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CHIP FORMATION STUDIED BY HIGH SPEED PHOTOGRAPHY DURING LOG FRAGMENTATION BY A CHIPPER-CANTER

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Abstract: Videos of wood chip formation were taken with a high speed camera during the fragmentation of black spruce logs with a chipper-canter. The effects of the cutterhead diameter and attack angle on the mechanism of chip formation and chip size distribution were evaluated. Two cutterhead diameters (661.5, and 448.7 mm) combined with three infeed positions were tested. The mean attack angle (or cutting orientation) of the chipping edge was calculated for each infeed position. The nominal cutting speed was fixed at 23.5 m/s. The rotation and feed speeds were adjusted to obtain a nominal chip length of 25.4 mm. The fragmentation of two logs (under frozen and unfrozen wood condition) per each infeed position was recorded. The images captured the fragmentation sequence along the cutting path of each knife. They showed that the chip thickness depend strongly on the attack angle of the chipping edge as it varies with the log infeed position and through the cutting path. The evaluation of the chip size distribution confirmed these observations. It showed that the increase of the attack angle decreased the chip thickness. Therefore, there was an increase of acceptable chips (2 to 8 mm thick), a decrease in overthick (more than 8 mm thick chips) but an increase on thin chips. Furthermore, frozen logs produced thinner chips than unfrozen logs (regardless the cutterhead diameter and/or the attack angle). The maximum amount of pulpable chips was produced during the fragmentation of unfrozen logs at the higher attack angle for both cutterhead diameters.

Keywords: Attack angle, chipper-canter, black spruce, pulp chips.

1. INTRODUCTION

In Quebec province, sawmills are the main provider of pulp chips, which are principally produced by chipper-canters. These machines have been designed to obtain, in a single operation, cants and chips from small and medium diameter logs with very low sawdust production. The cants are then processed to obtain studs and other members used for structural purposes. Although the production of chipper-canters is quite satisfactory, the dimensions of chips are not inherently uniform and are considered to be too thick. Thus, the reduction of their thickness has been the focus of some studies (Hernández and Quirion 1993, 1995; Hernández and Boulanger 1997; Hernández and Lessard 1997).

Chip quality is mainly measured according to the size (mean and distribution), density, moisture content, bark content, and wood species mix (Bergman 1985). The uniformity of these factors must be also considered. Indeed, raw material uniformity is the key factor of any pulping process (Pulkki, 1991). For the purpose of this study, chip quality refers exclusively to chip size and its distribution.

The homogeneity of the chip size allows for a more uniform and consistent pulping resulting in an improved finished product. Chip classification can improve chip homogeneity by ensuring the appropriate size and thickness of the pulpable fraction. However, some of the raw material such as fines and oversize chips has to be removed. The oversize material is generally re-chipped but the smaller fractions are recycled for less profitable uses, such as fuel. Consequently, narrow the size distribution of wood chips produced by chipper-canters is certainly desirable.

The size and size distribution of wood chips depend on the cutting parameters of the equipment used to produce them and on the characteristic of the raw material. For example, some researchers have found that the cutting speed (Hernández and Boulanger 1997), cutting width (and Lessard 1997) and the design of the knife clamp (Hernández and Quirion 1993, 1995) have an important influence on size distribution of pulp chips produced by a Swecan chipper-canter. Recently, Cáceres et al (2015) have also demonstrated that larger cutting widths produce thicker chips. They also found that the provenance of the logs affect the size distribution of the pulp chips. For a given cutting width, the black spruce logs coming from a slow growth rate site with high ring density attribute and corresponding high basic density and mechanical properties would provide thinner chips. The temperature of logs has also a significant influence on chip size distribution. Frozen wood produce thinner chips than unfrozen wood, which implies a higher proportion of smaller chips and a smaller amount of oversizes (Hernández and Quirion 1993, 1995; Hernández and Boulanger 1997; Hernández and Lessard 1997).

High speed cameras are increasingly being used to capture high speed events. Thus, any wood cutting process can be recorded at full or real speed. Thus, the purpose of this study was to analyze the chip formation mechanism of a chipper-canter via high speed photography, taking into account the effects of the cutterhead diameter and attack angle of the chipping edge. These videos were made to complement a research project where the goal was to increase the pulp chip quality produced by chipper-canters.

