Effects of Wood Species on the Energy Requirements and Size Distribution of Strands Produced by a Strander-Canter

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The effects of wood species on the performance of the strander-canting process were studied. Logs of balsam fir (*Abies balsamea* (L.) Mill.), black spruce (*Picea mariana* (Mill.) B.S.P.), and jack pine (*Pinus banksiana* Lamb) were processed under two temperature conditions (-13.3 °C and 22.3 °C). The cutting and feed speeds, rake angle, cutting width, and strand thickness were kept constant. The strander-canting process was evaluated by the strand dimensions and yield, as well as by the energy requirements. The results showed that wood species significantly affected the proportions of strands and fines, maximum power, mean energy consumption, and specific cutting energy when processing the logs under frozen conditions. In unfrozen conditions, wood species only affected the strand width and the maximum power. Unfrozen logs produced higher proportions of strands and a lower volume of pin chips and fines than frozen logs. The maximum power, mean energy consumption, and specific cutting energy were, on average, 2 to 4 times higher for the processing frozen logs than for unfrozen logs.

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INTRODUCTION

Sawmills are one of the principal components in the supply chain of the forest products industry. They convert logs into semi-finished products and supply them to several secondary wood processing industries. Their byproducts, such as wood chips, sawdust, and bark, can be used to produce pulp and paper, bioenergy, bedding on the farm, or landscaping mulch. In addition, sawmills also play important economic and social roles. In the Quebec province, the sawmills and wood preservation industry contributed around CAN $687.9 million to the nominal gross domestic product of the province in 2019 (ISED 2022), employed more than 9500 people, and had an export product value of up to CAN $1.5 billion (MFFP 2021a).

Most of the softwood sawmills in Quebec process logs using chipper-canters. These machines are typically equipped with a truncated conical-shaped cutterhead fitted with several knives. Chipper-canters transform the logs into cants and wood chips in a single operation (Cáceres *et al.* 2016; Elloumi *et al.* 2022). The cants are then cut into lumber while the wood chips are sold to pulp and paper industries.

The decline in the pulp and paper industry in recent years has been the main challenge for Quebec sawmills. For the last five years, pulp production in the province decreased by 22%, while paper and cartons decreased by 16% (MFFP 2021a). This condition directly affects the sawmill revenue, since pulp and paper mills are the primary consumers of their chips. In 2020, the stock of unsold wood chips in Quebec's sawmill yards reached around 100000 oven-dry metric tons, an increase of almost 200% from the wood chips stock in 2016 (MFFP 2021b). Innovation efforts should continue to sustain the sawmills and adapt them to consumer demand. If the problem persists, the sawmills will have no choice but to limit the production of chips in the future, which will undoubtedly have an economic impact on the industry.

One possible solution to solving the oversupply of pulp chips is to convert the chips to make other types of wood products. The oriented strand board (OSB) is one of North America's most used engineered panels for structural construction (Hiziroglu 2017). Canada and the USA are the biggest producers of this panel, with around 85% of the world's production (Dumitrascu *et al.* 2020). Producing wood strands instead of pulp chips may provide an advantage not only for sawmills, but also for OSB mills as an optional source of raw material (Alipraja *et al.* 2022).

A new cutterhead was developed to produce strands as a byproduct of the primary breakdown process (Alipraja *et al.* 2022). This new cutterhead had good feasibility for strand production from logs in sawmills. However, the strand dimensions still needed to be optimized. Thus, studies must be conducted to optimize the machining parameters to obtain optimal strand sizes. Since strander-canting is a relatively new machining process, many aspects related to cutting parameters and their effects on strand quality, surface roughness, energy consumption, *etc.*, still need to be investigated. One of the factors that can affect the performance of this machining process is the behavior of different wood species. Several factors related to the wood species, *i.e.*, moisture content, sapwood thickness, and density, may affect the product quality of strander-canting.

The performance of the new cutterhead must also be evaluated by the size distribution of the strands produced. In addition, power consumption is also an important parameter to assess the efficiency of a strander-canting process. Reducing energy consumption will directly reduce production costs, thereby increasing profits (Kuljich *et al.* 2015).

In North America, energy costs range between 3% to 10% of the total manufacturing cost of the sawmill, depending on the type of machinery and the energy used (Nagubadi and Zhang 2006; Zhang and Nagubadi 2006; Gopalakrishnan *et al.* 2012). These energy sources generally come from electricity, natural gas, gasoline, or hog fuel (Meil *et al.* 2009; Loeffler *et al.* 2016). Electricity is the primary energy source in the green lumber sawmills, while natural gas and wood waste are the primary energy sources in the dry lumber sawmill (Maddula 2014). In a modern sawmill, electrical motors are used for most equipment, such as the debarker, head saws, trimmer, planer, and chipper. These motors consume approximately 90% of the electrical energy used in the sawmill. Thus, data on the specific energy consumption of motors by particular log size of a given wood species becomes essential.

