

EFFECT OF TOOL TIP RADIUS ON RING DEBARKER PERFORMANCE OF FROZEN AND UNFROZEN BLACK SPRUCE LOGS

Claudia B. Cáceres

Former Research Associate
E-mail: claudia.caceres@mffp.gouv.qc.ca

*Roger E. Hernández**†

Professor
Département des Sciences du Bois et de la Forêt
Centre de Recherche sur les Matériaux Renouvelables
Université Laval
2425 Rue de la Terrasse
Quebec G1V 0A6, Canada
E-mail: roger.hernandez@sbf.ulaval.ca

Jedi Rosero-Alvarado

Postdoctoral Fellow
E-mail: jedi.rosero-alvarado@bidgroup.ca

Rentry Augusti Nurbaity

Research Associate
E-mail: reny.nurbaity@sbf.ulaval.ca

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Abstract. The effects of the tool tip radius on debarking quality of unfrozen and frozen black spruce logs were studied. The power, energy consumption, and torque on frozen conditions were also studied. A prototype one-arm ring debarker was used. The experiment consisted of debarking logs using three tool tip radii (40, 180, and 300 μm) for each temperature (-20°C and $+20^{\circ}\text{C}$). The rotational and feed speeds, tip overlap, and rake angle were kept constants. Debarking quality was evaluated by two criteria: the proportion of bark remaining on log surfaces and the amount of wood in bark residues (WIB). Log characteristics, used as covariates, ie dimensions, eccentricity, bark thickness, knot features, bark/wood shear strength (BWSS), basic densities and moisture contents of sapwood and bark were measured, as well as total removed material after debarking. The results showed that tool tip radius had a significant effect on debarking quality of frozen and unfrozen logs. The proportion of bark on log surfaces increased and the amount of WIB decreased as tip radius increased. At the same applied radial force, a wider tip radius showed a shallower tip penetration leaving bigger regions of bark on the log surfaces. In contrast, a narrower tip radius showed a deeper tip penetration resulting in important wood fiber tear-out. The bark thickness and inner bark MC also affected debarking quality. The mean power, mean torque, and energy consumption increased as the tip radius decreased. However, this effect will depend on the choice of the applied radial force during debarking. Motor performance was also affected by the total removed material, log diameter, and BWSS. Overall, the results highlight the importance of choosing an adequate combination of tool tip radius and applied radial force to obtain the most profitable debarking quality with an efficient energy consumption.

Keywords: Tool tip radius, log temperature, debarking quality, energy consumption, black spruce.

INTRODUCTION

Log debarking is one of the first steps in most of the primary wood manufacturing processes. Several techniques are used for the removal of bark from logs, such as ring, drum, and cradle debarking.

* Corresponding author

† SWST member

In Canada, sawmills producing softwood lumber products mostly use ring debarkers. This debarker is equipped with an array of swing arm knives, mounted on a rotating ring that scrapes down the bark off by a shearing action at the cambium layer as the logs are fed through the ring (Chahal and Ciolkosz 2019). The ring debarker is commonly chosen when superior fiber protection, very clean debarking, and a steady supply of logs into the mill are needed. The main advantages of ring debarkers respect to other techniques are the higher feed speed, reduced maintenance, improved bark removal, and enhanced processing of crooked wood (Bajpai 2016).

The efficiency of debarking is generally assessed by two quality indicators. The first one is the proportion of bark remaining on the log (BRL) surface. This parameter is closely related to the bark particles that will be contained in pulp chips. In Quebec, 71% of the wood raw material supply for the pulp and paper industry already comes in the form of wood chips from sawmills (MFFP—Ministère des Forêts, de la Faune et des Parcs 2018). Bark content in chips is a critical factor that negatively affects the pulping processes, by decreasing pulp brightness, strength, and yield (Erickson 1979). Therefore, an increase in bark content will gradually reduce the value of the chips. The pulp mill tolerances of bark content depend on various factors like the type of pulping process, equipment, and final product (Hartler and Stade 1979). Eastern Canadian pulp mills generally accept up to 1% of bark content, which can increase to 1.5% during winter when logs are frozen (Ding et al 2012). In addition, any BRL prevents an accurate log scanning, which is crucial for maximizing lumber value in sawmills (Bajpai 2016). The second quality indicator is the loss of wood fibers during debarking. In practice, bark removal always generates some wood losses from sapwood. This results in a decrease in log diameter, which will negatively affect chip and lumber recoveries.

The performance of a ring debarker is affected by several factors such as the log environmental and storage conditions, and debarking parameters (Ding et al 2012). Log dimensions, straightness, taper, eccentricity (Kharrat et al 2020a,b), surface

roughness (Berlyn 2000), the presence of cracks and knots (Hatton 1987; Kharrat et al 2020a,b), and bark thickness (Wilhelmsson et al 2002; Marshall et al 2006; Ding et al 2012) affect the performance of the ring debarker. The wood species, MC, harvesting season, and log freshness are also related to debarking quality (Baroth 2005) as they directly affect bark/wood shear strength (BWSS) (Fiscus et al 1983; Moore 1987; Belli 1996; Prislán et al 2013; Ugolino et al 2020). This property plays a major role on the efficiency of debarking (Chahal and Ciolkosz 2019; Kharrat et al 2020a,b). Thus, the amount of bark remaining on the surface of logs and the loss of wood fibers are usually higher in winter due to an important increase in BWSS occurring when the log temperature decreases under frozen conditions (Calvert and Garlicki 1974; Laganière 2003; Chow and Obermajer 2004; Laganière and Bédard 2009; Kharrat et al 2020a,b).