2. MATERIALS AND METHODS

2.1 Testing material

The tests were carried out with 96 stems of black spruce [*Picea mariana* (Mill) B.S.P.] coming from the region of Mauricie, in central Quebec. The stems were freshly debarked and crosscut into 2.80 m logs. Twelve logs were used to capture the high speed images and the remaining 84 logs (14 per cutting condition) were transformed in order to analyse the chip size distribution. The crosscutting position was chosen to have a small end diameter of 152.4 mm which yielded a mean taper of 6.6 mm/m. The logs were without crook or visible decay, had straight grain and concentric growth rings. Logs obtained were stored green at -30°C to keep the moisture content (MC) until the day of the log transformation. Two discs from each end of the log were first cut to prepare specimens for physical tests (thickness of sapwood, moisture content (MC) and mean specific gravity (SG) of both sapwood and heartwood at the time of log fragmentation.

2.2 Log transformation

Logs were processed with a prototype chipper-canter equipped with one cutterhead manufactured by DK-SPEC, which have the shape of shallow truncated cone (Fig 1). The cutterhead was fitted with eight or six (depending of their diameter) uniformly distributed knife holders, each of them with a bent knife and a knife clamp. The experiment consisted of processing black spruce logs of 2.40 m in length using two cutterheads having 661.5 and 448.7 mm of inner cutting diameter. For each cutterhead, logs were fed at three infeed positions. This position is defined by the vertical distance between the cutterhead axis center and the bedplate on which the log is supported (Fig 2A). The cutting orientations of the chipping edge rake face with respect to the grain (or attack angle) were then calculated for each log infeed position. The attack angle changes during the cutting path on the log (Fig 2B) and depend on the infeed position as shown in figure 2B. Thus, the mean attack angle is the average angle between the entrance and exit of the log (Table 1 and Fig 2B). In general, the chipping edge cuts across the end-grain (tendency to a 90°-90°cutting mode). The knife angle of the chipping edge was 33°, with a rake angle of 47.7° and a clearance angle of 9.3°. These angles were calculated for a cutting width (CW) of 25.4 mm in a plane which is parallel to the cutting direction. The knife clamp angle was 30° and the distance between the knife clamp edge and the knife edge was 22 mm. All knives were freshly ground before the experiment to minimize the effect of tool wear on chip size. The CW was held constant at 25.4 mm to reduce the effects of the log taper and cutting height on wood fragmentation. Five clamps in the carriage held the log in place to reduce vibration during the fragmentation. The linear cutting speed was set at 23.5 m/s and calculated at the junction point between the canting and chipping edges of the knife. The rotation speed and feed speed were adjusted to obtain a nominal chip length of 25.4 mm. The cutting parameters are shown in Table 1.

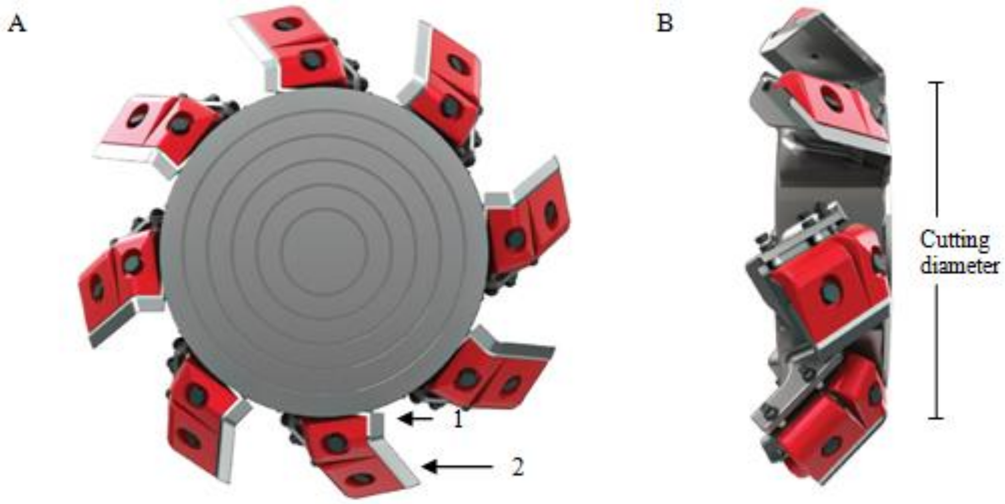

Figure 1: Front (A) and side (B) views of a conical-shaped cutterhead fitted with eight uniformly distributed knife holders, each with a bent knife and a knife clamp. The bent knife has two cutting edges that are joined at an angle; (A1) the shorter or canting edge smoothes the cant and (A2) the longer or chipping edge severs a slice to produce chips (Courtesy of Dk-Spec Inc.).