Several material and machining operational factors can contribute to the energy consumption variability during the wood machining process. Wood characteristics such as density, dimension, moisture content, grain orientation, and the presence of knots or decays are known to significantly affect energy consumption (Gopalakrishnan *et al.* 2012; Di Fulvio *et al.* 2015; Kuljich *et al.* 2015; Pinkowski *et al.* 2016). Cutting power increases as the wood density increases (Oliveira Guedes *et al.* 2020). Power also increases with an increase in the spiral grain angle (Pinkowski *et al.* 2016). Furthermore, different machining parameters, *i.e.*, cutterhead diameter, cutting speed, feed speed, *etc.*, can also affect energy or power consumption (Kuljich *et al.* 2015; Kubš *et al.* 2016). In temperate regions, wood temperature becomes essential since it affects wood's mechanical properties (Hernández *et al.* 2014). Processing frozen wood generally requires more energy than unfrozen wood due to the presence of ice inside the wood (Orlowski *et al.* 2009; Kuljich *et al.* 2015; Pecenka *et al.* 2020).

This study investigated the effects of wood species on the quality of strands and the electrical performance of the strander-canting process. The proportion of strands, fines, pin chips, as well as the distribution of the width of strands were measured to assess the quality of the strand. The electrical performance was evaluated by the maximum power, energy consumption, and specific cutting energy.

EXPERIMENTAL

Materials

Logs of three important wood species growing in Eastern Canada, balsam fir (*Abies balsamea* (L.) Mill.), black spruce (*Picea mariana* (Mill.) B.S.P.), and jack pine (*Pinus banksiana* Lamb), were used in this study. These species are typical trees from the boreal forest and are widely used as raw materials for pulp and industrial lumber. Fifteen logs per species were carefully selected with straight shapes and no visible defects. The logs were hand debarked and crosscut into about 2.4 m long pieces. All knots larger than 10 mm in diameter were removed by hand drilling to minimize knife wear or damage to the knife during the tests.

Two opposite sides of each log were selected considering their straightness. The first side was cut under frozen conditions, while the other was cut under unfrozen conditions. The length and diameter of the logs were measured to obtain the cutting volume. The logs were then wrapped with a plastic film and stored in a freezer at -19 °C to limit moisture content (MC) loss until tests were performed.

Methods

Specific gravity, MC, and sapwood thickness measurements

A 25 mm-thick disk was cut from each end of the logs to measure their physical properties. Sapwood thickness (ST) was measured at three points, following the radial direction for each cutting width side of the log (Fig. 1). Two samples of 25 mm (axial direction) x 20 mm (tangential direction), representing sapwood and heartwood, were then cut from each cutting width side. The thickness of samples (radial direction) varied depending on the sapwood thickness of each side. MC was calculated based on the ratio between the water and oven-dry weights of the wood sample. Specific gravity (SG) was determined as the ratio between the oven-dry weight and green volume.

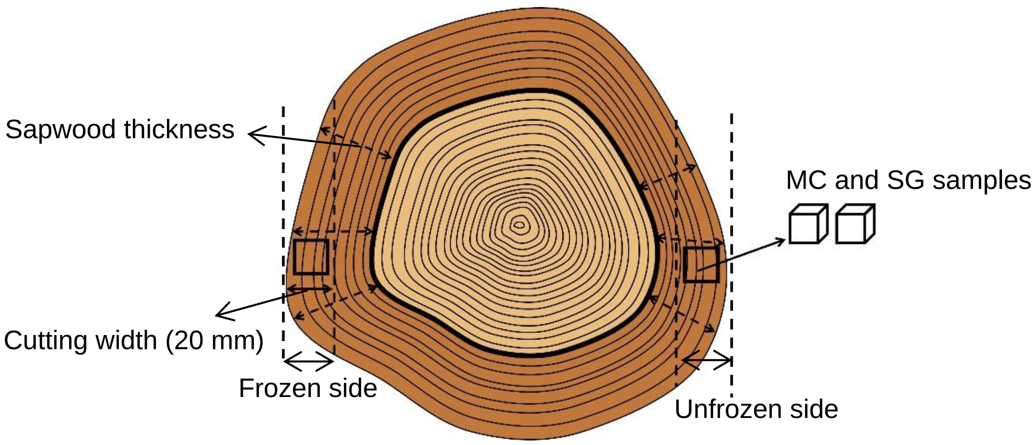

Fig. 1. Schema showing measured positions of the sapwood thickness and sampling locations for the MC and SG specimens