Among the parameters of the ring debarker, the feed speed, rotational speed, tool radial force, rake angle, tool tip path overlap, and tool tip radius are the most important affecting the debarking process. In wood machining operations, the shape and condition of the cutting edge is crucial (Denkena and Biermann 2014) as it affects the quality of the machined surface. The shape of the tool tip is usually described by the radius of the tool edge, which is formed by the junction between the rake and clearance faces (Zhao et al 2017). During ring debarking, the strain field in a log produced by the radial force applied is affected by the edge radius of the tips. This would affect the quality of debarking in terms of the two quality indicators cited earlier. Calvert and Garlicki (1972) recommended a tip edge radius between 254 and 1016 μm for debarking both white spruce and balsam fir logs. Laganière and Hernández (2005) used an intermediate tip edge radius of 600 μm for balsam fir. Kharrat et al (2020a) used a freshly sharpened tip edge radius of 78 μm for debarking black spruce. At a same level of radial force, a small edge radius should penetrate more into the bark, pass through the cambium and even remove fibers from sapwood. Conversely, a large edge radius is less powerful, which will prevent adequate penetration of

the tip into the bark, resulting in a greater proportion of BRL surface.

In addition, the applied radial force must be increased during winter given that the BWSS increases. This force can directly increase energy consumption. Knowledge of the effect of wood cutting parameters on energy consumption could increase energy efficiency, reduce operating costs, and increase profitability (Cristóvão et al 2013). Within this context, the aim of this study was to analyze the effects of tool tip radius on the debarking performance of unfrozen and frozen black spruce logs.

MATERIALS AND METHODS

Testing Material

Fifty black spruce (*Picea mariana* [Mill.] B.S.P.) trees were harvested during the winter season (January) from the Montmorency research forest, 72 km North from Quebec City. The stems were cross-cut into two or three logs of 2.4 m long. From these, the best logs were selected. Thus, 90 straight logs of 1.20 m long without any visible decay were obtained. They were separated in two

groups of 45 logs each and exposed to two temperature conditions, -20°C and 20°C , respectively. Each group was divided into three subgroups of 15 logs to be assigned to each debarking condition. Small and large end diameters were measured and taper, and log eccentricity were calculated on each log. The eccentricity, defined as the ratio between the smallest and biggest diameter of each end, was calculated as the average of both ends. Log characteristics are described in Table 1. Mean values of these characteristics were examined for each group to keep them as close as possible among groups.

Characterization of the Tool Tip Radius

Three tool tips manufactured by DK-SPEC Inc were used in this study. They had two opposite edges of 50 mm width and a tip edge angle of 32° . Both edges of each tool tip were sharpened until reaching 40, 180, and 300 μm of radius. The final step of this sharpening was carried out by manually honing the edges using an abrasive ceramic water stone (Lee Valley Inc.) with 8000 ($2\ \mu$) followed by 10,000 ($1.2\ \mu$) grit.

The uniformity of the radii obtained for the edges was evaluated on the central 25 mm of the tool

Table 1. Log characteristics and debarking parameters for each debarking treatment.

Log characteristics and debarking parameters	Temperature condition					
	20°C		-20°C			
Log characteristics	—	—	—	—	—	—
Small end diameter (mm)	151 (4) ^a	145 (5)	145 (5)	155 (6) ^a	155 (6)	146 (6)
Large end diameter (mm)	161 (6)	154 (5)	153 (5)	165 (6)	166 (7)	156 (6)
Taper (mm/m)	8 (2)	8 (1)	7 (1)	10 (1)	10 (1)	9 (2)
Eccentricity	0.94 (0.01)	0.944 (0.004)	0.952 (0.009)	0.940 (0.008)	0.939 (0.007)	0.940 (0.009)
Bark thickness (mm)	4.3 (0.2)	4.2 (0.2)	4.3 (0.2)	4.4 (0.2)	4.5 (0.2)	4.0 (0.2)
Number of knots	6 (1)	6 (1)	5 (1)	9 (1)	9 (1)	7 (1)
Mean knot diameter (mm)	13.0 (0.4)	14 (1)	12 (1)	9.4 (0.7)	11.8 (0.6)	10.7 (0.4)
Mean knot area (cm^2)	2.5 (0.3)	5 (1)	4 (1)	3.0 (0.3)	4.5 (0.8)	2.7 (0.6)
Proportion of knot area after debarking (%)	0.23 (0.04)	0.45 (0.05)	0.38 (0.05)	0.20 (0.03)	0.25 (0.05)	0.24 (0.04)
Number of logs	13	14	15	15	12	13
Cutting parameters	—	—	—	—	—	—
Tool tip radius (μm)	40 ^b	180	300	40	180	300
Static radial force (N/mm)	16	16	16	16 ^b	22	22
Rake angle ($^{\circ}$)	80	80	80	80	80	80

^a Numbers in parentheses are standard errors of the mean.

^b The static radial force for the 40 μm tool tip radius test at -20°C was reduced to 16 N/mm due to excessive fiber tear-out.

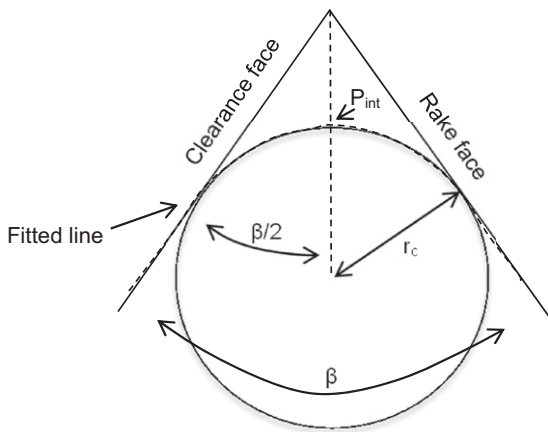


Figure 1. Characterization of a tool tip profile by the gaussian fitted circle method (adapted from Wyen and Wegener 2010).

tip using a ContourGT-I optical profiler (Bruker company, Tucson, AZ). Scan parameters were selected as follows: speed 1×, backscan 0 μm, length 250 μm, thresholding 1%, overlap of 40%, and green illumination. Later, one profile per millimeter was extracted from each surface profile and analyzed with image pro plus V6.2 software.

