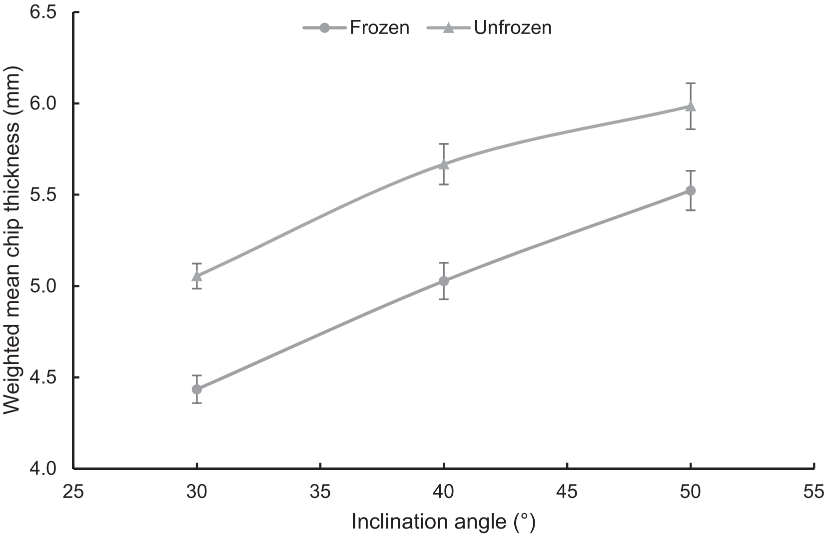

Figure 5. Chip mean thickness as a function of chipping knife IA and wood state (frozen/unfrozen).

Univariate ANCOVA was performed for each chip class of Domtar and Williams distributions. The significant covariates obtained in the MANCOVA were kept in each class analysis to observe their specific influence on each chip class. As shown in Table 6, for Domtar chip class distribution, both IA and TC significantly influenced all chip classes. The interaction IA × TC was poorly represented among Domtar chip classes (fragile chips and oversize classes). For Williams distribution, only the main effects, IA and TC, significantly affected chip classes, as previously shown by the MANCOVA. The covariates affected chip classes individually. For Domtar distribution, the knot ratio had a significant negative effect on fragile and accepts chip

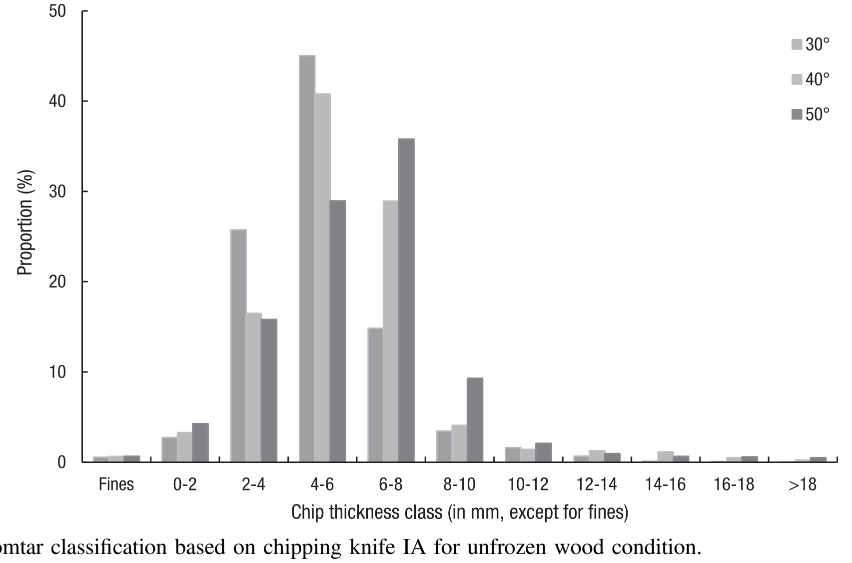

Figure 6. Domtar classification based on chipping knife IA for unfrozen wood condition.

Table 5. *F*-values obtained from compositional data MANCOVA of Domtar and Williams chip class distributions.

