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ORIGINAL ARTICLE

Evaluation of two surfacing methods on black spruce wood in relation to gluing performance

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Abstract Surface quality and gluing performance of black spruce samples prepared by peripheral straight-edge knife planing and sanding were studied. Four wavelengths (1.5, 1.9, 3.1, and 6.5 mm) and four rake angles (15°, 20°, 25°, and 30°) were tested for peripheral planing. Three feed speeds (4, 10.5, and 17 m/min) and three grit size sandpapers (80, 100, and 120) were studied for sanding. The resulting surfaces were glued with an isocyanate adhesive and tested to evaluate their gluing performance (shear strength and percent wood failure). Results revealed that planing with a rake angle of 20° and wavelengths of up to 3.1 mm produced wood surfaces with adequate glueline shear strength. Sanding with 80-grit sandpaper produced the best glueline shear strength, regardless of feed speed. After accelerated aging, the loss of gluing performance was lower for the sanded samples compared with that of planed samples. In general, sanding process produced better wood surfaces for bonding with the adhesive studied.

Keywords Peripheral planing · Sanding · Gluing performance · Isocyanate · Black spruce wood

Introduction

In woodworking, planing and sanding operations are commonly used to obtain acceptable surfaces prior to adhesive application. One of the most important properties influencing further manufacturing processes such as coating or glue application and their adhesion is surface roughness of solid wood. Previous works have reported better glue joint mechanical properties when surface roughness is increased in spruce wood [1], Japanese woods [2], red oak [3], and hard maple woods [4].

According to Koch [5], quality of peripheral-planed surfaces is generally improved by short wavelengths (or feed per knife) and low height of knife marks. This is generally accomplished by increasing the cutting circle diameter, number of jointed knives, or by reducing feed speed. Indeed, reduction in feed speed decreases the normal cutting force [5, 6] by reducing chip dimensions. Rake angle and jointing operation are also important factors influencing surface quality during planing process. For several species, better surface quality is observed as rake angle decreases from 30° to 15° [7–9], whereas the effect of jointing operation depends on wood species and knife wear [3, 10, 11]. On the other hand, Carrano et al. [6] reported an increase in surface quality when decreasing the depth of cut. However, Iskra and Hernández [12] found that surface quality is not affected by depth of cut during routing paper birch wood with different grain orientations. Difference between these two studies could be related to the efficiency of feeding systems used for conducting the experiments (vibrational effects).

Quality of sanding depends on several parameters like wood species, interface pressure, type of abrasive mineral, sanding orientation, and grit size. For example, silicon carbide sandpaper yielded better surface quality than

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aluminum oxide sandpaper [13–15]. Furthermore, sanding parallel to the grain produced smoother surfaces than across to the grain [13]. In peripheral sanding, Carrano et al. [16] observed better surface quality with P220-grit compared with P150-grit sandpaper for white oak, sugar maple, and white pine woods. Significant effects of feed rate and spindle speed were also reported on surface roughness. Moreover, Sinn et al. [17] observed a strong linear positive correlation between roughness and grit size for spruce and beech woods.

Properties, such as surface roughness and wettability, and characteristics, which refer to the anatomic structure and how it is affected by machining, of planed and sanded surfaces differ largely. Microscopical surface analyses show that crushed or damaged cells are more common in abrasive-planed material than in knife-planed wood [18, 19]. More specifically, sanded wood is characterized by a layer of crushed cells at the surface and subsurface, lumens clogged by fine dust, scratches, and packets of micro-fibrils torn out from cell walls [20]. Generally, planed surfaces show less crushed and damaged cells compared to sanded surfaces [21]. However, lower roughness values in sanded surfaces of aspen [22] and paper birch [23] woods compared with that of planed surfaces were observed. According to Richter et al. [24] and Hernández and Cool [23], sanding produces homogeneous surfaces that could reduce the influence of the anatomical structure on the roughness profile.

The species studied in this paper, black spruce, is one of the most important boreal species in Canada. The wood is widely used in construction applications such as lumber and glued structural members. However, little information is available on its machining properties. This species has been included in a general study on Canadian woods undertaken by Lihra and Ganev [25]. Based on the ASTM D1666 [26], cutting parameters for planing this wood were suggested when using a conventional peripheral planing process. Compared with other wood species, black spruce proved difficult to plane in a manner that produces defect-free surfaces. However, Cool and Hernández [21, 27] recently showed that peripheral planing induced good surfaces for mechanical adhesion of poly (vinyl acetate) glue and an acrylic water-based coating. This study was oriented to use this wood for appearance purposes.