The tool tip radius was measured following the Gaussian fitted circle method (Wyen and Wegener 2010) (Fig 1). First, a fitted straight line was drawn on each rake face and clearance face of the tip. Second, a dotted straight line was projected from the intersection between the rake and clearance faces. The angle between the fitted lines is β° . A fitted circle was then drawn intersecting

the tangents of each fitted straight lines and the point: P_{int} . The radius of the fitted circle (r_c) represents the tool tip radius. Tip radii of the 41, 183, and 308 μm were obtained after honing. 3D and 2D profiles of the tool tips are shown in Fig 2.

Bark/Wood Shear Strength, Basic Density, and MC Measurements

A 200 mm disc was cross-cut from each log to obtain cores for BWSS tests. The discs were wrapped in polyethylene and kept at -20°C to maintain their MC until the beginning of the sample preparation. Three cores of 12.7 mm in diameter and 25 mm in length were obtained from each disc in the radial direction. The core extraction and bark/wood adhesion tests in the transverse direction were performed according to Ugulino et al (2020). Bark thickness, including inner and outer barks, of each core was measured before testing (Table 1). BWSS (MPa) was calculated by dividing the load at failure (N) by the cross-sectional area of the wood/bark interface (mm^2) (Table 2).

Immediately after shearing tests, inner and outer barks were separated using a razor blade. Green mass and volume of sapwood, inner bark, and outer bark samples were then collected. Volume was measured by the water displacement method according to ASTM D2395-17 (2017). Samples were then oven-dried at 103°C for at least 24 h to obtain their oven-dry mass. All-mass measurements were made to the nearest 0.0001 g. Finally, the MC by the oven-drying method (ASTM D4442-16 2016) at the time of

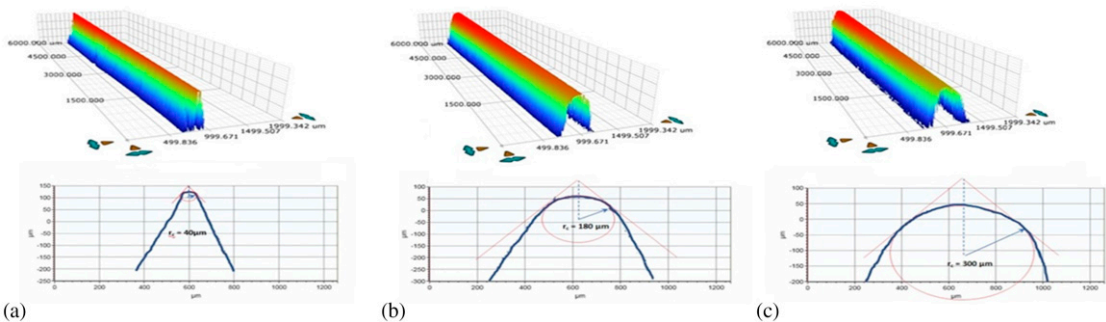


Figure 2. Tool tips 3D and 2D profiles: (a) 40 μm, (b) 180 μm, and (c) 300 μm of radius.

Table 2. Wood properties and total removed material for each debarking condition.

Wood properties	Temperature condition					
	Unfrozen			Frozen		
	Tool tip radius					
	40	180	300	40	180	300
BWSS (MPa)	0.35 (0.02) ^a	0.39 (0.01)	0.35 (0.01)	0.85 (0.06)	1.05 (0.09)	1.05 (0.08)
Sapwood MC (%)	109 (5)	114 (5)	117 (6)	120 (6)	121 (6)	110 (4)
Inner bark MC (%)	150 (5)	146 (5)	152 (5)	136 (5)	139 (6)	134 (8)
Outer bark MC (%)	69 (6)	67 (4)	78 (4)	66 (4)	58 (4)	61 (3)
Sapwood basic density (kg/m ³)	421 (10)	420 (4)	439 (8)	424 (9)	412 (10)	425 (10)
Inner bark basic density (kg/m ³)	412 (13)	401 (6)	410 (5)	417 (13)	418 (6)	414 (18)
Outer bark basic density (kg/m ³)	455 (12)	460 (9)	453 (7)	462 (11)	492 (19)	437 (24)
Total removed material (m ³)	—	—	—	0.0023 (0.0001)	0.0019 (0.0001)	0.0011 (0.0001)

BWSS, Bark/wood shear strength.

^a Numbers in parentheses are standard errors of the mean.

testing as well as basic densities were calculated. Table 2 shows the mean values of sapwood and bark properties for each debarking condition.

Debarking Experiments and Measurement of Energy Requirements

The debarking operation was performed with a debarker prototype, which is described in detail elsewhere (Kharrat et al 2020a). The debarker was equipped with one tool arm and tips provided by DK-SPEC. The three tool tips described before were used. The feed speed (4.5 m/min) and the rotational speed (100 rpm) were set to have a tool overlap of 10%. The rake angle was fixed at 80° according to the recommendation given by Calvert and Garlicki (1974). Tests were conducted at two log temperatures: 20°C and −20°C. Temperature was measured with an IR thermal camera (Fluke TiX500) just after each debarking test. The static radial force applied for logs at 20°C was 16 N/mm. For logs at −20°C, a radial force of 22 N/mm was applied given that the BWSS increases at temperatures below 0°C (Ugulino et al 2020). However, this force was kept at 16 N/mm when frozen logs were debarked with the 40 μm of tip radius to avoid severe fiber tear-out during testing. Moreover, the radial force at the end of

the tip was recorded with the data acquisition system (LabVIEW program) connected to the load cell of the tool arm. Debarking was always done from the small end to the big end of the log. Immediately after debarking, all bark residues were collected, placed in plastic bags, and stored at −20°C for later analysis.