Log transformation

The cutting process was done using a prototype strander-canter equipped with an experimental cutterhead manufactured by DK-SPEC (Quebec, Canada). This cutterhead was designed to produce wood strands during the log transformation. The inner diameter of the cutterhead was 900 mm, and it was fitted with 33 sets of straight knives arranged in a spiral direction. These knives were radially offset by 0.9 mm to obtain strands with this thickness. Knives had 59° of rake angle, 30° of knife angle, and 1° of clearance angle. Counter-knives were mounted on the rake face (Fig. 2a) of knives with a distance between its edge and the cutting knife-edge of 6 mm. This study used two counter-knife angles (20° and 35°). A hydraulic feed carriage kept the log fixed during processing. The vertical position of the cutterhead was controlled to obtain a specific log infeed position. Log infeed position was defined as the vertical distance from the cutterhead axis to the bedplate. The log infeed position was determined so that the knife-edge position was parallel to the wood grain when the knife passed the middle of the log (Fig. 2b). The infeed position was determined by simulation using the Solidworks software (Waltham, MA, USA).

The cutting process was done in two steps to simulate seasonal differences in temperature during log transformation. One side was cut under frozen conditions with the counter-knife angle of 20°, while the other was cut 24 hours later (under unfrozen conditions) with the counter-knife angle of 35°. These different counter-knife angles were chosen from a previous study and aimed to obtain strips with widths close to those used in the OSB industry (Alipraja *et al*. 2022). The temperature of the frozen and unfrozen sides were -13.3 °C and 22.3 °C, with standard errors (SE) of 0.2 °C and 0.6 °C, respectively. This temperature was measured using a digital thermometer to the nearest 0.1 °C, at two previously drilled small holes located at 30 cm from each end of the log.

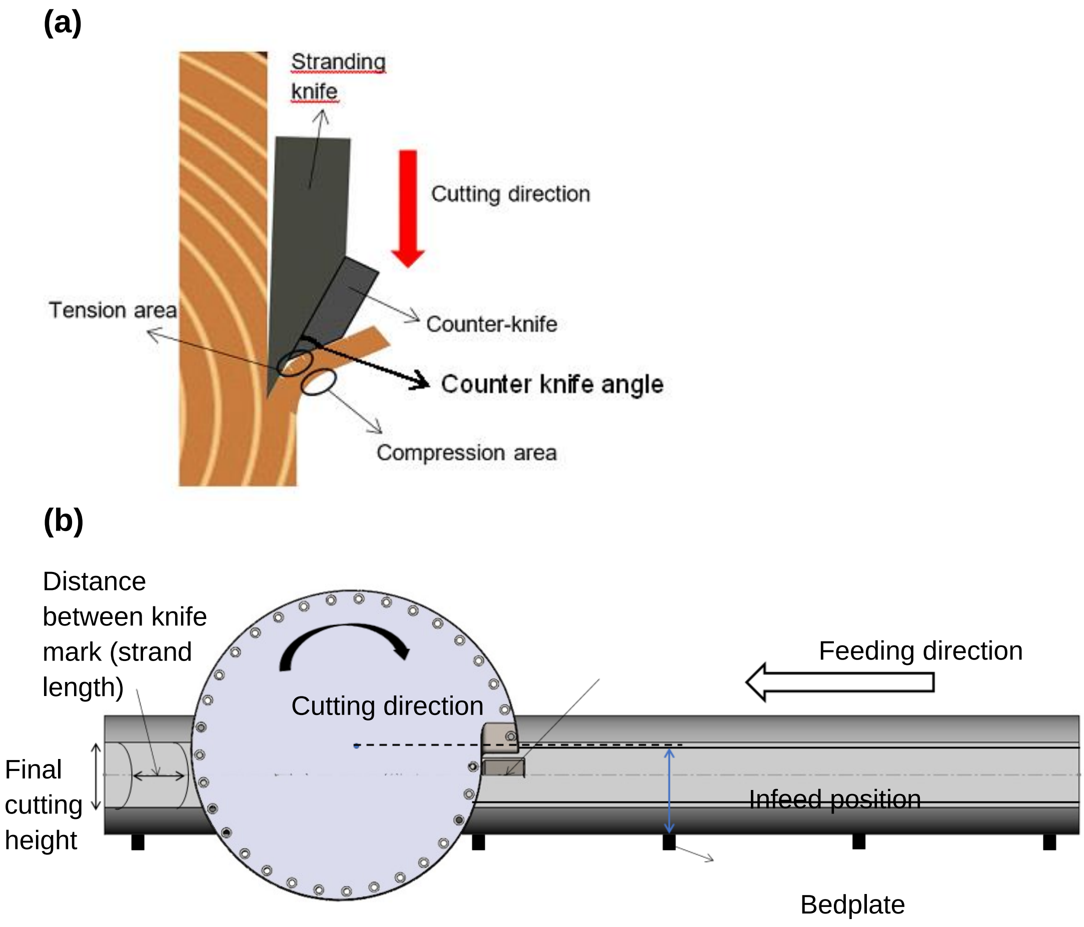

Fig. 2. (a) Illustration showing the knife and counter-knife actions and (b) Cutting schema on the strander-canter (Adapted from Alipraja *et al.* 2022)

The logs were cut with a mean cutting width of 20 mm, which was measured for every 200 mm log length. Logs were fed into the strander-canter by the small end first. The rotational speed of the cutterhead was 427 rpm and the feed speed was 43.6 m/min. This produced a linear cutting speed of 25 m/s and a nominal strand length of 102 mm. The cutting parameters of the stranding canting process are shown in Table 1. All particles produced were collected and air-dried before the subsequent analysis.