It is also of interest to optimize the machining parameters for preparing the surfaces of this wood for the production of glued structural members. Therefore, the aim of the present work was to evaluate the effect of peripheral straight-edge knife planing and sanding processes applied on black spruce wood prior to isocyanate glue bonding. Four feed speeds and four rake angles for peripheral planing, and three feed speeds and three grit size sandpapers for sanding were studied. The gluing shear performance was evaluated at constant hygrothermal conditions and after exposing specimens to an accelerated aging treatment.

Materials and methods

Testing materials

Tests were carried out with black spruce [*Picea mariana* (Mill) B.S.P.] wood, which came from Chibougamau region, in northern Quebec. A total of 250 kiln-dried boards of 38 mm × 64 mm were stored in a conditioning room at 20 °C and 60 % relative humidity (RH) until they reached 12 % equilibrium moisture content (EMC). After conditioning, each board was crosscut into three matched sections of 660 mm (*L*) length. All sections were machined to 60 mm (*T*) width, and 21 mm (*R*) thickness. Boards were then separated into twenty-five groups, with each group to be submitted to a specific treatment. Mean density (mass divided by volume at 12 % EMC) and the variation coefficient of each group were 538 kg/m^3 and 5.8 %, respectively. Each board underwent a surfacing treatment and was resectioned to prepare specimens for roughness [50 mm (*L*)] and gluing [two laminated blocks of 305 mm long (*L*) each].

Machining treatments

A peripheral straight-edge knife planing was used to surface the specimens. Previous cuts were carried out to level samples prior to each surfacing treatment. The planing treatment was done with a Weining Powermat 1000 moulder equipped with a cutterhead having 51 mm of cutting radius. The cutterhead rotation speed was kept at 4800 rpm with four different feed speeds, 7, 9, 15, and 31 m/min. The last two feed speeds are substantially faster than those of previous studies and consequently more comparable to the ones normally used by the industry of glued structural members. This produced wavelengths (or feed per knife) of 1.5, 1.9, 3.1, and 6.5 mm, respectively. Cutting depth was 2 mm and the rake angle was studied at four levels: 15°, 20°, 25°, and 30°. The clearance angle was kept constant at 20° for each rake angle.

Sanding treatment was performed with a Costa wide-belt sander provided with closed coat paper-backed sanding belts. The boards were sanded with aluminium oxide sandpaper. Three sanding programs were tested: 80-, 80-100- and 80-100-120-grit stages. The 80-grit, 100-grit, and 120-grit sanding belts worked with a 0.5, 0.3, and 0.2 mm removal depth, respectively. All sanding belts were installed onto a drum and feeding was carried out fiberwise. Three feed speeds were used: 4, 10.5, and 17 m/min.

The linear velocity of drums was kept constant at 20 m/min for all sanding programs. Oscillating blowers performed cooling and cleaning of the belt during sanding.

After surfacing, boards were glued with a resin formulation according to the technical recommendations supplied by the adhesive manufacturer. An ISOSET WD3-A322 emulsion resin combined with an ISOSET CX-47 crosslinker was used. This adhesive is part of the group of isocyanates, which is different to those used in previous studies. The adhesive was applied within a 3-h period after machining to ensure fresh and clean wood surfaces. Glue was applied on one face at a spread rate of 227.4 g/m^2. The assembled boards were cured by a Wilkesboro NC radio frequency press, a method currently used in the industry. A uniform pressure of 1207 kPa was applied during 575 s (an initial pressure of 15 s followed by 20 s of radio frequency, and 540 s of final pressure). After curing, the laminated boards were stored in a conditioning room at 20 °C and 60 % RH for 1 week before cutting the gluing shear test specimens.

Microscopic evaluation

Cubes of 10 mm were cut to observe tangential and end-grain surfaces. Tangential surfaces were used to evaluate fibrillation level and open lumens, whereas end-grain surfaces were used to analyze cell damage. One end-grain surface was carefully cut with a razor blade mounted on a microtome. All cubes were desiccated with phosphorous pentoxide (P_2O_5) for 1 week and mounted onto standard aluminum stubs. Environmental scanning electron microscopy micrographs were taken for two representative machined samples for each machining condition.

Surface quality evaluation

Surface topography measurements were carried out on defect-free zones with a Micromeasure confocal microscope equipped with a 3-mm optical pen having a precision of 0.4 µm. A representative surface of 1.25 × 1.25 cm was analyzed per sample. Data was collected with the Surface Map 2.4.13 software using an acquisition frequency of 300 Hz and a scanning speed of 12.5 mm/s. The digitizing step was therefore 41.6 µm. Three dimensional parameters were determined using Mountains software. Mean roughness (S_a), root-mean-square roughness (S_q), maximum height of peaks (S_p), maximum depth of valleys (S_v), and ten point height of surface (S_z) were calculated according to ISO 4287 [28]. The core roughness depth was calculated from the Abbot curve according to ISO 13565-2 [29]. A threshold was set to artificially truncate extreme values (at the top and/or bottom), which can be generated by a profilometer in optical triangulation. A cut-off length of 2.5 mm combined with a robust Gaussian filter based on ISO/DTS 16610-31 [30] were applied for calculations.

