EVALUATION OF FOUR SURFACING METHODS ON BLACK SPRUCE WOOD IN RELATION TO POLY(VINYL ACETATE) GLUING PERFORMANCE

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Abstract. Oblique cutting, peripheral planing, face milling, and sanding were used to surface black spruce wood prior to gluing with a two-component poly(vinyl acetate) adhesive. Surface roughness, anatomical features of surfaces, and glueline interfaces as well as the glueline shear strength before and after aging were evaluated. Oblique-cut surfaces presented no subsurface damage, little fibrillation, low roughness, thin gluelines, and little adhesive penetration. Peripheral-planed and face-milled surfaces both showed slight cell deformation and a higher level of fibrillation. The large number of cell lumens available and the fibrillation appeared to favor the penetration of adhesive as well as to increase surface roughness. Sanded surfaces were the smoothest, and their anatomical structures were the least visible of the four machining processes. These samples also showed more important subsurface damage, which limited the penetration of adhesive. For the glueline shear strength before and after weathering, no significant differences occurred among the surfacing treatments. The microscopic and topographic differences among the surfacing treatments were not sufficient to generate significant differences in glueline shear strength. Peripheral planing and face milling should be better alternatives with respect to productivity.

Keywords: Sanding, oblique cutting, peripheral planing, face milling, roughness, environmental scanning electron microscopy, poly(vinyl acetate), black spruce wood.

INTRODUCTION AND BACKGROUND

Black spruce (*Picea mariana* [Mill.] B.S.P.) is one of the most important boreal tree species in Canada. Its properties and abundance make it a valuable resource for wood industries. The wood is widely used in the pulp and paper industry and in construction applications such as lumber and glued structural members. However, little information is available on its machining properties. This species has been included only in a general study on machining Canadian woods (Lihra and Ganev 1999). Based on ASTM D 1666 (ASTM 2004), cutting parameters for planing this wood were suggested for a conventional peripheral process. However, compared with other wood species, it is difficult to produce defect-free surfaces when planing black spruce. Numerous knots and grain deviation result in torn grain, whereas differences in density among earlywood and latewood cause raised grain. Therefore, more research is needed to produce satisfactory surfaces.

Crushed cells and checks on the surface and in the subsurface are often produced during conventional planing (Stewart and Crist 1982). This damage could hinder varnish penetration in sugar maple wood (de Moura and Hernández 2005). However, Hernández and Naderi (2001)

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suggested that permeability of heterogeneous woods such as red oak and white spruce could be increased by the compression force induced during cutting. As a result, gluing strength was enhanced. Alternative surfacing techniques such as oblique cutting and face milling should also be considered.

Oblique cutting differs from orthogonal cutting by the inclination given to the cutting edge with respect to its direction of movement (Koch 1985). The oblique angle induces important changes in tool geometry, cutting forces, and surface quality (Ozaki and Fukui 1982, 1985; Ozaki and Kimura 1989; Stewart 1989; Jin and Cai 1996, 1997; de Moura and Hernández 2007). As the oblique angle increases, the actual rake angle increases and the clearance and knife angles decrease (Ozaki and Kimura 1989; Jin and Cai 1996, 1997). Furthermore, as cutting occurs more obliquely, the knife edge radius decreases, enhancing tool sharpness (Jin and Cai 1997). In general, this process produces surfaces virtually free of damage, although slight crushing occasionally occurs on the most outward cell layers (de Moura and Hernández 2007). The relatively sound superficial tissues of oblique-cut samples should enhance their long-term performance (de Moura et al 2010).

Face milling is the result of a combined action of cutting edges located at the periphery and face of a cutter, resulting in a flat surface perpendicular to the cutter axis (Stewart 1974). Cutting forces in face milling decrease as rake angle increases and as cutting depth decreases (Stewart 1983). This process generates low cutting forces that should normally produce surfaces of good quality. Even so, Hernández and Cool (2008a) reported that cutting depth had no significant effect on surface roughness. Moreover, face milling typically occurs across the grain and produces a suitable level of fibrillation at the surface (Hernández and Cool 2008a, 2008b; de Moura et al 2010). This fibrillation increases the actual surface available for mechanical anchorage of adhesives, possibly improving their adhesion.