Table 1. Cutting Parameters of the Strander-Canter during Fragmentation

Rake and Knife Angles	59°, 30°
Clearance Angle	1°
Counter-knife Angle	20° (frozen side), 35° (unfrozen side)
Edge Distance[1]	6 mm
Cutting Speed	25 m/s
Average Cutting Width	20 mm
Nominal Strand Length and Thickness	102 mm, 0.9 mm
[1] distance between the knife edge and the counter-knife edge	

Measurement of strand dimensions

Wood particles were air-dried at room temperature until they reached the equilibrium moisture content (about 10% MC). The particles were then screened with a LabTech classifier (Tampa, FL, USA) for 15 min to separate the strands, pin chips, and fines. Strands were defined as the chips retained in 9.5, 15.9, 22.2, 28.6, 45 mm, and 70 mm hole diameter screens. Pin chips were the particles that passed a 9.5-mm-diameter screen hole and were retained in a 4.8-mm-diameter screen hole. Fines were the small particles that passed a 4.8-mm-diameter screen hole. The proportion or yield of each chip class was then measured.

One hundred strands, taken proportionally from each screen, were then chosen randomly. The strands were scanned by the Epson Expression 1640XL scanner (Epson, Los Alamitos, CA, USA) with a resolution of 400 dpi. The strand dimensions were measured by using Image-J 1.53e software. Strand width was the mean of five measurements perpendicular to the grain evenly distributed throughout the strand.

Power and energy consumption measurements

During the cutting process, the rotational speed and torque of the tool head motor were measured at regular intervals using an encoder installed in the strander-canter. The encoder was connected to a "DAQLog" data acquisition system. The scan rate was fixed at 2500 cycles/sec. The feed speed and voltage data were used to calculate the power and energy consumption when passing each log. The maximum power was measured on the middle six feet of the log (1828.8 mm).

Power consumptions were calculated by subtracting the unload power from the average power measured for each log (Eq. 1). Subsequently, the energy consumed was calculated by multiplying the power required by the cutting time for each log (Eq. 2). The specific cutting energy (SCE) was also estimated for each cutting condition. SCE is the ratio between energy consumption (Wh) and wood volume (m^3) transformed into chips. This volume of wood was estimated according to the method used by Kuljich *et al.* (2015).

$$PC = \mu PC - uP \quad (1)$$

$$EC = PC \ x \ 1000 \ x \ t \quad (2)$$

where *PC* is power consumption (kW), *µPC* is the mean power when cutting the 6 central feet of the log (kW), *uP* is the unload power (kW), *EC* is energy consumption (Wh), and *t* is the time needed to cut the 6 central feet of the log (hour).

Statistical analyses

Statistical analyses were performed using SAS version 9.4. Analyses of covariance (ANCOVA) and comparison tests were done to evaluate the effects of wood species on the strand width, the proportions of strands, fines, and pin chips, the maximum power, energy consumption, and specific cutting energy, for each log temperature separately. Cutting volume was used as a covariate. The Shapiro-Wilk and the kurtosis tests verified the normality of data, and the graphical analysis of residuals verified the homogeneity of variance.

RESULTS AND DISCUSSION

The physical properties of balsam fir, black spruce, and jack pine logs are shown in Table 2. In general, the means of MC and SG of all species used in this experiment were within the range of MC and SG reported in previous studies conducted in Eastern Canada (Hernández and Boulanger 1997; Hernández and Lessard 1997; Garrahan *et al.* 2008; Elloumi *et al.* 2021). Only the MC of jack pine sapwood (112%) was slightly lower than the MC reported in a previous study (124%) by Garrahan *et al.* (2008). As expected, sapwood had a higher moisture content than heartwood regardless of the wood species, while SGs for sapwood and heartwood were relatively similar. Jack pine had the greatest sapwood thickness (31.1 mm) compared to balsam fir (18.9 mm) and black spruce (23.2 mm). For black spruce, its sapwood thickness (23 mm) was relatively greater than that reported in a previous study (15.1 to 16.5 mm) (Elloumi *et al.* 2021, 2022). Different harvest seasons, geographic areas, and soil types may cause variations in the physical properties of wood (Zhang and Koubaa 2008).