Accelerated aging

Half of shear strength specimens underwent an accelerated aging treatment based on ASTM D 3434 [31]. The treatment consisted of 12 cycles of immersing samples in boiling water for 10 min, cooling for 4 min at 23 °C and drying for 57 min at 107 ± 2 °C. After aging, the specimens were conditioned at 20 °C and 60 % RH until they reached their initial EMC of 12 %. The other half of the specimens were kept unaged.

Glueline mechanical tests

The glueline strength of the accelerated aged and unaged specimens was evaluated according to ASTM D 905 [32]. An MTS RT50 universal testing machine having a maximum capacity of 50 kN and 0.18 % precision fitted-out with a gluing shear fixture was used. Load was applied at a speed of 5 mm/min until separation of the substrates. Cross section of the specimen and load at failure were recorded, and the average gluing shear stress was calculated. The percent wood failure was estimated by image treatments using Photoshop CS4 software based on the method described in Cool and Hernández [21]. Percent wood failure gives information on bond formation: low percent values indicate that the bond is weaker than the wood, whereas high percent values are associated with a bond that is stronger than the wood [33]. The premise of measuring percent wood failure is that structural adhesives are generally assumed to be stronger than the substrate. Therefore, failure plane in properly fabricated joints should be located in the wood and not in the glueline.

Statistical analysis

Statistical analysis was performed by means of the SAS package version 9.2 [34]. Raw data (in all cases) was first transformed using the rank transformation. An analysis of variance (ANOVA) was used to evaluate the variation of roughness and torn grain incidence. The sources of variation were feed speed and rake angle for planed boards, and feed speed and grit size for sanded boards. Given the number of roughness parameters studied, a principal component analysis (PCA) was first applied to data to group them into common factors and facilitate their analysis. Finally, another ANOVA was performed to assess gluing shear strength and percent wood failure between aged and unaged specimens. Given that these specimens were matched, data was analyzed considering a repeated measures design. Mean difference comparison tests were performed at 5 percent probability level when required. Simple correlation analysis was performed between surface quality parameters and shear strength and wood failure data. The normality of the data was verified using Shapiro–Wilk test.

Results and discussion

Microscopy

End-grain surfaces

Peripheral planing treatments studied in this experiment induced little subsurface damage in black spruce wood surfaces. This damage was characterized by slight cell wall deformation in the first row of earlywood cells (not shown). The occurrence of permanent cell wall deformation was scarce and most samples were sound (Fig. 1). Furthermore, few differences were observed among samples regardless of machining parameters. Previous research reported little impact of feed speed in anatomic features of planed black spruce wood samples [27]. As shown in Fig. 1, cutting action in latewood often took place in or close to the middle lamella. In opposition, cutting knives appeared to have cut through earlywood cells. Similar results were reported previously by Cool and Hernéandez [27] for planed black spruce wood.

Sanding treatments induced a certain level of damage in black spruce wood surfaces (Fig. 2). For all studied conditions, earlywood cells were more damaged than those of latewood. Because cutting forces involved in sanding are important, earlywood cells were crushed and deformed down a depth of about 50 µm (Fig. 2b). As reported by Cool and Hernández [35], subsurface damage did not consist of a uniform layer of crushed or deformed cells and some earlywood cells appeared sound. On the other hand, latewood cells were only slightly deformed and most remained sound (Fig. 2). Their thicker cell walls, in comparison to those of the earlywood, offer a greater stiffness and strength to the cutting action. However, micro-ruptures were induced in the middle lamella or through rays (Fig. 2) and extended down the first 4–5 cells (~70 µm). As mentioned by Cool and Hernández [21], these micro-ruptures could act as discontinuities during the moisturizing-drying cycles of weathering. Thus, they could contribute to release stresses produced in wood during weathering.

Tangential surfaces

Planed surfaces were characterized by open lumens of tracheids and rays, plateau-like areas, and fibrillation (Fig. 3). The availability of lumens should favor glue filling and penetration as well as increase mechanical anchorage of glue (Fig. 3) [21]. Fibrillation should also increase mechanical anchorage of glue by enhancing the actual surface available for adhesion. According to micrographs, little effect of feed speed could be observed, whereas the rake angle had a higher impact on the planed surfaces. At low rake angles, surfaces showed similar features to those reported previously when similar cutting parameters were used [27]. In contrast, as rake angle was increased, fibrillation was reduced but some micro-tearing appeared (Fig. 3b). This tearing could be associated to type I chip formation, which is normally favored when using high rake angles or when planing occurs in presence of grain deviation.