Source of variation	Domtar chip classes	Williams chip classes
Knot ratio	14.7**	2.9*
TKA	ni	3.0*
IA	32.0**	9.1**
TC	51.5**	30.1**
IA*TC	3.2**	0.7 ns

TKA, total knot area; IA, chipping edge inclination angle; ni, not included in the MANCOVA; ns, not significant.
** Significant at the 0.01 probability level; * significant at the 0.05 probability level.

classes, and a positive effect on overthick chip class. The three classes altogether represented 97% of the total volume of chips. The increase in the knot ratio would result in the increase in thicker chips and the diminution of thinner chips. The fines and oversize classes were not affected by the studied covariates. For Williams distribution, the knot ratio and TKA were the covariates affecting small chips and accepts chip classes, which represented 91% of the total chips. In this case, the presence of bigger knots would produce wider/longer chips. Accordingly, chip formation was primarily affected by the IA and TC, in addition to the effects associated with the raw material features, such as knot characteristics.

The mean and standard error of all chip classes (according to Domtar and Williams classifications) produced at each cutting condition are given in Table 7. For the Domtar chip classes, the increase in the IA from 30° to 50° produced a decrease in accepts and oversize chip classes, in contrast to the increase in fines, fragile, and overthick chip classes, for both frozen and unfrozen woods (Table 7). Chipping with an IA of 50° reduced accepts chips class, whereas the proportion of fines and fragile chip classes increased when compared with 40° and 30° IAs, which were comparable. Moreover, the IA decrease produced an important shift of the proportions between the thickness classes of 2-4 mm, 4-6 mm, and 6-8 mm, which represent altogether the accepts class. For unfrozen conditions, an IA of 50° had the greatest chip proportion (35.8%) in the class of 6-8 mm, which for the IAs of 40° and 30° was at 4-6 mm. However, the chip proportion was higher at 30° (45.0%) than 40° (40.8%). Accordingly, there was a more important chip concentration in the target chip class when using a smaller IA (30°). In addition, an IA of 30° increased the chip proportion of 2-4 mm (25.7%) compared with 40° (16.5%) and 50° (15.8%), which remained similar (Fig 6). In general, our results show a tendency to a chip concentration toward the smaller thickness classes when chipping at 30° of IA. Therefore, chipping with 30° IA improved the chip size distribution by the increase in accepts chips and the decrease in overthick chips. By contrast, it also increased the oversize class (chips larger than 45 mm diameter) because of the form of some chips (elongated wider chips), mainly for the unfrozen wood condition (Table 7). As explained before, the chip formation mechanism was different at 30° IA; thus, further studies on tool wear and energy consumption should be of interest. The chipping edge at 30° is longer, and its cutting action changed compared with 40° and 50°, which could have an effect on tool wear, cutting forces, and energy consumption. In addition, chipping frozen wood resulted in the increase in fines and fragile

Table 6. *F*-values obtained from the ANCOVAs for each Domtar and Williams chip class.

	Domtar chip classes					Williams chip classes				
Source of variation	Fines	Fragile chips	Accepts	Overthick	Oversize	Fines	Pin chips	Small chips	Accepts	Oversize
Knot ratio	3.2* ns	8.2**	18.0**	33.6**	0.6 ns	2.6 ns	3.7 ns	7.5**	6.0*	0.5 ns
TKA	ni	ni	ni	ni	ni	0.05 ns	1.1 ns	7.9**	5.7*	4.1 ns
IA	4.5*	5.1*	21.3**	47.2**	127.5**	11.7**	15.0**	9.7**	10.7**	7.6**
TC	90.4**	213.6**	0.01 ns	19.2**	74.2**	94.3**	61.0**	16.6**	35.2**	2.8 ns
IA*TC	1.8 ns	3.7*	3.2 ns	0.4 ns	6.2**	0.3 ns	1.1 ns	1.0 ns	0.1 ns	0.4 ns

TKA, total knot area; IA, chipping edge inclination angle; TC, temperature condition; ns, not significant; ni, not included in the ANCOVA.
** Significant at the 0.01 probability level; * significant at the 0.05 probability level.

Table 7. Domtar and Williams black spruce chip size distributions by chipping edge IA and TC.