The study was done in two steps to simulate seasonal differences during log transformation (frozen and unfrozen wood conditions). Fourteen logs were processed for each cutting condition. The temperature of the log was measured at two uniformly distributed points at a depth of 25 mm with a digital thermometer to the nearest 0.1°C. The log was always fed with the small end first, and it was machined flat on one side at frozen wood conditions (-25°C). The other side was processed after the log was at room temperature (18°C, unfrozen side). As soon as the log was transformed, all chips produced were collected in plastic bags. The cants were wrapped in polyethylene and stored in a -5°C freezer along with the chips bags for further analysis.

2.3 High-speed photography

The mechanisms of chip formation were evaluated with a high speed camera (MotionPro Y4-S3) equipped with a 35mm/f1.4 Kowa lens, which was installed below the cutterhead. The field of view was approximately 35x35 cm and focused the rake face of the knives. The images were taken with an acquisition frequency of 3000 Hz and an exposure time of 1/49091s by means of Motion Studio software. Images were acquired at maximum resolution (1024x1024 pixels) with a pixel depth of 10 bit (monochrome).

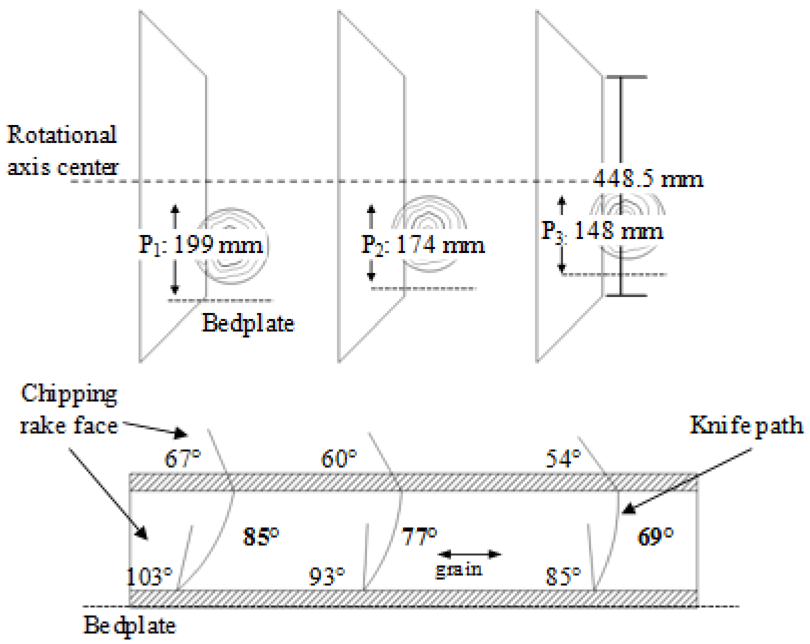

Figure 2: Diagram showing log feed entrance for the smaller cutterhead tested (ø 448.5 mm).

2.4 Chip classification

The chips were air dried indoors for 10 days to facilitate their separation. A sample of about 2 kg from each plastic bag was taken using a Domtar separator. The chip size distribution was then evaluated following the Domtar method, in which the chips were separated according to thickness (into 2mm classes) and length. The chip size distribution can be also described by means of the weighted average chip thickness [(Hernández and Boulanger (1997) and Hernández and Lessard (1997)]. The weighted mean chip thickness was calculated by using the median value for each 2 mm Domtar thickness classes. The target chip thickness was 5 mm, the median value for the pulpable fraction (2 to 8 mm thick chips).

2.5 Statistical analysis

The statistical analysis was performed by means of the SAS package version 9.3. A split-plot design was established for the experiment. The cutterhead diameter and angle of attack of the chipping edge (or log infeed position) were the sources of variation as main plot and the wood condition (frozen and unfrozen) was the source of variation as subplot. The attack angle was nested within the cutting diameter since it was specific to each cutterhead (Table 1). First, a multivariate analysis of variance (MANOVA) was performed to test whether the physical properties were equal among the 6 groups of logs used for testing the cutting conditions studied. The SG and MC of sapwood and hardwood, mean thickness of sapwood, and wood volume removed during each cut were the variables tested.