A length of 0.85 m of each log was debarked in 10.7 s. During this time, a data acquisition system connected to the motor drive that rotated the log, was used to record the rotational speed (rpm) and the mean power (W) at a rate of 39 Hz. These values were used to calculate the torque of the motor (N·m) as follows: mean power × 9.549/rotational speed. The energy consumption (W·h), which is the electrical energy supplied for debarking per unit of time, was also calculated. These measurements were performed solely for the frozen condition. The energy measurements considered the energy needed to rotate the log, which depends to its size and mass; plus the debarking energy, which is the energy needed to remove material.

Debarking Quality Indicators

Proportion of BRL. All debarked surfaces were scanned using a Go!Scan Creaform handheld 3D scanner. The proportion of BRL surface

was measured based on the scanned images using a Python program, which was coded to identify and measure all the bark patches remaining on log surfaces. The task of identifying bark regions out of a wood log image was formulated as a semantic segmentation task. The approach used a fully convolutional neural network architecture capable of learning this task on a dataset of log images. Bark patches remaining on the log surfaces were manually tagged to improve the overall accuracy of this program. An overall accuracy of 95% was obtained for the images studied. For a more detailed description, refer to Kharrat et al (2020a). In addition, the number and size (two diameters) of knots bigger than approximately 10 mm were measured on each log. Afterward, the mean knot surface and the proportion of knot surface on the log were calculated (Table 1).

Proportion of WIB. Bark particles were recovered after each debarking test and air-dried indoors to facilitate their separation. Particles were then screened with a classifier in four classes (large, intermediate, small, and fines) following the methods used by Kharrat et al (2020a). All large and intermediate particles were manually separated into their wood and bark components. The size of the small particles makes the separation rather complicated and time consuming. Thus, a Domtar particle separator was used to obtain a representative sample corresponding to one quarter of the small particles. This subsample was also manually separated into wood and bark parts. Results from this subsample were used to define the amount of wood in bark residue for all small particles. The average mass of fine particles represented <1% of bark residues for unfrozen logs and <4% for frozen logs. For this reason, fine particles were not taken into account when measuring the amount of wood in bark residue. Finally, the amount of WIB was expressed as a percentage of the total mass of the debarking residue.

The total removed material was estimated as the addition of the bark and fiber volumes that were removed during debarking (Table 2). The former was estimated using the log dimensions, bark thickness, and BRL and the latter was calculated

using the mass of fibers removed and the sapwood basic density.

Statistical Analysis

Statistical analysis was performed by means of the SAS package version 9.4 (SAS Institute 2014, Cary, NC). An analysis of covariance (ANCOVA) and multiple comparisons tests were done to evaluate the effect of the tool tip radius on BRL and WIB for each log temperature separately. The mean power, energy consumption, and torque were also evaluated but only for frozen condition. Log characteristics and wood properties were introduced as covariates, keeping only the ones significant for each model. Finally, the normality was verified with Shapiro–Wilk’s test, the homogeneity of variance was verified with the graphical analysis of residuals, and statistical significance was tested at 5% and 1% probability levels.

RESULTS AND DISCUSSION

Debarking Quality Parameters

The uniformity of the diameter, taper, and eccentricity of the logs among groups (Table 1) facilitated the study of the effect of the tip radius on the debarking quality indicators. The edge radius of the tip showed a significant effect on BRL and WIB for frozen and unfrozen black spruce logs. BRL significantly increased as tool tip radius increased, regardless of the log temperature (Fig 3). More

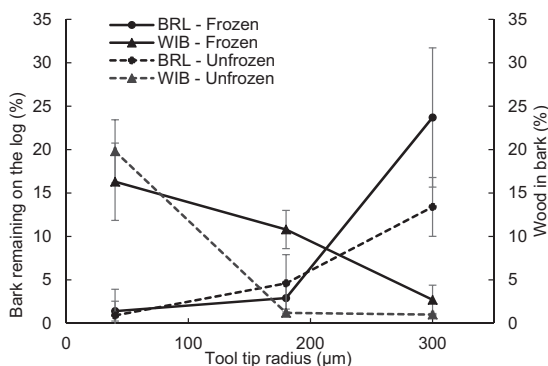


Figure 3. Proportions of bark remaining on the log and wood in bark as a function of the tool tip radius for unfrozen and frozen black spruce logs.

Table 3. Mean values of the proportions of bark remaining on the log and wood in bark for unfrozen and frozen conditions and also mean power, energy consumption, and mean torque for the frozen condition, for three tool tip radius.

Tool tip radius (μm)	Unfrozen condition		Frozen condition				
	BRL (%)	WIB (%)	BRL (%)	WIB (%)	Mean power (W)	Energy consumption (W-h)	Torque (N-m)
40	1 (1) ^a A ^b	20 (4) B	1 (1) A	16 (4) B	20584 (753) B	60 (2) B	1966 (74) B
180	5 (3) B	1.2 (0.4) A	3 (2) A	11 (2) B	18351 (896) A	54 (3) A	1787 (88) A
300	13 (3) B	1.0 (0.1) A	24 (8) B	3 (2) A	17255 (612) A	51 (2) A	1679 (60) A

WIB, wood in bark residues; BRL, bark remaining on the log.

^a Numbers in parentheses are standard errors of the mean.