Table 2. Characteristics of Logs of Three Wood Species Used in This Study

Wood Species	Average Diameter (mm)	Log Taper (mm/m)	Sapwood Thickness (mm)	Moisture Content (%)		Specific Gravity	
				Sapwood	Heartwood	Sapwood	Heartwood
Balsam fir	171(9)	10(51)	19(28)	164(28)	101(32)	0.374(11)	0.347(12)
Black spruce	197(12)	13(54)	23(26)	108(20)	45(16)	0.443(9)	0.416(8)
Jack pine	205(11)	10(57)	31(24)	112(19)	32(16)	0.458(9)	0.424(10)
Coefficient of variation (%) in parentheses							

The results showed that the performance of the strander-canter was different when processing unfrozen logs than frozen logs. Thus, for the three wood species tested, unfrozen logs required less cutting energy, and they produced higher volumes of strands and lower proportions of pin chips and fines than frozen logs. Besides the difference in wood temperature, the counter-knife angle used for the two machining conditions differed (35° for the unfrozen logs and 20° for the frozen logs). However, the contribution of counter-knife compared to that of the wood temperature should be minor since the actual cutting action is performed by the knives, which had the same cutting geometry for both wood temperature conditions. According to previous results (Alipraja *et al*. 2022), if the fragmentation had been carried out with the same counter-knife angle, the difference in behavior between the two wood temperatures would have been even greater.

Proportions of Strands, Pin Chips, and Fines

The recovery of strands for balsam fir, black spruce, and jack pine was approximately 91.0%, 90.3%, and 86.8% for frozen wood and increased to 94.5%, 94.7%, and 95.3% for unfrozen wood, respectively. The strand yield obtained in this experiment was relatively higher than in the previous strander-canter study, where the strand proportions ranged only from 40% to 71% for frozen wood and from 68% to 90% for unfrozen wood (Alipraja *et al.* 2022). This difference was mainly because the counter-knife angle used in this study (20° for frozen wood and 35° for unfrozen wood) was smaller than the previous one (60° to 90° for frozen wood and 75° to 105° for unfrozen wood). A smaller counter-knife angle produced less bending stress on the strand sheet as it passed over the counter-knife. As a result, the probability of wood fracturing during the formation of strands becomes lower, which contributed to an increase in the volume of strands.

For this reason, the resulting volume of small particles produced in this study was relatively low. For frozen logs, pin chips proportions ranged between 5% and 6.9%, while fines ranged between 3.8% and 6.2%. These proportions were even lower for unfrozen logs, ranging between 1.4% and 2% for pin chips and 2.7% and 3.6% for fines (Table 4). This result shows that the pin chips were more sensitive to changes in temperature than fines, where the proportion of pin chips was three times higher when cutting frozen wood instead of unfrozen wood.

Generally, at OSB mills, fines can account for 20% to 40% of the total mill furnish mass (Cafferata 2003), depending on the log size and conditions (Akrami *et al.* 2014). Other authors recommend no more than 10% of fines for OSB manufacturing (Barnes 2000). Thus, it is best to produce as few fines as possible in the stranding process, as this minimizes waste. The results of the present study indicate that, by applying adequate machining parameters, the strander-canter can produce significantly less volume of fines compared to the conventional stranding process, even when processing frozen logs (at -13°C).

Table 3. F-values Obtained from the ANCOVA for Proportions of Strands, Pin Chips, and Fines

Source of Variation	Strand	Pin Chips	Fines	Strand Width
Frozen Condition				
Cutting volume	9.3**	13.4***	8.3**	10.7**
Wood species	3.6*	1.4ns	6.1**	2.3ns
Unfrozen Condition				
Cutting volume	2.7 ns	3.5 ns	0.6 ns	15.5***
Wood species	0.1ns	2.6ns	0.6ns	13.6***
***statistically significant at 0.001 probability level; **statistically significant at 0.01 probability level; * statistically significant at 0.05 probability level; ns: not statistically significant.				

Table 4. Means of Strands, Pin Chips, Fines Proportions, and Strand Width for Frozen and Unfrozen Logs of the Three Wood Species Studied

Wood Temperature	Wood Species	Strand Proportion (%)	Pin Chips Proportion (%)	Fines Proportion (%)	Strand Width (mm)
Frozen wood	Balsam fir	91.0 (1.7) ^{A}	6.1 (1.3) ^{A}	3.8 (0.8)^{A}	25.5 (2.6)^{A}
	Black spruce	90.3 (1.6) ^{AB}	5.0 (0.9) ^{A}	4.7(0.7)^{AB}	30.4 (2.7)^{A}
	Jack pine	86.8 (1.2) ^{B}	6.9 (0.8) ^{A}	6.2 (0.5)^{B}	24.7 (1.4)^{A}
Unfrozen wood	Balsam fir	94.5 (1.3)^{a}	1.4 (0.4)^{a}	3.6 (0.7)^{a}	53.9 (1.6)^{a}
	Black spruce	94.7 (0.7)^{a}	2.0 (0.3)^{a}	3.3 (0.4)^{a}	69.6 (1.8)^{b}
	Jack pine	95.3 (0.5)^{a}	2.0 (0.4)^{a}	2.7 (0.2)^{a}	66.3 (2.0)^{b}
Means within a column followed by the same letter are not significantly different at the 5% probability level. Comparison tests were done separately between frozen and unfrozen conditions. Standard errors of means in parentheses					