Sanded surfaces were characterized by an important level of fibrillation (Fig. 4). If not firmly attached to the surface, this fibrillation could reduce adhesion. However, adhesion could be increased by the level of fibrillation since it increases the actual surface available for mechanical anchorage. The abrasives also produced grooves in the surfaces that were visible at the microscopic level and should favor glue spreading in the longitudinal direction.

Surface topography

PCA was performed to reduce the number of observed variables (surface quality parameters) to a smaller number of components. PCA mathematically produces several

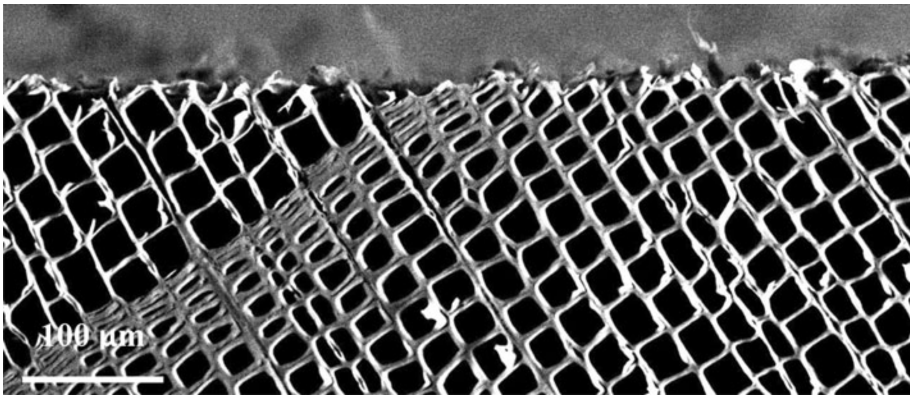

Fig. 1 Transverse ESEM micrograph of a black spruce wood sample planed with a rake angle of 20° and a wavelength of 1.5 mm

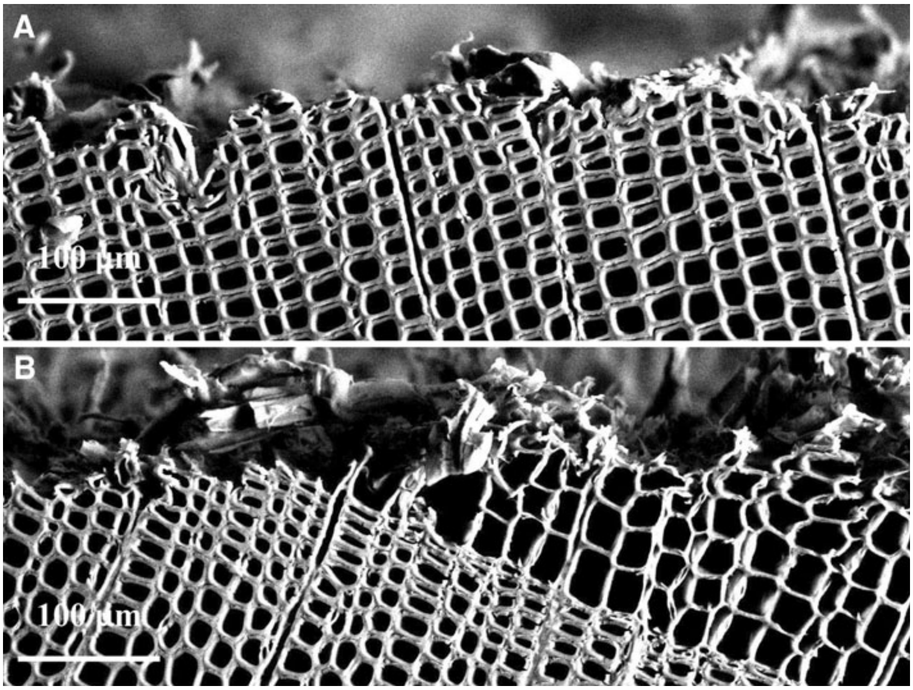

Fig. 2 Transverse ESEM micrograph of a black spruce wood sample sanded with a single-stage sanding program (**a**) and a three-stage sanding program (**b**)

linear combinations of observed variables where each linear combination is a component. Variables that are correlated with another but largely independent of other subsets of variables are combined into components [36]. The number of components was estimated according to the Kaiser Criterion, which retains only components with an eigenvalue >1. Consequently, the surface parameters for each machining treatment were grouped into one principal component. For peripheral planing, the factor loadings S_a (0.99), S_q (0.98), S_p (0.97), S_v (0.93), S_z (0.92), and S_k (0.48) explained 80.2 % of the total variance. The principal component for sanding accounted for 94.3 % of the total variance and included S_a (0.99), S_q (0.99), S_p (0.99), S_v (0.94), S_z (0.94), and S_k (0.96) as factor loadings.