^b Means within a column followed by the same uppercase letter are not significantly different at the 5% probability level.

specifically, BRL was statistically similar between 40 and 180 μm but significantly different from 300 μm of tip radius, for both temperature conditions (Table 3). The increase in BRL between 180 and 300 μm of tip radius was more important in frozen conditions (Fig 3). According to Table 3, an increase of 120 μm between the two higher radii (180 and 300 μm) resulted in an increase of 8.8% of BRL for unfrozen logs compared with 20.8% for frozen logs. Therefore, BRL in frozen condition appeared to be more sensitive to a tip radius increase within higher ranges, thus leading to larger regions of bark attached to the log after debarking. The presence of ice in the bark negatively affected the penetration of the tip edge. Below 0°C, a shallow penetration was in fact observed compared with unfrozen condition for the same applied force. In addition, the bark/wood bond becomes stronger below 0°C (Ugulino et al 2020), which will make the debarking action more difficult (Laganière and Hernández 2005; Kharrat et al 2020a,b). As explained earlier, the radial force

applied with 40 μm tip radius at frozen condition was maintained at 16 N/mm (same as unfrozen condition) to prevent severe fiber tear-out. Table 3 shows that the BRLs obtained with this tip radius were 0.9% and 1.4% for unfrozen and frozen logs, respectively. Accordingly, a radial force of 16 N/mm adequately removed the bark in frozen logs because of the sharpness of the tip.

The ANCOVA showed that BRL was also affected by the inner bark MC for frozen and unfrozen logs and by the bark thickness for the unfrozen logs (Table 4). A higher MC of the inner bark would facilitate the debarking action, thus reducing the amount of BRL surface for both temperature conditions. Moreover, thicker bark will lead to a higher proportion of BRL in unfrozen condition probably due to a lower penetration of the tip. Thus, an increase in the applied radial force will be required.

WIB decreased significantly as the tool tip radius increased for both log temperatures (Fig 3). The *F*-values showed that effect of the tip radius on

Table 4. *F*-values obtained from the ANCOVAs of the effect of tool tip radius on the proportions of bark remaining on the log and wood in bark for unfrozen and frozen conditions and also mean power, energy consumption, and mean torque for the frozen condition.

Source of variation	Unfrozen condition		Frozen condition				
	BRL	WIB	BRL	WIB	Mean power	Energy consumption	Torque
Bark thickness	9.6 ** ^a	ni	ni	14.5 **	ni	ni	ni
Inner bark MC	13.1 **	ni	6.4 *	5.5 *	ni	ni	ni
Total removed material	ni ^b	ni	ni	ni	7.2 *	6.9 *	7.0 *
Mean log diameter	ni	ni	ni	ni	91.9 **	81.8 **	83.1 **
BWSS	ni	ni	ni	ni	5.0 *	ni	ni
Tool tip radius	10.0 **	89.9 **	19.7 **	21.6 **	9.3 **	6.6 **	6.6 **

WIB, wood in bark residues; BRL, bark remaining on the log; BWSS, bark/wood shear strength.

^a *, ** significant at 5% and 1% probability level respectively.

^b ni: not included in the ANCOVA.

WIB was stronger for the unfrozen logs than for frozen logs (Table 4). For unfrozen logs, WIB was statistically different between 40 μm and the other two tip radii (180 and 300 μm), which were similar between them (Table 3). For frozen logs, there were no differences in WIB between 40 and 180 μm of tip radius but both were significantly different from 300 μm of tip radius. However, the decrease in WIB between the tip radii of 40 and 180 μm was more abrupt in unfrozen condition (Fig 3). According to Table 3, an increase of 140 μm in the tip radius resulted in a decrease of 18.6% of WIB for unfrozen logs compared with 5.5% for frozen logs. Moreover, a decrease of 18.1% of WIB was found for the latter condition with a much higher increase in tip radius of 260 μm (from 40 to 300 μm). Thus, the use of a tip radius close to 180 μm in unfrozen condition and close to 300 μm in frozen condition would significantly reduce fiber tear-out during debarking. However, this would also result in a noticeable increase in BRL for the latter. In addition, there was no significant difference in WIB between frozen and unfrozen conditions at 40 μm tip radius (Fig 3). Therefore, the fiber tear-out was effectively controlled by keeping the radial force at 16 N/mm for both log temperatures.

On the other hand, none of the studied covariates showed a significant effect on WIB for the unfrozen condition. But, for the frozen condition, WIB was significantly affected by the inner bark MC and by the bark thickness (Table 4). A higher MC in the inner bark and a thinner bark would result in higher fiber tear-out at temperatures below 0°C. The *F*-values showed that the effect of bark thickness on WIB was stronger than that of the inner bark MC. It is important to understand that the proportion of fiber tear-out is the result of a tip penetration (exceeding the cambium layer) at a certain radial force, which is usually higher when debarking frozen logs (Kharrat et al 2020a). Fiber tear-out could, thus, happen more easily and continuously when the bark is thinner. This could be associated to excessive radial force. This result is important because the bark thickness varies within species depending on the site, tree age, individual

trees, and along the stem (Smith and Kozak 1971; Laasasenaho et al 2005; Marshall et al 2006).