Then, a MANOVA was performed using the Aitchison approach of compositional data (Aitchison 1982) to analyze the size distribution of chips. This approach takes into account the existing dependence among the classes as they function as a whole. The interest of the Aitchison approach lies in the relative proportion of the measured components. Thus, the data is first transformed using a ratio based transformation called isometric logratio (ilr) [Egozcue et al 2003]

Table 1: Cutting parameters of the chipper-canter during the log transformation

Cutterhead diameter[a]	Number of knives	Infeed position[b]	Angle of attack[c]			Nominal linear cutting speed[e]	Rotation speed	Feed speed	Nominal chip length
			Entrance	Exit	Mean				
mm		mm		°		m/s	rpm	m/min	mm
448.7	6	199	67	103	85	23.5	1000	152	25.4
		174	60	93	77				
		148	54	85	69				
661.5	8	280	76	101	88		679	138	
		232	67	89	78				
		178	57	78	68				

[a]Distance between the junction point between the canting and chipping edges of two opposite knives; [b]vertical distance between the center of the rotational axis of the cutterhead and the bedplate on which the log is supported; [c]see Fig 2; [d]calculated at the junction point of canting and chipping edges of the knife.

The advantage of the ilr transformation is an especial device of balances or linearly independent ratios among components called sequential binary partition (SBP). A balance between groups of parts is a measure of the relative importance of one group against the other. A positive balance means that the group of parts in the numerator has more weight in the composition than the group in the denominator (and conversely for negative balances) [Pawlowsky-Glahn et al. 2007]. Since Domtar classifier retained 4 chip categories 3 balances were specified. Finally, univariate ANOVAs were used to evaluate each balance and the variation of the weighted mean chip thickness. Moreover, the mean thickness of sapwood was added as covariate as it was significant to the model. Means were compared with the least squares means statement at a 95% confidence level. The normality of the data was verified using Shapiro-Wilk test.

3. RESULTS AND DISCUSSION

3.1 Mechanisms of chip formation

The process of chip formation with a conical chipper-canter starts with the simultaneous action of both edges of the cutting knife, the chipping and canting edges. As figure 3 shows, the chipping edge severs a slice of wood to produce the chips and the canting edge smoothes the surface of the cant. The feed per knife determines the thickness of the slice and consequently, the chip length.

The chipping edge compresses the wood perpendicularly in order to sever the slice by shearing perpendicular to the grain or near to it. The slice of wood undergoes stresses parallel to the grain, which should start the slice fragmentation. The slice is then directed to the knife clamp placed at some distance of the knife edge. The change in the trajectory angle of the slice, caused by the knife clamp, produces other stresses that contribute to the fragmentation. The chips are mainly produced by splitting or shear failure parallel to the grain. The knife clamp angle and the distance between the knife edge and the knife clamp edge affect the development of these stresses and, consequently, the chip size (Hernández and Quirion 1993). The cutting speed, which regulates the required time to cover the distance knife clamp/knife edge as well as the impact force, also influences the chip size (Hernández and Boulanger 1997).

This study showed that the type of wood failure during fragmentation also depended on the orientation of the chipping edge with respect to the grain (or attack angle). This angle varies with the log infeed position and through the cutting path. Figure 3 shows the fragmentation process when using a 448.7 mm cutterhead combined with three infeed position (or attack angles). Figure 3A, 3B, and 3C show the chip formation when using an attack angle of 69°, 77° and 85°, respectively. These figures demonstrate that the chip thickness was reduced as the attack angle increases regardless of the wood temperature condition (frozen and unfrozen wood).