The variation in roughness produced by peripheral planing was explained by one principal component, which was significantly affected by feed speed (Table 1). Although little impact of feed speed was visible on micrographs, surface roughness increased with wavelength from 1.5 to 6.5 mm (7–31 m/min of feed speed). Table 2 shows that as feed speed decreased mean surface roughness (S_a), one of the surface quality parameters included in the PCA, decreased. S_a decreased 68 % when wavelength changed from 1.5 to 6.5 mm. Similar results were observed when helical planing black spruce wood from 1.1 to 2.0 mm of wavelength [37]. Shorter wavelengths are associated with lower peaks in machined surfaces. Thus, values of S_p (not shown) also showed this tendency. According to Carrano et al. [6] shorter wavelengths reduce surface damage. Furthermore, as machining conditions become more aggressive, the cutting forces increase, which can accelerates tool wear. As wear progresses, the cutting tool will have more problems to generate clean and smooth surfaces. On the other hand, variation in rake angle did not affect surface roughness produced by peripheral planing. Cool and Hernández [27] did not also find any difference in roughness between 15° and 20° rake angle when peripheral straight-edge knife planing black spruce wood prior to varnishing (at wavelengths lower than 1.3 mm). As mentioned earlier, rake angle had an effect on chip production at the microscopic level (Fig. 3). A decrease in fibrillation combined with an increase in micro-tearing was observed when rake angle was increased. However, these observations were not confirmed by the roughness measurements probably because the reduction in fibrillation was compensated by the increase in micro-tearing. Another reason could be that the digitizing step used for roughness measurement (41.6 μm) was not short enough to detect these features. Consequently, mean surface roughness did not change with the rake angle variation.

The variation in roughness due to sanding was also explained by one principal component. Thus, it represented adequately surface roughness of boards. A statistically significant double interaction was found between sanding program (or grit size) and feed speed (Table 1). As grit size decreased from 80-grit to 120-grit, along with the decrease of feed speed from 17 to 4 m/min, surface roughness decreased (Table 3). As expected, grit size had a significant impact on the smoothness of surface. Thus, sanding with lower grit size improves roughness of wood surfaces [15, 17]. Furthermore, lower feed speed means a longer dwelling time on the same spot during machining. This condition could remove some of the spring-back that