Debarking quality parameters affect the sawmill productivity in two distinctive ways. The relative importance of each one depends on the particular optimization guidelines of each sawmill. First, the BRLs will affect the proportion of bark in chips, thus affecting their commercialization to pulp mills. However, the degree of its influence on chip quality depends at the same time on the size and shape of the log, as well as the selection of the cutting width, which depends on the cutting pattern chosen for the sawing process. For these reasons, it is quite difficult to estimate a critical amount of BRL as a threshold to keep the required chip quality along the production line. In any case, bark content in chips must not exceed 1% in mass (Ding et al 2012). Second, the amount of wood fibers found in bark residues will affect the global efficiency and sawn lumber yield of a sawmill. Bark residues are usually burn as fuel, including the wood fibers found within them (Isokangas and Leiviskä 2005). In general, sawmills use higher radial forces than the necessary to avoid pulp mills penalties for bark in chips. Although this will assure minimum BRL levels, it would disproportionately increase the amount of WIB at the same time. The selection of an appropriate tool tip radius could be an interesting option to avoid an additional increase of the radial force during debarking. At equal radial force, a narrower tip radius (sharper) will assure a deeper tip edge penetration compared with a wider radius. Therefore, the applied radial force could be regulated to a level that will allow to efficiently remove the bark from the log without tearing-off the wood fibers.

Considering the opposite behavior of the two debarking indicators, the improvement of one indicator goes to the detriment of the other one and vice versa. Thus, the curves between BRL and WIB for unfrozen and frozen log conditions in Fig 3 intersect at a given point. This point should represent a suitable compromise when considering the two debarking quality indicators at an equal degree of importance. The tool tip radii of 158 and 213 μm resulted in 4% and 8.5% for both quality parameters for the unfrozen and frozen logs, respectively

(Fig 3). These tip radii would be the more satisfactory for debarking specifically with the chosen radial forces. Particularly, the lower limit would be more fitted for unfrozen condition and the higher one for the frozen condition (-20°C). However, the same degree of debarking quality could not be reached in both cases with the given radial forces. Figure 3 shows that the radial force applied with a $40\ \mu\text{m}$ tip radius ($16\ \text{N/mm}$) was still too high. BRL was 1.2% but WIB was 18.1% (frozen and unfrozen logs pooled). Therefore, it could have been possible to lower the radial force to decrease WIB but without increasing BRL. At $180\ \mu\text{m}$, BRL (4.6%) was higher than WIB (1.2%) in the unfrozen condition, and, thus, the radial force applied ($22\ \text{N/mm}$) could have been slightly increased to reduce BRL but without increasing WIB. But for the frozen condition the same radial force seems to be a little too high, resulting in a WIB of 10.8% and a BRL of 2.9%. At $300\ \mu\text{m}$, BRL was 18.6% but WIB was 1.8% (frozen and unfrozen logs pooled), thus, a higher radial force could have been used to reduce BRL. However, applying more radial force using a bigger tool tip radius would probably result in an increase in the power consumption, mainly in the frozen condition. Consequently, the best compromise between the BRL and WIB could be obtained with an intermediate tip radius (between 158 and $213\ \mu\text{m}$) combined with the more appropriate radial force depending on the temperature condition.

Power, Energy Consumption, and Torque Under Frozen Conditions

The ANCOVAs showed that the electrical performance of the motor was significantly affected by the tool tip radius (Table 4). The mean power, energy consumption, and torque decreased as the tip radius increased. These indicators were, thus, significantly higher for $40\ \mu\text{m}$ than for the other two tip radii (180 and $300\ \mu\text{m}$) even though the applied radial force was lower for the former tool tip ($16\ \text{N/mm}$) compared with the other tip radii ($22\ \text{N/mm}$) (Table 3).

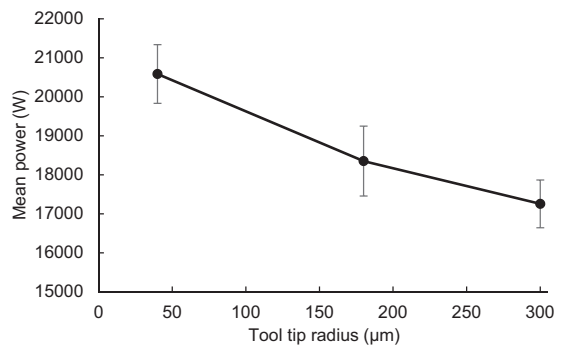


Figure 4. Mean power as a function of the tool tip radius.

Some of the studied covariates showed a significant effect on the motor electrical performance (Table 4). Mean power, energy consumption, and torque were positively affected by the total removed material and by the log diameter. Accordingly, as more material was removed, the debarking forces increased and, therefore, the mean power, energy consumption, and torque also increased. These parameters also increased as log diameter increased. In addition, a higher mean power was needed for debarking as BWSS increased.

The relationship between mean power and tool tip radius is shown in Fig 4. An increase of $140\ \mu\text{m}$ of tool tip radius (from 40 to $180\ \mu\text{m}$) resulted in a decrease of 11% of mean power; however, a consecutive increase of $120\ \mu\text{m}$ (from 180 to $300\ \mu\text{m}$) resulted in a decrease of only 6% of mean power. Power is the work performed over a specific amount of time, thus, it could be stated that more work is needed for debarking frozen logs using narrower tool tips. The same behavior was found for the energy consumption. Hence, debarking frozen logs with a tip radius of $40\ \mu\text{m}$ resulted in higher energy consumption compared with using 180 and $300\ \mu\text{m}$.