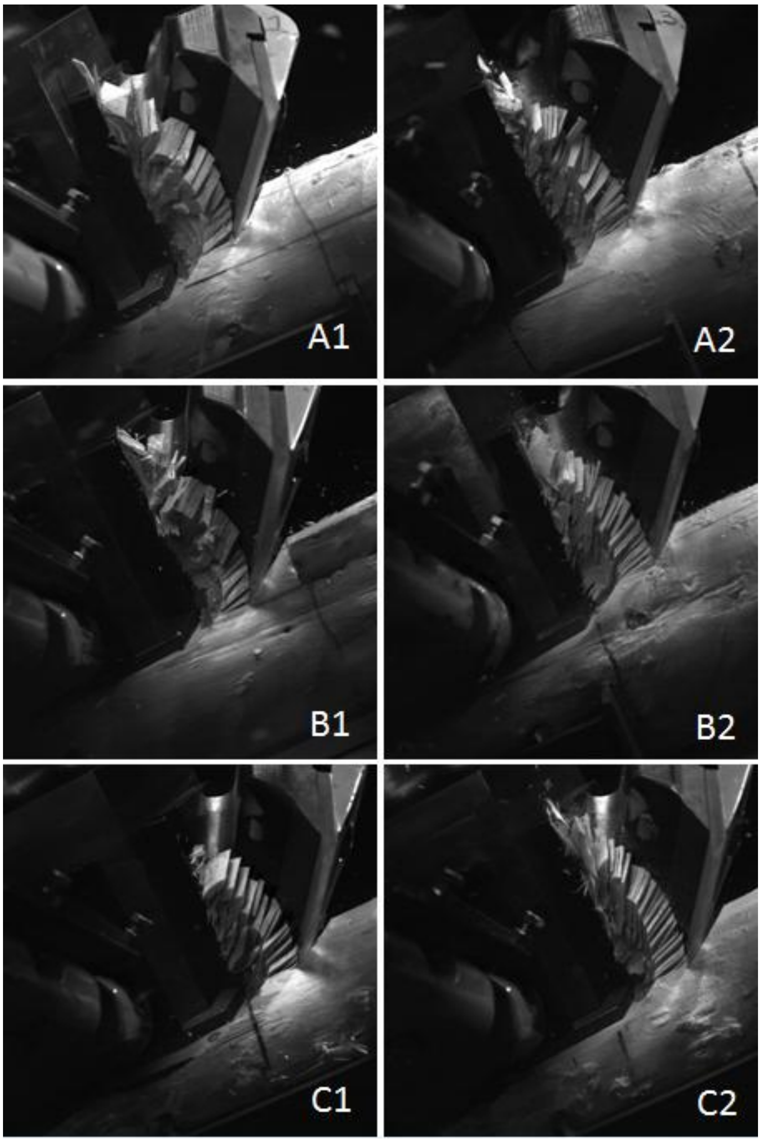

Figure 3. Log fragmentation using a 448.7 mm cutterhead diameter. A1) Attack angle: 69° (infeed position: 148 mm), unfrozen wood condition; B1) Attack angle: 77° (infeed position: 174 mm), unfrozen wood condition; C1) Attack angle:85° (infeed position: 199 mm), unfrozen wood condition; A2) Attack angle: 69° (infeed position: 148 mm), frozen wood condition; B2) Attack angle: 77° (infeed position: 174 mm), frozen wood condition and C2) Attack angle:85° (infeed position: 199 mm), frozen wood condition

The temperature condition had also an important effect on the size of chips. The columns 1 and 2 in figure 3 show the chip formation under unfrozen and frozen conditions, respectively. Unfrozen logs produced thicker chips compared to frozen logs. The differences in chip size are more evident when using an attack angle of 85° (Fig 3C) or even 77° (Fig 3B) compared to an attack angle of 69° (Fig 3A). The mechanical properties involved in wood fragmentation are affected by the wood temperature. The knife penetration in wood would be lower and thinner chips should be formed as the splitting and shear strength increase because of the decrease in temperature - from 0 to -30°C (Hernández et al 2014). The decrease in chip thickness can also be explained by the fact that the wood becomes more brittle under freezing conditions (Lunstrum 1985).

Figure 4. Fragmentation of an unfrozen log using a 448.7 mm cutterhead diameter combined with an attack angle of 85° (infeed position: 199 mm). The black arrow shows a chip thickness that was defined by tangential ruptures and the white arrow shows a chip thickness that was defined by radial ruptures.