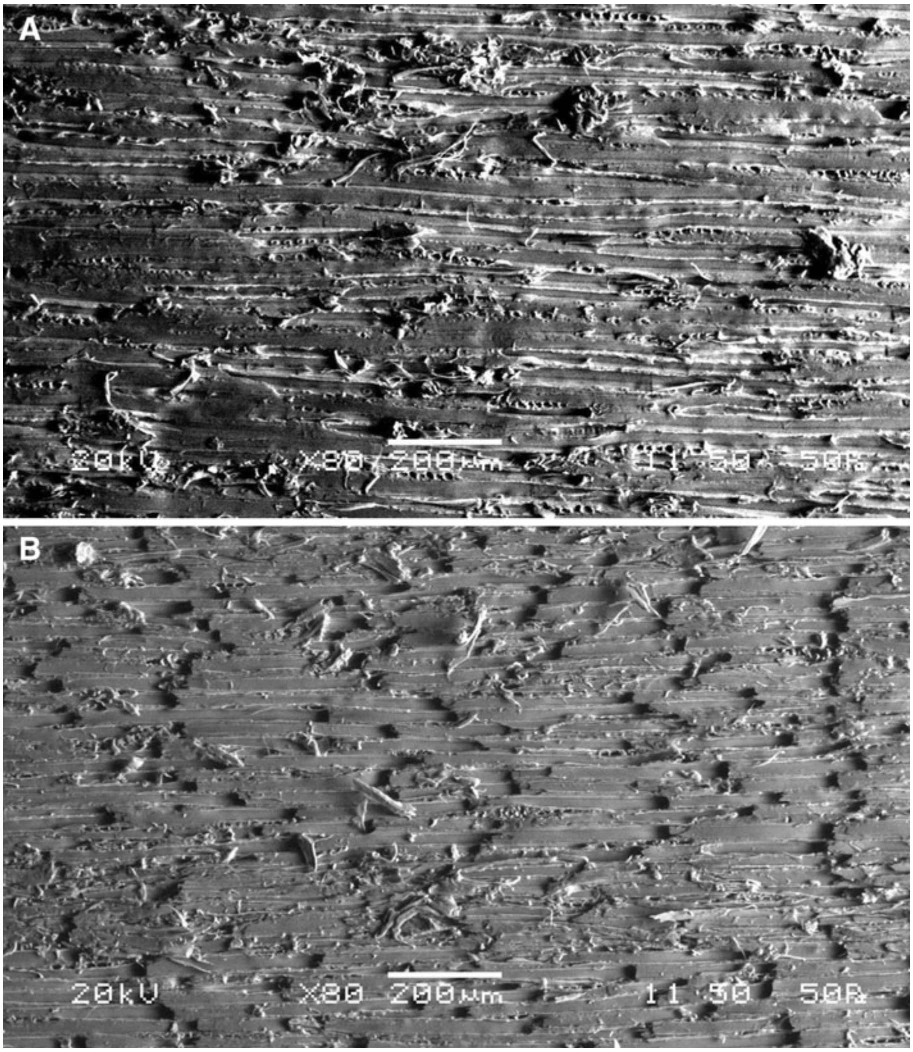

Fig. 3 Tangential ESEM micrograph of a black spruce wood sample planed with a rake angle of 15° and a wavelength of 1.5 mm (**a**) and a rake angle of 30° and a wavelength of 3.1 mm (**b**)

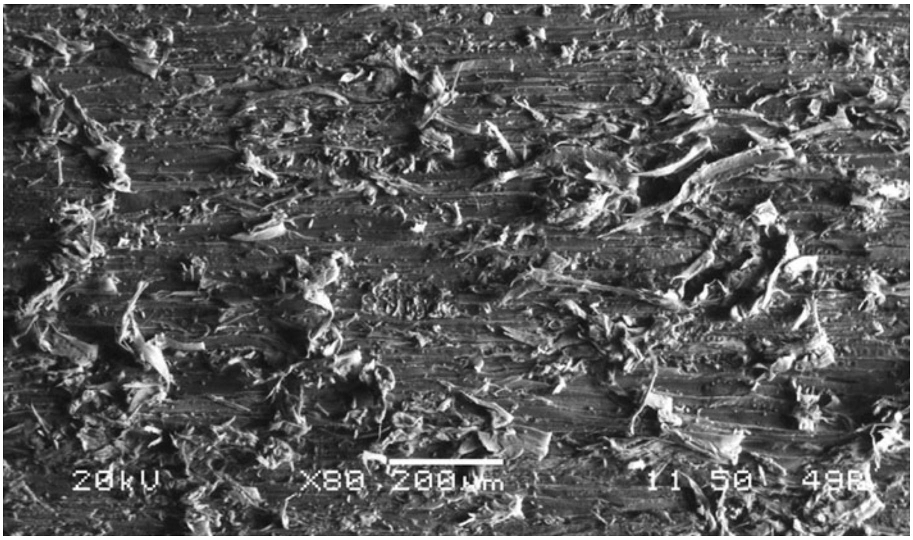

Fig. 4 Tangential ESEM micrograph of a black spruce wood sample sanded with a three-stage sanding program

occurs in softwoods under high loads and contributes to improve wood surface quality. Consequently, the surface roughness decreases when machining with lower feed speeds. Similar effects were reported by Carrano et al. [16]. The combined effect of the sanding program (or grit size) and feed speed is shown in Table 4. Hence, a three-stage

Table 1 *F* value obtained from the ANOVA for peripheral straight-edge knife planing and sanding

Source of variation	Peripheral planing			Sanding		
	Roughness factor	Gluing shear strength	Percent wood failure	Roughness factor	Gluing shear strength	Percent wood failure
Feed speed (FS)	83.75*	16.71*	4.69*	143.9*	0.25	0.45
Rake angle (RA)	1.77	2.53	1.81	–	–	–
Grit size (GS)	–	–	–	646.9*	13.28*	7.21*
FS × RA	0.86	1.91	1	–	–	–
FS × GS	–	–	–	2.70*	0.15	2.03
Aging (AG)	–	760.17*	192.5*	–	211.4*	74.19*
FS × AG	–	4.04*	4.84*	–	2.85	0.03
RA × AG	–	4.95*	2.03	–	–	–
GS × AG	–	–	–	–	0.32	0.23
FS × RA × AG	–	0.96	1.68	–	–	–
FS × GS × AG	–	–	–	–	0.79	0.43

* Statistically significant at the 5 % probability level

Table 2 Mean surface roughness parameter (S_a) of black spruce prepared by peripheral straight-edge knife planing at four feed speeds

Wavelength (mm)	Feed speed (m/min)	S_a (μm)
1.5	7	6.9[a] (0.1)[b]A[c]
1.9	10	7.3 (0.1)B
3.1	16	7.8 (0.1)C
6.5	33	11.6 (0.5)D

[a] Mean of 120 replicates (four rake angles pooled)

[b] Standard error of the mean in parentheses

[c] Means followed by the same letter are not significantly different at 5 % probability level

Table 3 Mean surface roughness parameter (S_a) of black spruce prepared by sanding with three-stage programs and four three speeds