		Domtar chip classes					Williams chip classes				
IA (°)	TC	Fines	Fragile	Accepts	Overthick	Oversize	Fines	Pin chips	Small chips	Accepts	Oversize
		(%)					(%)				
30	Frozen	1.0 (0.17)[a]	6.6 (0.8)	86.9 (0.8)	3.6 (0.3)	1.9 (0.3)	2.4 (0.4)	6.6 (0.7)	15.4 (0.9)	75 (2.0)	0.4 (0.2)
	Unfrozen	0.55 (0.02)	2.7 (0.2)	85.6 (0.9)	5.9 (0.5)	5.2 (0.7)	0.93 (0.06)	3.5 (0.3)	11.3 (0.6)	83.0 (0.8)	1.3 (0.4)
40	Frozen	1.1 (0.12)	6.4 (0.3)	86 (1.0)	6.6 (0.9)	0.18 (0.04)	3.1 (0.3)	8.8 (0.5)	19.0 (0.7)	69.1 (1.3)	0.02 (0.01)
	Unfrozen	0.63 (0.05)	3.3 (0.2)	86 (1.1)	8.6 (0.8)	1.2 (0.3)	1.4 (0.2)	5.4 (0.5)	15.2 (0.9)	77.5 (1.3)	0.6 (0.3)
50	Frozen	1.3 (0.12)	6.5 (0.5)	80 (1.2)	12 (1.3)	0.04 (0.05)	3.5 (0.3)	8.3 (0.5)	18.8 (0.8)	69.4 (1.5)	0.09 (0.05)
	Unfrozen	0.66 (0.06)	4.3 (0.4)	81 (1.2)	14 (1.3)	0.4 (0.1)	1.7 (0.2)	5.8 (0.5)	15.5 0.9	76.6 (1.5)	0.3 (0.1)

IA, chipping edge inclination angle; TC, temperature condition.
[a] Numbers in parentheses are the standard errors.

chip classes, which was compensated by the decreased overthick and oversize chip classes. Therefore, the accepts chip class was not affected by the TC (Table 7). The mean behavior of the chip classes is reflected on the WCT observations (Fig 5).

Williams chip class distribution also differs with a change in the IA. The knife with 30° IA produced higher proportion of accepts chips and lower proportions of fines, fragile, and small chips than those produced by the 40° and 50° IA knives, which were comparable (Table 7). Thus, the smaller chips generally increased, and the larger chips decreased as the IA increased. Furthermore, chipping frozen wood produced more fines, pin and small chips, and less accepts and oversize chips, for all IAs. Accepts chips decreased by 8% when chipping frozen wood at −10°C. Hernández and Boulanger (1997) and Kuljich et al (2017) reported a similar behavior when chipping frozen wood compared with unfrozen wood. Chipping with a small chipping IA produced the best results for both wood TCs by increasing the accepts class by 6%.

On the other hand, the choice of the chip dimension classification method in sawmills (Domtar and/or Williams) depends on the potential clients for the chips (pulp and paper industries). Based on the pulping process (chemical and/or mechanical), some industries could select the thickness distribution or the width/length distribution. The desirable chip class will vary accordingly. Our results showed that thickness accepts class was 13% and 5% higher than the width/length accepts class, for frozen and unfrozen wood, respectively (Table 7). However, it is a current practice in certain pulp industries to accept up to 20% of the small chip class without penalties to the sawmill. Overall, chip size distribution can be improved by changing the chipping edge IA to correspond to the specific chip dimension requirements of the pulp and paper industries.

CONCLUSIONS

Dimensions of black spruce chips produced by a chipper-canter were significantly affected by the chipping edge IA. Changes in IA caused different chip formation mechanisms, varying both the shape of the slice that was transformed into chips and the chip geometry, which resulted in different chip size distributions. A lower chipping edge inclined angle (30°) produced a chip distribution more concentrated around the desired mean chip thickness. Chips were thinner and had the form of elongated parallelepipeds. Accordingly, mean chip thickness and chip size increased as IA increased, for both frozen and unfrozen logs. The wood TC also significantly affected chip dimensions. Frozen logs (at $-10°C$) produced smaller and thinner chips than unfrozen logs. Variation in knot characteristics appeared to play an important role in the chip size distribution. Therefore, chipping knives could be optimized to increase the yield of pulp chips of desired dimensions. However, changes in IA also involve changes in the tool cutting action. Thus, differences in tool wear and machine power consumption should be expected and need to be further studied.

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REFERENCES

Aitchison J (1982) The statistical-analysis of compositional data. J Royal Stat Soc Ser B-Methodological 44(2): 139-177.

Bergman T (1985) Quality chips – essentials and improvements. Proceedings Tappi Pulping Conference, Hollywood, FL, 3-7 November. pp. 31-36.