The tip of $40\ \mu\text{m}$ radius showed a deeper penetration into the bark compared with wider tips, which occasionally exceeded the cambium layer. The shearing action in that case took place in the sapwood instead of the bark/wood interface. Therefore, the volume of WIB for this condition reached 16.3% (Table 3). Hernández et al (2014) found a shear strength parallel-to-the grain of $9.2\ \text{MPa}$ in

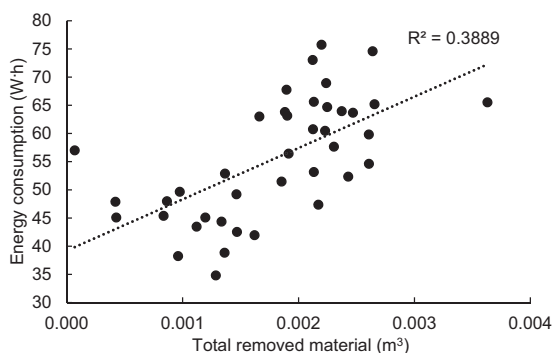


Figure 5. Energy consumption as a function of the total removed material.

black spruce sapwood at -20°C , which could be quite similar in the perpendicular direction. This strength is significantly higher than the BWSS (0.85 MPa for $40\ \mu\text{m}$, Table 2) needed to remove the bark at the cambium layer. Thus, the energy consumption will increase each time that the shearing action takes place in the sapwood, which could happen more regularly when using narrow tip radius combined with too high radial forces. Therefore, if excessive radial force is applied during debarking with narrow tool tips, the energy consumption would increase even more as it is positively related to the amount of material removed, as previously explained. Hence, Fig 5 shows a significant positive correlation between the energy consumption and the total material removed (R^2 : 0.39). From a practical point of view, these results emphasize the importance of choosing an appropriate combination of tool tip radius and applied radial force to sustain an efficient use of energy. Thus, the use of a small tip radius with just enough radial force could be more beneficial to reduce both the energy consumption and mainly the WIB. However, further studies should be done to establish the more adequate combinations of tool tip radius and radial force to confirm this behavior.

The torque of an electric motor is a measure of the driving force that can cause an object to rotate around an axis. Torque was calculated using power, and thus it showed the same behavior in relation to the tool tip radius as shown in Fig 4.

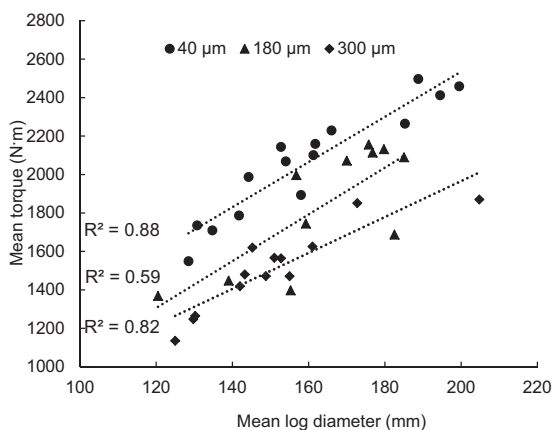


Figure 6. Mean torque as a function of the mean log diameter for each tool tip radius.

Debarking frozen logs with a tip radius of $40\ \mu\text{m}$ needed a greater torque compared with using 180 and $300\ \mu\text{m}$. As explained earlier, the studied motor performance indicators were significantly affected by the mean log diameter (Table 4). Among them, we choose torque to show this relationship. A strong correlation between the size of the log and the torque needed for debarking is shown in Fig 6. Coefficients of determination (R^2) that ranged from 0.59 to 0.88 were found depending on the tool tip radius. Debarking bigger logs will require greater torque than smaller ones. However, debarking logs of the same diameter will require higher torque when using narrower tool tip radius. This agrees with the results found for mean power and energy consumption.

From an industrial perspective, a direct application between our results and the ring debarking rotor would be difficult. Contrary to the action of the ring debarker, which is a rotating ring provided with tool arms that scrape the bark off the logs as they are fed through the ring; the laboratory debarker pushed the tool arm into the log as it was rotating and moving horizontally (Kharrat et al 2020a). However, at the same applied radial force, a narrow tip radius could penetrate deeper into the bark significantly increasing the amount of fiber tear-out and consequently the energy consumption. On the contrary, a large tip radius could not penetrate enough into the bark leaving larger

regions of bark on the log surface and, thus, lessen the energy consumption. Therefore, it would be more reasonable to recommend an intermediate tip radius (158 and 213 μm depending on log temperature) that will assure a satisfactory debarking quality, for both BRL and WIB, with an efficient use of energy.

CONCLUSIONS

Black spruce ring debarking quality was significantly affected by the tip edge radius and the log temperature. Inner bark MC and bark thickness also affected the debarking action. For frozen and unfrozen conditions, a wider tip radius made a shallower incision in the bark, which left larger patches of bark on the surfaces of debarked log. On the contrary, a narrower tip radius made a deeper incision in the bark increasing the number of torn fibers in the bark residues. Therefore, an acceptable compromise between BRL and WIB could be achieved by using an intermediate tip radius (between 158 and 213 μm) applying sufficient radial force, depending on log temperature.

Mean power, energy consumption, and torque decreased as the tip radius increased. These parameters were also positively affected by the total material removed and the log diameter. Higher power will be needed when the bark/wood adhesion is stronger. A small tip radius will consume more energy if the applied radial force results in a debarking action performed in the sapwood instead of the cambium layer. Also, a large tip radius will require higher radial forces to reach the cambium layer and will, therefore, consume more energy. Therefore, selecting an appropriate combination of tool tip radius and applied radial force to achieve debarking most often at the cambium layer is critical to achieving good quality debarking quality and energy efficiency.