Sanding program	Feed speed (m/min)	S_a (μm)
80-grit	4	8.8[a] (0.2)[b]E[c]
	10.5	10.8 (0.2)G
	17	11.9 (0.2)H
80-100-grit	4	7.5 (0.1)D
	10.5	8.9 (0.1)EF
	17	9.3 (0.1)F
80-100-120-grit	4	5.4 (0.1)A
	10.5	6.4 (0.1)B
	17	6.8 (0.1)C

[a] Mean of 30 replicates

[b] Standard error of the mean in parentheses

[c] Means followed by the same letter are not significantly different at 5 % probability level

sanding program (80-100-120-grit size) combined with a feed speed of 4 m/min produced the best surface for sanded boards. In contrast, a single-stage sanding program (80-grit size) associated with a feed speed of 17 m/min increased surface roughness because it produced larger grooves on the surface.

The analysis of the topography showed that sanding with a three-stage program produced the best surface roughness (regardless of feed speed) compared with that of other sanding conditions and planed samples. These results are in agreement with Ritcher et al. [24], Hernández and Cool [23], and Cool and Hernández [21]. Sanding produces homogeneous surfaces and alters the cellular structure so that anatomical roughness is less distinguishable.

Glueline shear strength

For peripheral planing, the ANOVA showed that glueline shear strength and percent wood failure were affected by the interaction between feed speed and accelerated aging treatment. Table 4 shows that planing wood with wavelengths up to 1.9 mm produced surfaces with the best glueline shear strength for the unaged samples. Equally, planing with wavelengths up to 3.1 mm generated wood surfaces with similar glueline shear strength for the aged samples. However, glueline shear strength was significantly reduced when planing at 6.5 of wavelength for both conditions (unaged and aged samples). It is therefore demonstrated that glueline shear strength decreased with increasing feed speed for the unaged and aged specimens. Moreover, percent wood failure increased slightly as feed speed increased, especially for aged specimens (Table 4). During up-milling, as wavelength increases, direction of the resulting cutting forces will change from a pushing action to a pulling action [38]. This should increase surface roughness (as shown previously) and also produce more cellular damage, especially micro-ruptures formed between

Table 4 Mean glueline shear strength (SS) and percent wood failure (WF) of black spruce surfaces prepared by peripheral straight-edge planing using four wavelengths for samples without and with an aging treatment

Wavelength (mm)	Unaged samples		Aged samples		Adhesion loss	
	SS (MPa)	WF (%)	SS (MPa)	WF (%)	SS (%)	WF (%)
1.5	9.5[a] (0.1)[b]A[c]	53 (2)b	6.2 (0.2)D	35 (2)d	35	34
1.9	9.4 (0.1)A	59 (2)ab	6.4 (0.2)D	35 (2)d	32	41
3.1	9.1 (0.2)B	60 (2)a	6.0 (0.2)D	39 (2)d	34	34
6.5	8.0 (0.2)C	58 (3)ab	5.2 (0.2)E	46 (2)c	35	21

[a] Mean of 120 replicates (four rake angles pooled)

[b] Standard error of the mean in parentheses

[c] Means followed by the same letter are not significantly different at 5 % probability level. Uppercase letters are for SS comparison; lowercase letters are for WF comparison (in both cases for aged and unaged samples taken together)

Table 5 Mean glueline shear strength (SS) and percent wood failure (WF) of black spruce surfaces prepared by peripheral straight-edge planing using four rake angles for samples without and with an aging treatment

Rake angle (°)	Unaged samples		Aged samples		Adhesion loss	
	SS (MPa)	WF (%)	SS (MPa)	WF (%)	SS (%)	WF (%)
15	8.8[a] (0.2)[b]B[c]	55 (2)a	5.8 (0.2)C	36 (2)b	34	35
20	9.4 (0.1)A	59 (2)a	6.0 (0.1)C	36 (2)b	36	39
25	9.1 (0.1)B	58 (2)a	5.9 (0.2)C	41 (2)b	35	29
30	9.0 (0.2)B	58 (3)a	6.4 (0.2)C	41 (2)b	28	29

[a] Mean of 120 replicates (four wavelengths pooled)

[b] Standard error of the mean in parentheses

[c] Means followed by the same letter are not significantly different at 5 % probability level. Uppercase letters are for SS comparison; lowercase letters are for WF comparison (in both cases for aged and unaged samples taken together)

Table 6 Mean glueline shear strength (SS) and percent wood failure (WF) of black spruce surfaces prepared by sanding with three grit size programs

Sanding program	SS (MPa)	WF (%)
80-grit	9.1[a] (0.1)[b]A[c]	54 (2)A
80-100-grit	8.2 (0.2)B	47 (2)B
80-100-120-grit	8.2 (0.2)B	44 (2)B

[a] Mean of 90 replicates (three feed speeds pooled)

[b] Standard error of the mean in parentheses

[c] Means within a column followed by the same letter are not significantly different at 5 % probability level

and within cells. These micro-ruptures would develop deeper during the aging treatment, which could increase the percent wood failure.