Bjurulf A (2005) Effects on chip size distribution when an extra screen is added in SCAN-CM 40: 01. Tappi J 4(4): 28-31.

Broderick G, Cacchione E, Heroux Y (1998) The importance of distribution statistics in the characterization of chip quality. Tappi J 81(2):131-142.

Cáceres CB, Hernández RE, Koubaa A (2015) Effects of the cutting pattern and log provenance on size distribution of black spruce chips produced by a chipper-canter. Eur J Wood Wood Prod 73(3):357-368.

Cáceres CB, Hernández RE, Koubaa A (2016) Effects of log position in the stem and cutting width on size distribution of black spruce chips produced by a chipper-canter. Wood Fiber Sci 48(1):25-42.

Cáceres CB, Hernández RE, Koubaa A (2017) Effects of log position in the stem and commercial thinning on jack pine chip dimensions produced by a chipper-canter. Eur J Wood Wood Prod 75(3):359-373.

DeCarlo LT (1997) On the meaning and use of kurtosis. Psychol Methods 2(3):292-307.

Feiner JH, Gallay W (1962) The effect of chip thickness on sulphite pulp yield and quality. Pulp Pap Can 63(9): T435-T441.

Hatton JV, Keays JL (1973) Effect of chip geometry and moisture and moisture on yield and quality of kraft pulps from western hemlock and black spruce. Pulp Pap Can 74(1):79-87.

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

Hernández RE, Quirion B (1995) Effect of knife clamp, log diameter, and species on the size distribution of pulp chips produced by a chipper-canter. Forest Prod J 45(7/8):83-90.

Hernández RE, Boulanger J (1997) Effects of the rotation speed on the size distribution of black spruce pulp chips produced by a chipper-canter. Forest Prod J 47(4): 43-49.

Hernández RE, Lessard J (1997) Effects of the cutting width and cutting height on the size distribution of black spruce pulp chips produced by a chipper-canter. Forest Prod J 47(3):89-95.

Hoekstra PL, Veal MA, Lee PF, Sinkey JD (1983) The effects of chip size on mechanical pulp properties and energy consumption. Tappi J 66(9):119-122.

Kuljich S, Hernández RE, Blais C (2017) Effects of cutterhead diameter and log infeed position on size distribution of pulp chips produced by a chipper-canter. Eur J Wood Wood Prod 75(5):747-760.

Lapointe JA (1979) Domtar classifier accurately measures thickness and length of wood chips. Paper Trade J 8:28-30.

Lönnberg B, Robertsén L (1986) Significance of chip thickness in CRMP and RMP: A laboratory study with pine chips. Pap Puu Pap Tim 68(1):36-41.

McKenzie WM, Franz NC (1964) Basic aspects of inclined or oblique wood cutting. Forest Prod J 14(12):555-566.

MFFP (2017a) Ministry of Forests, Wildlife and Parks. Exportations de produits forestiers du Québec 1er trimestre 2018. https://mffp.gouv.qc.ca/wp-content/uploads/exportations.pdf (29 April 2019).

MFFP (2017b) Ministry of Forests, Wildlife and Parks. Ressources et industries forestières du Québec. Portrait Statistique. Édition 2017. https://mffp.gouv.qc.ca/wp-content/uploads/portrait-statistique-2017.pdf (29 April 2019).

NRCAN (2017) Natural resources Canada. The state of Canada's Forests. Annual report 2017. http://cfs.nrcan.gc.ca/pubwarehouse/pdfs/38871.pdf (29 April 2019).

Ozaki S, Kimura L (1989) The oblique cutting of wood V.–splits below the cutting plane and the ratio of shrinkage of the chips in a 90 °-90 ° cutting situation. Mokuzai Gakkaishi 35(10):896-905.

Smith DE, Javid S (1992) New approaches to fines and pins screening. Tappi J 75(1):93-97.

Tikka P, Tähkänen H, Kovasin K (1993) Chip thickness vs kraft pulping performance experiments by multiple hanging baskets in batch digesters. Tappi J 76(3):131-136.

Zhang SY, Koubaa A (2008) Softwoods of eastern Canada: Their silvics, characteristics, manufacturing and end-uses. Special Publication SP-526E. FPInnovations, Quebec, Canada. pp. 1-28.