The ANCOVA showed that wood species only significantly affected the proportions of strands and fines under the frozen condition (Table 3). Balsam fir had a higher volume of strands for frozen logs than jack pine, which simultaneously produced the smallest volume of fines (Table 4). It is well known that at subzero temperatures, the brittleness of wood increases due to the presence of ice (Elloumi *et al.* 2021), which eventually affects the stranding process (Alipraja *et al.* 2022). The mean width of the cut used for fragmentation was 20 mm. The mean thickness of the jack pine sapwood was 31.1 mm, indicating that the fragmented part of the log took place entirely in the sapwood (with a higher presence of ice compared to its heartwood). This was not the case for balsam fir, which presented a mean sapwood thickness of 18.9 mm with a coefficient of variation of 28%. Thus, the fragmented part of the balsam fir log contained both sapwood and heartwood, although the moisture content of the latter was also high (101%, Table 2). However, this higher MC of balsam fir did not necessarily cause a greater production of fines compared to jack pine. The higher specific gravity of the jack pine probably led to a more brittle behavior in the frozen state, tending to produce fewer strands and more fines. Frozen logs of black spruce produced similar proportions of strands, pin chips, and fines than jack pine, two species having similar specific gravities (Table 2).

In addition, the volume of the fragmented part of the log also significantly affected the proportions of strands, pin chips, and fines in the frozen wood conditions. The strand proportion increased and that of fines decreased as this volume increased (Fig. 3). The effect of the cutting volume per log was mainly related to the variation in diameter and taper of the logs. As mentioned before, the cutting width was kept constant at 20 mm along the length of the log. In contrast, the cutting height increased with increasing log diameter or taper (Table 2). Thus, larger sheets were produced, with more possibilities of generating strands than fines and pin chips (Alipraja *et al.* 2022). In the unfrozen state, the cutting volume did not affect the particle size distribution as the sheets were significantly larger, as discussed below.

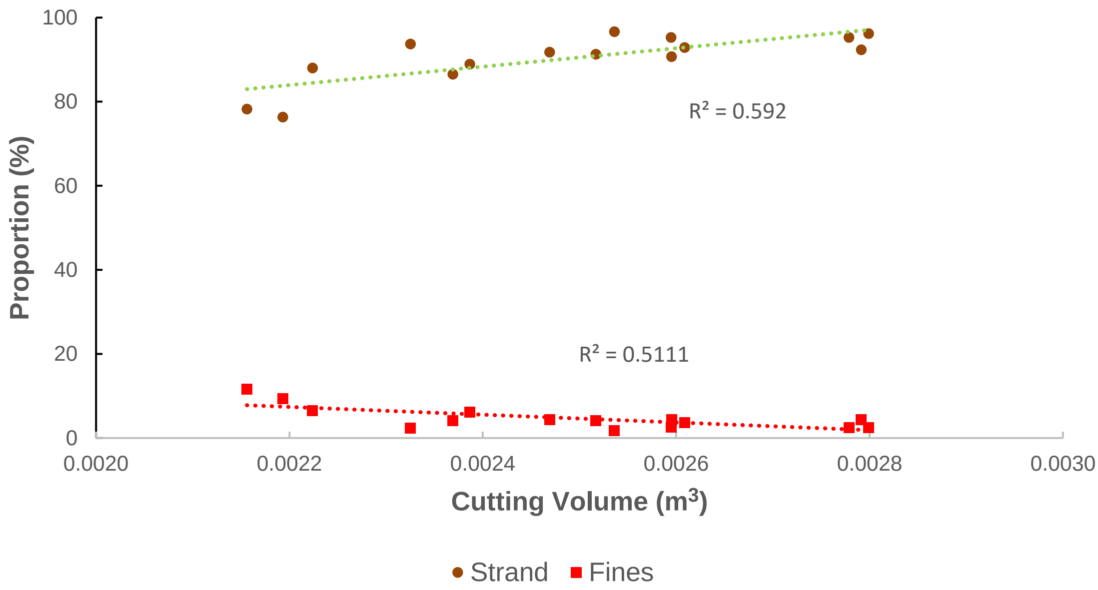

Fig. 3. Relationship between cutting volume and the proportions of strands and fines of black spruce under frozen conditions