Gluing shear strength was also significantly affected by the interaction between rake angle and aging treatment. However, *F* values showed that the effect of rake angle on gluing shear strength was lower than that observed for feed speed variation (Table 1). Mean values of glueline shear strength of surfaces prepared by peripheral planing using four rake angles are presented in Table 5. For unaged samples, planing with a rake angle of 20° produced wood surfaces with better glueline shear strength compared with that of other rake angles. This rake angle should correspond to the production of type II chips, associated with high quality surface and low subsurface damage. In contrast, after aging there were no significant differences between shear strength means. Furthermore, glueline shear strength decreased as a result of the aging treatment underwent by the wood specimens (mean loss of 34 % in shear strength).

For sanding experiments, the ANOVA (Table 1) showed simple statistically significant effects of grit size and aging treatment on glueline shear strength and percent wood failure. As grit size increased, shear strength and percent wood failure increased (Table 6). The 80-grit sandpaper produced wood surfaces with a glueline shear strength and percent wood failure greater than the other two sanding programs tested (80-100- and 80-100-120-grit stages). Feed speed did not affect the glueline performance of the sanded boards.

It appears that finer roughness produced higher shear strength for planed specimens. In contrast, greater fibrillation level corresponding to higher surface roughness seems to generate better glueline shear strength and higher percent wood failure for sanded specimens. However, the

Table 7 Mean glueline shear strength (SS) and percent wood failure (WF) of black spruce surfaces prepared by sanding using three grit size programs and three feed speeds for samples without and with an aging treatment

	Unaged samples	Aged samples	Adhesion loss (%)
SS (MPa)	9.5[a] (0.1)[b]A[c]	7.5 (0.1)B	22
WF (%)	54 (2)a	42 (2)b	22

[a] Mean of 270 replicates (three sanding programs and three feed speeds pooled)

[b] Standard error of the mean in parentheses

[c] Means within a row followed by the same letter are not significantly different at 5 % probability level

correlation analysis between the surface parameters and shear strength revealed some statistically significant but very low correlation coefficients. Similar results were reported by Cool and Hernández [21]. According to Follrich et al. [1], tensile strength of joints increased with increasing surface roughness. Their finding was attributed to the enlarged surface and hence the enhanced bonding area facilitating mechanical interlocking between the adhesive and the wood surface. In contrast, lower roughness would decrease the mechanical anchorage of the surface. The molecules of the adhesive could also be too large to penetrate into the wood by the pits, which are generally aspired when kiln drying this wood species. As a consequence, glue penetration will be lower and glueline more affected during the aging treatment. Therefore, a certain level of roughness would be desirable to improve bonding of black spruce surfaces with the adhesive studied. Thus, a grit size of 80 was the most suitable for producing wood surfaces with adequate glueline performance when sanding black spruce. Similar results were reported by Shida and Hiziroglu [2] for four Japanese wood species.

As mentioned previously, glueline shear strength and percent wood failure values of each machining processes were affected by the aging treatment. For peripheral planing, these factors decreased about 34 and 33 % after aging, respectively (adhesion loss in Tables 4, 5). For sanding, reduction in gluing performance due to weathering was lower (adhesion loss of 22 %, Table 7). Moisture saturation and subsequent drying cycles may have produced internal stresses related to swelling and shrinkage of wood. These stresses would reduce the gluing performance by breaking wood-glue bonds and by increasing the number of micro-ruptures. Similar effects of aging treatments have been reported elsewhere [3, 10, 19, 39].

Results revealed, for peripheral straight-edge knife planing, that a rake angle of 20° and wavelength of up to 1.9 mm produced wood surfaces with adequate glueline shear strength for samples without an aging treatment. After aging, wavelength could be increased up to 3.1 mm at any of the rake angles studied. For sanding, 80-grit sandpaper produced better glueline shear strength, regardless of feed speed. Weathering provoked a higher loss in adhesion for planed samples compared with those sanded. Therefore, sanding process seemed to produce better wood surfaces for bonding with the type of adhesive used (isocyanate).

Conclusions

Wood surfaces of black spruce obtained by sanding gave better gluing performance than those obtained by peripheral straight-edge knife planing. This behavior was observed using an isocyanate adhesive and was more noticeable after an accelerated aging treatment. This result was unexpected as sanding is currently not used in the fabrication process of glued structural members. The level of fibrillation induced during sanding increases the actual surface available for mechanical anchorage. It was also demonstrated that using faster feed speeds, similar to those used in the industry, resulted in significant higher shear strengths. This demonstrates the relevance of reproducing industrial conditions in research. It was also shown that greater surface roughness produced better glueline shear strength, which was consistent with previous works.

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