The ANOVA (not shown) for the chip mean thickness confirmed these observations. This parameter was statistically affected by the attack angle of the chipping edge. Thus, when using a cutterhead diameter of 448.7 mm, the increase of the attack angle from 69 to 85° produced a decrease from 5.84 to 4.77 mm of chip thickness. Similarly, for the bigger cutterhead (661.5 mm) the increase of the attack angle from 68 to 88° produced a decrease from 5.77 to 4.91 mm of the mean chip thickness. Furthermore, frozen logs produced thinner chips than unfrozen logs regardless the cutterhead diameter and/or the attack angle. Hence, unfrozen chips were in average 1.13 mm thicker than frozen chips for a same chip length. The mean chip thickness also showed a negative relationship with the mean thickness of sapwood. Thus, as thickness of sapwood increased, mean chip thickness decreased. The mean thickness of sapwood was 15 mm with a MC of 125%. Similar results were obtained by Hernández and Quirion (1993), Hernández and Boulanger (1997) and Hernández and Lessard (1997).

The attack angle of the chipping edge varies with the log infeed position. Considering a mean angle of attack, as the distance from the bedplate to cutterhead rotation center increases, the attack angle also increases (Fig 2). Equally, as the chipping edge advances through the cutting path the attack angle increases, being higher at the exit point of log (Fig 2). When processing with the bigger attack angles the chip fragmentation occurred more by splitting parallel to the grain (Fig 3C). Furthermore, as the log infeed position approaches the cutterhead rotation axis, the attack angle decreases, producing thicker chips by longitudinal shear failure because of a higher parallel to the grain compression component (Fig 3A). The type of wood failure will also affect the energy requirements of the chipper- canter, being higher when the fragmentation takes place by shear parallel to the grain compared to parallel splitting (Kuljich et al 2015).

The high speed images also show that the thickness of chips is determined by radial, tangential, and in a lesser degree, by oblique ruptures. Figure 4 shows that thickness of the first chips was defined by tangential rupture. The thickness of the followed chips was determined by radial rupture. Thus, at the beginning of the cut chip thickness is determined by tangential ruptures and as the chipping edge advances through the cutting path, the thickness is more defined by radial ruptures. It is known that the majority of wood species will split easily following the rays rather than the annual growth rings.

3.2 Size distribution of chips

The first MANOVA (not shown) revealed that the six groups of logs used for the cutting conditions studied were equivalent in terms of their physical properties. Thus, mean values of SG and MC of sapwood and hardwood, thickness of sapwood, and wood volume transformed into chips during each cut were similar for all groups of logs. The mean SG was 0.445 for sapwood and 0.438 for heartwood; the difference was not statistically significant. However, the MCs of sapwood (125%) and heartwood (38%) were statistically different. The thickness of sapwood and wood volume removed during each cut were in average 15 mm and 0.0048 m^3, respectively.

The multivariate analysis of variance of chip size distribution showed statistically significant effects of the attack angle, cutterhead diameter, and wood condition (unfrozen or frozen wood) [not shown]. This analysis also showed a significant effect of the mean thickness of sapwood on the size distribution of chips. The mean and standard error of all chip classes produced at each cutting condition are given in Table 2. Chip classes are expressed as percent weight of the total chips.

The MANOVA (not shown) for Domtar balances showed statistically significant effects of the three sources of variation studied [the attack angle, cutterhead diameter and temperature condition (frozen and unfrozen wood). The compositional data analysis for Domtar size distribution defined three balances. The first one represented the balance between the pulpable chips versus the rejects fraction (fines, fragile, and oversize chips), the second one corresponded to the balance between the oversizes versus the small particles (fines and fragile chips), and the third one stood for the balance between fragile chips versus fines. The last balance does not have any practical importance.

Balance 1 was always positive which means that the acceptable fraction had more weight in the composition of this balance than the reject fraction (fines, thin chips, and oversize). Furthermore, the weight of the acceptable proportion increased on the composition of balance 1 as the attack angle increased (for both cutterhead diameters). Also, the weight of the acceptable proportion on balance 1 increased when transforming unfrozen wood compared to frozen wood. Balance 2 was always negative which means that the group formed by fines and fragile chips had more weight in the composition of this balance than the oversize proportion. Moreover, the weight of fines and fragile chips increased on balance 2 as the attack angle increased (for both cutterheads) and when transforming frozen wood. Conversely, the weight of the oversize fraction decreased on the composition of balance 2 as the angle of attack increased (for both cutterhead diameters) and when transforming frozen wood. In addition, balance 2 was affected by the mean thickness of sapwood. A positive relationship was found (not shown) which means that the weight of fines and fragile chips will increase with the increase of the mean thickness of sapwood.