Strand Width

Great differences in the width of strands were observed between frozen and unfrozen logs. Depending on the wood species, the mean width of strands ranged from 24.7 mm to 30.4 mm for frozen logs and increased significantly from 53.9 mm to 69.6 mm for unfrozen logs (Table 4). The changes in the width of strands between frozen and unfrozen logs were slightly higher for jack pine than for balsam fir and black spruce (Table 4). Only the strands produced from frozen balsam fir and jack pine logs were within the range of the commercial strand width, around 10 mm to 25 mm (Van *et al.* 2019; Lunguleasa *et al.* 2021). Unfrozen logs produced strands that were too wide. The counter-knife's angle greatly affects the width of the strands (Alipraja *et al*. 2022). The present results show that the angle used (35°) was not high enough to obtain narrow strands from unfrozen logs.

Contrary to the yield analysis, wood species only affected the strand width when transforming unfrozen logs (Table 3). Unfrozen balsam fir logs produced narrower strands than black spruce and jack pine logs, which were relatively similar. Differences in strand width between species under unfrozen conditions can be attributed to their differences in wood specific gravity. Balsam fir had a smaller SG compared to black spruce and jack pine woods (Table 2). A comparison of previous works also shows that balsam fir has wider and less dense earlywood bands than the other two wood species (Koga and Zhang 2004; Zhang and Koubaa 2008). Consequently, the splitting of balsam fir sheets provoked by the counter-knife occurred more regularly, generating narrow strands. This effect was not observed when cutting the logs in freezing conditions, which may be due to the higher presence of ice on balsam fir which can increase the strength of its wood, and equal that of the two other wood species.

Furthermore, the ANCOVA showed that the cutting volume influenced the strand width for both temperature conditions. As the cutting volume increased, the cutting height also increased, which resulted in larger strands.

Electrical Consumption

A decrease in log temperature from 22°C to -13°C increased the electrical requirements of the strander-canting process. Depending on the wood species, the maximum power was 2 to 3 times higher to transform frozen logs compared to unfrozen logs. Similarly, the mean energy consumptions required to process balsam fir, black spruce, and jack pine logs were 2.8, 2.7, and 3.9 times higher for frozen wood than unfrozen wood, respectively. SCE was also 3 to 4.2 times higher when processing frozen logs than unfrozen logs (Table 6). These results confirm previous studies reported on other wood machining processes, *i.e.*, sawing (Orlowski *et al.* 2009; Schmidt *et al.* 2018), chipping (Pecenka *et al.* 2020), and chipper-canting (Kuljich *et al.* 2015; Elloumi *et al.* 2022), where the electrical consumption increased as temperature decreased.

The ANCOVA showed that the wood species significantly affected the maximum power, mean energy consumption, and specific cutting energy required to process the frozen logs (Table 5). Jack pine logs needed more power and energy than balsam fir and black spruce logs (Table 6). For instance, the SCE to process jack pine frozen logs (7382 Wh/m^3) was 42% and 46% higher compared to black spruce (5208 Wh/m^3) and balsam fir logs (5042 Wh/m^3). The difference in power and energy requirements between species for frozen logs can be attributed to a combined effect of the physical properties of the three woods, mainly the moisture content, specific gravity, and strength properties. Under frozen conditions, the mechanical properties of wood increase (Hernández *et al.* 2014) due to the ice formation inside the wood (Jiang *et al.* 2014; Pecenka *et al.* 2020). Consequently, the knife needs more force to penetrate and sever the wood cells when cutting frozen wood.

The moisture content influences the electrical consumption during log transformation under freezing conditions. Higher moisture content provides greater wood reinforcement due to a higher proportion of ice (Hernández *et al.* 2014), thus increasing the cutting resistance (Orlowski *et al.* 2009), which leads to higher energy requirements. Because the sapwood zone generally has a higher moisture content than the heartwood, logs with thicker sapwood tend to require higher power consumption. The stiffening of wood cell wall substance (Koran 1979; Orlowski *et al.* 2009) can also play an important role in increasing the cutting resistance of wood under frozen conditions. According to Kubler *et al.* (1973), when green wood is exposed to sub-zero temperatures, some bound water in the wood cells diffuses into the lumen. This water will then be crystallized on the walls of the lumen, stiffening them, which will increase the cutting forces.

The wood species significantly affected the maximum power required to transform the unfrozen logs (Table 5). However, the differences between species were smaller, with low values of F and significance. The balsam fir would require less maximum power (Table 6), probably due to its lower wood density. Meanwhile, the mean energy required to cut unfrozen logs was not affected by the wood species. Moreover, when the energy is expressed in relation to the volume of the wood cut (SCE), the differences between species were also statistically not significant (Table 6). In fact, the mean volume of wood cut was 5.4% lower for balsam fir (0.002488 m^3) than for jack pine (0.002622 m^3). Thus, the SCEs required for unfrozen logs of the three wood species were statistically similar, although varying between 1652 and 1815 Wh/m^3 (Table 6).