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REFERENCES

- ASTM (2016) D4442-16. Standard test methods for direct moisture content measurement of wood and wood-based materials. American Society for Testing and Materials, West Conshohocken.
- ASTM (2017) D2395-17. Standard test methods for density and specific gravity (relative density) of wood and wood-based materials. American Society for Testing and Materials, West Conshohocken.
- Bajpai P (2016) Energy conservation measures for raw material preparation. Chapter 4, Pages 51-66 in Bajpai J, eds. Pulp and Paper Industry, Energy Conservation, Elsevier.
- Baroth R (2005) Literature review of the latest development of wood debarking. University of Oulu, Finland.
- Belli ML (1996) Wet storage of hickory pulpwood in the southern United States and its impact on bark removal efficiency. *Forest Prod J* 46(3):75-79.
- Berlyn R (2000) Debarking. Tech 2000: Chip & wood quality. Professional development committee, Pulp & Paper Technical Association of Canada, Montreal, Canada, 29 pp.
- Calvert WW, Garlicki AM (1972) A study of bark removal at low temperatures by simulated cambium shear methods. *Forest Prod J* 22(2):37-43.
- Calvert WW, Garlicki AM (1974) The use of ring debarkers at low temperatures. Publication No. 1334. Department of the Environment, Canadian Forest Service, Ottawa, ON.
- Chahal C, Ciolkosz D (2019) A review of wood-bark adhesion: Methods and mechanics of debarking for woody biomass. *Wood Fiber Sci* 15(3):1-12.
- Chow S, Obermajer A (2004) Wood-to-bark adhesion of subalpine fir (*Abies lasiocarpa*) in extreme temperatures. *Wood Sci Technol* 38(6):391-403.
- Cristóvão L, Ekevad M, Grönlund A (2013) Industrial sawing of *Pinus sylvestris* L.: Power consumption. *Bio-Resources* 8(4):6044-6053.
- Denkena B, Biermann D (2014) Cutting edge geometries. *CIRP Ann Manuf Technol* 63(2):631-653.
- Ding FP, Ibrahim F, Gagné F (2012) MPC based ring debarking process optimization. in 25th IEEE Canadian Conference on Electrical and Computer Engineering (CCECE). Montreal, QC.
- Erickson JR (1979) Separation of bark from wood. Pages 145-170 in Hatton JV ed. Chip quality monograph. Joint Textbook Committee of the Paper Industry, Vancouver, BC.
- Fiscus MH, Vanepereen RH, Einspahr DW (1983) Method for obtaining wood bark adhesion measurements on small samples. *Wood Fiber Sci* 15(3):219-222.

- Hatton JV (1987) Debarking of frozen wood. *Tappi J* 70: 61-66.
- Hartler N, Stade Y (1979) Chip specifications for various pulping processes. Pages 273-301 in Hatton JV ed, *Chip quality monograph*. Joint Textbook Committee of the Paper industry, Vancouver, BC.
- Hernández RE, Passarini L, Koubaa A (2014) Effects of temperature and moisture content on selected wood mechanical properties involved in the chipping process. *Wood Sci Technol* 48(6):1281-1301.
- Isokangas A, Leiviskä K (2005) Optimisation of wood losses in log debarking drum. *Pap Puu-Pap Tim* 87(5): 324-328.
- Kharrat W, Hernández RE, Cáceres CB, Blais C (2020a) Effects of radial force and log position on the stem on ring debarker efficiency in frozen black spruce logs. *Wood Mater Sci Eng* 16(3):211-220.
- Kharrat W, Hernández RE, Cáceres CB, Blais C (2020b) Ring debarking efficiency of frozen balsam fir logs is affected by the radial force but not by the log position on the stem. *Can J Res* 50(12):1323-1332.
- Laasasenaho J, Melkas T, Aldén S (2005) Modelling bark thickness of *Picea abies* with taper curves. *For Ecol Mgmt* 206:35-47.
- Laganière B (2003) Manual-ring debarking. Special publication SP-525E. Forintek Canada Corp, Québec, QC.
- Laganière B, Bédard N (2009) Debarking enhancement of frozen logs. Part I. Effect of temperature on bark/wood bond strength of balsam fir and black spruce logs. *Forest Prod J* 59(6):19-24.
- Laganière B, Hernández RE (2005) Effects of radial force and tip path overlap on the ring debarking efficiency of frozen balsam fir logs. *Forest Prod J* 55(3):44-49.
- Marshall H, Murphy G, Lachenbruch B (2006) Effects of bark thickness estimates on optimal log merchandising. *Forest Prod J* 56(11):87-92.
- MFFP—Ministère des Forêts, de la Faune et des Parcs (2018) Ressources et industries forestières du Québec. Portrait statistique (In French). https://mffp.gouv.qc.ca/wp-content/uploads/PortraitStatistique_2018.pdf (1 December 2020).
- Moore GA (1987) The variation of bark/wood bond strength with moisture content of *Pinus radiata* and three eucalypt species during storage. *Aust For Res* 17: 73-78.
- Prislan P, Cufar K, Koch G, Schmitt U, Gricar J (2013) Review of cellular and subcellular changes in the cambium. *IAWA J* 34:391-407.
- SAS Institute (2014) SAS/Stat user's guide. SAS Institute Inc. Version 9.3. Cary, NC.
- Smith JH, Kozak A (1971) Thickness, moisture content, and specific gravity of inner and outer bark of some Pacific northwest trees. *Forest Prod J* 21(2):38-40.
- Ugulino B, Cáceres CB, Hernández RE, Blais C (2020) Influence of temperature and moisture content on bark/wood shear strength of black spruce and balsam fir logs. *Wood Sci Technol* 54:963-979.
- Wilhelmsson L, Arlinger J, Spangberg K, Lundqvist S, Grahn T, Hedenberg O, Olsson L (2002) Models for predicting wood properties in stems of *Picea abies* and *Pinus sylvestris* in Sweden. *Scand J Fr Res* 17(4):330-350.
- Wyen CF, Wegener K (2010) Influence of cutting edge radius on cutting forces in machining titanium. *CIRP Ann Manuf Technol* 59(1):93-96.
- Zhao T, Zhou JM, Bushlya V, Ståhl JE (2017) Effect of cutting edge radius on surface roughness and tool wear in hard turning of AISI 52100 steel. *Int J Adv Manuf Technol* 91:3611-3618.