Table 2: Domtar chip classes means obtained for each cutting condition

Cutterhead diameter (mm)	Infeed position	Mean attack angle °	Wood condition	Fines		Thin chips		Accepts		Oversize	
				……………….……………………………...%................................							
448.7	199	85	UFW[a]	1.8[c]	(0.1)[d]	4.7	(0.3)	84.9	(0.7)	8.6	(0.8)
			FW[b]	5.3	(0.4)	10.7	(0.5)	78.9	(0.9)	5.1	(0.5)
	174	77	UFW	1.8	(0.1)	4.2	(0.5)	80.1	(0.8)	13.9	(0.9)
			FW	5.5	(0.4)	9.6	(0.4)	78.2	(0.7)	6.7	(0.4)
	148	69	UFW	1.6	(0.1)	3.8	(0.3)	71.0	(1.2)	23.6	(1.4)
			FW	4.4	(0.4)	7.6	(0.5)	75.2	(0.9)	12.8	(1.0)
661.5	280	88	UFW	1.2	(0.1)	4.4	(0.3)	86.6	(0.6)	7.8	(0.7)
			FW	2.9	(0.1)	9.9	(0.4)	82.4	(0.7)	4.8	(0.5)
	229	78	UFW	1.3	(0.0)	4.0	(0.3)	79.4	(1.2)	15.3	(1.4)
			FW	3.4	(0.3)	9.9	(0.7)	77.7	(0.8)	9.0	(1.0)
	178	68	UFW	1.3	(0.0)	3.6	(0.3)	72.7	(1.9)	22.4	(2.1)
			FW	3.7	(0.4)	8.9	(0.7)	73.2	(1.5)	14.2	(1.8)

[a] Unfrozen wood; [b] frozen wood; [c] mean of 14 replicates; [d] standard error of mean in parentheses.

Gains in the acceptable proportion obtained by increasing the attack angle can be associated with the decrease of chip thickness. Higher attack angles resulted in a transfer from the oversize to the acceptable fraction because chip thickness decreased as the angle of attack increased. This happens when processing logs with both cutting diameters regardless the temperature condition (unfrozen or frozen logs). When transforming logs with the smaller cutterhead diameter (448.7 mm), as the angle of attack increased from 69 to 85°, the acceptable proportion increased from 73.1 to 81.9%. Accordingly, the oversize fraction decreased from 18.2 to 6.9%. Similarly, when transforming logs with the bigger cutterhead diameter, as the attack angle increased from 68 to 88°, the acceptable proportion increased from 73.0 to 84.5% and the oversize fraction decreased from 18.3 to 6.4%.

Moreover, the temperature condition (unfrozen or frozen wood) also affected the Domtar balances regardless the cutterhead diameter. In general, unfrozen wood produced slightly more acceptable chips compared to frozen wood (Table 2). The weight of fines and thin chips increased (balance 2) as the angle of attack increased for both cutterhead diameters. It also increased when transforming frozen wood. For example, when transforming logs with the smallest cutterhead, as the attack angle increased from 69 to 85°, the proportion of thin chips increased from 5.7 to 7.7%. Similarly, for the bigger cutterhead, as the attack angle increased from 68 to 88°, the proportion of thin chips increased from 6.3 to 7.2% (wood temperature pooled).

The increase in the attack angle produced more accepts at expense of the oversize proportion regardless the cutterhead diameter. The increase in the attack angle also increased the proportion of thin chips. The maximum amount of pulpable chips was obtained at the higher attack angle tested for both cutterheads (85 and 88° for 448.7 and 661.5mm of cutting diameter, respectively).

4. CONCLUSIONS

This study shows that the cutting diameter, angle of attack, and wood condition affect the mechanisms of chip formation and size distribution of black spruce pulp chips produced by a chipper-canter. The high speed images demonstrates that the chip thickness depend strongly on the angle of attack of the chipping edge as it varies with the log infeed position and through the cutting path. The statistical analyses also showed that the chip thickness decreased as the angle of attack was increased. The best results in terms of amount of acceptable chips produced were obtained with the highest angle of attack tested for both cutting diameters (85 and 88° for 448.7 and 661.5mm of cutting diameter, respectively). The temperature of logs (unfrozen and frozen wood) also played an important role in the mechanisms of chip formation and size distribution of black spruce pulp chips.

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