Table 5. F-values Obtained from ANCOVA for Maximum Power, Energy Consumption, and Specific Cutting Energy

Source of Variation	F- values		
	Maximum Power	**Energy Consumption**	**Specific Cutting Energy**
Frozen Condition			
Cutting volume	11.1**	11.9**	n.i.
Wood species	12.8***	13.3***	4.8*
Unfrozen Condition			
Cutting volume	2.2ns	18.3***.	n.i.
Wood species	3.6*	2.8ns	2.2ns
*** statistically significant at 0.001 probability level; **statistically significant at 0.01 probability level; * statistically significant at 0.05 probability level; ns: not statistically significant; n.i.: not included			

Table 6. Mean Value of Maximum Power, Energy Consumption, and Specific Cutting Energy

Wood Temperature	Wood Species	Max. Power (kW)	Energy Consumption (Wh)	Specific Cutting Energy (Wh/m^3)
Frozen logs	Balsam fir	24.3 (2.5)^{A}	11.6 (1.1)^{A}	5042 (572)^{A}
	Black spruce	27.5 (2.0)^{A}	12.7 (0.9)^{A}	5208 (459)^{A}
	Jack pine	37.6 (2.6)^{B}	17.9 (1.3)^{B}	7382 (623)^{B}
Unfrozen logs	Balsam fir	11.1 (0.5)^{a}	4.1 (0.1)^{a}	1652 (38)^{a}
	Black spruce	13.5 (0.7)^{b}	4.7 (0.2)^{a}	1815 (50)^{a}
	Jack pine	12.4 (0.5)^{ab}	4.6 (0.1)^{a}	1742 (39)^{a}
Means within a column followed by the same letter are not significantly different at the 5% probability level for frozen and unfrozen logs. Standard errors of means in parentheses				

The SCEs obtained in this study were similar to those required for a chipper-canter when processing black spruce logs under unfrozen conditions (Kuljich *et al.* 2015; Elloumi *et al.* 2022). Conversely, the changes in log temperature below 0 °C had a greater impact when processing logs using a strander-canter. For the conventional chipper-canter, a decrease in log temperature from 20 to -20 °C increased the SCE between 23% and 30% (Kuljich *et al.* 2015; Elloumi *et al.* 2022). In contrast, the SCE for processing frozen wood (-13°C) with the strander-canter was 187% higher than for unfrozen wood (22°C). Compared to the conventional chipper-canting process (Kuljich *et al.* 2015; Elloumi *et al.* 2022), the cutting mode of the strander-canter presented in this work is very different.

Indeed, these two processes differ widely in the orientation of the knives with respect to the wood grain, the chip thickness, and the feed per knife, as well as in the number of knives involved in the cut. These differences between the two processes were more significant when cutting frozen wood.

The higher energy consumption for frozen logs wood can be an issue in primary manufacturing. In addition to increased energy costs, the cutting tool life could be shortened due to the higher cutting forces involved. As a result, the frequency of downtime for changing knives will increase, reducing sawmill productivity. Heating the logs before processing can be a solution but requires an additional investment for the sawmill. Thus, further research on machining parameters is needed to obtain the optimum SEC when transforming the logs under frozen conditions.

From a practical point of view, the results of this study showed no differences in strand size distribution and energy consumption during the processing of unfrozen logs of the three species studied. Relatively small differences, in particular between balsam fir and jack pine were observed within frozen logs. As a first approach, these three species can therefore be machined together. Secondly, a study aimed at reducing the impact of jack pine wood freezing on the performance of the process could be encouraged.

CONCLUSIONS

1. Wood species affected the proportions of strands and fines, maximum power, mean energy consumption, and specific cutting energy when transforming the logs under frozen conditions (-13 °C). Balsam fir produced a higher proportion of strands and a smaller volume of fines than jack pine, while black spruce and jack pine produced similar proportions of strands, pin chips, and fines. Moreover, frozen jack pine logs required more cutting energy than black spruce and balsam fir logs.
2. When cutting the logs under unfrozen conditions (22 °C), wood species significantly affected the width of the strands, where balsam fir generated narrower strands compared to black spruce and jack pine. Wood species also affected energy consumption, although its effect was smaller than that required for frozen logs.
3. The cutting volume significantly affected all the parameters evaluated (the proportions of strand, pin chips and fines; width of the strand, maximum power, and energy consumption) when transforming frozen logs. As the cutting volume increased, the strand yield and width increased while the pin chips and fines decreased. Meanwhile, under unfrozen conditions, the volume of the fragmented part of the log only affected the strand width formation.

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