Sanding is one of the most skill-based, time-consuming, and expensive operations in the wood industry (Taylor et al 1999) and is also a health hazard (d'Errico et al 2009). The process produces defect-free uniform surfaces (Richter et al 1995). However, sanded surfaces are also characterized by a layer of crushed cells at the surface and in the subsurface, lumens often clogged by fine dust, scratches, and packets of microfibrils torn out from cell walls (Murmanis et al 1983, 1986; de Moura and Hernández 2006). Crushing and clogging of cells hindered penetration (de Meijer et al 1998), whereas fibrillation and scratches accelerated spreading of liquid coatings on sanded surfaces of sugar maple (de Moura and Hernández 2005).

The measurement of surface roughness is influenced by wood anatomy. Hence, roughness in wood is often considered as the sum of two distinct components. The first is related to its anatomical features such as intact cell lumens and the second to the effect of the machining process. Gurau et al (2005) suggested that the anatomical component should not be included when studying the effect of different machining processes on surface roughness. However, the total surface roughness has to be used for the evaluation of surface quality for subsequent processing steps such as finishing. Fujiwara et al (2005) suggested using the reduced valley depth (S_{VK}) parameter to evaluate the impact of anatomical features on surface roughness.

This work evaluated the effect of peripheral planing, oblique cutting, face milling, and sanding on the surface quality and poly(vinyl acetate) (PVA) gluing performance of black spruce wood samples. Different surface roughness parameters were evaluated to predict the long-term loss in adhesion of glued members.

MATERIALS AND METHODS

Testing Materials

Black spruce wood was selected for this study. Eighty kiln-dried flat-sawn boards 700 mm (L) long were stored in a conditioning room at 20°C and 40% RH until they reached 8% EMC.

After conditioning, all boards were machined to 52 mm (T) wide and 22 mm (R) thick. A section 25 mm long was crosscut from each specimen to measure the average (523 kg/m^3) and standard deviation (45 kg/m^3) of density ($m_{8\%\ EMC}/V_{8\%\ EMC}$). The specimens were divided into four groups, each having an average density of 523 kg/m^3. Subsequently, each group underwent a surfacing treatment. After surfacing, pieces were again crosscut to obtain specimens for roughness (25 mm L), microscopy (25 mm L), and gluing (2 × 305 mm L). After gluing, three matched shear blocks were machined according to ASTM D905 (ASTM 2003). Two of the blocks underwent either a light or severe accelerated aging treatment before undergoing shear tests. The third block did not undergo aging treatment.

Machining Treatments

Four machining processes were used to prepare the specimens for gluing. Oblique cutting was performed with a Marunaka Super Meca (Marunaka Tekkosho, Inc., Shizuoka City, Japan) at 65 m/min feed speed and 0.02-mm cutting depth. The freshly sharpened high-speed steel knife had a 32° knife angle and 58° rake angle. The oblique angle was 60°, which generated an effective rake angle of 74° (according to Ozaki and Kimura 1989). Peripheral planing was done with a Weinig Powermat 1000 molder (Tauberbischofsheim, Germany) equipped with a cutterhead that had 53-mm cutting radius. The rotation speed of the cutterhead was 6000 rpm, and the feed speed was 10 m/min, which produced six knife marks per 10 mm of length. The cutting depth was 0.5 mm, and the rake and knife angles were 12° and 40°, respectively. Face milling was carried out with an Ogden Rotoplane 16T (Ogden Enterprises, Inc., Matthews, NC) provided with a cutter-disk holding 34 new insert carbide knives with an angle of 60°. The positive axial rake angle and radial rake angle (according to Stewart 1974) were 15° and 13°, respectively. Feed speed was 10 m/min, which produced 107 knife marks per 10 mm of length, and cutting depth was 0.5 mm. The samples were fed through the centerline of the cutter disk and thus planed nearly to the 13-90° direction. Sanding was performed with a Costa sander (Costa and Grissom Machinery Co., Inc., Archdale, NC) with an 80-grit aluminum oxide sanding belt installed on a drum working with a 0.5-mm removal depth. Sander feeding was carried out in the fiber direction at 10-m/min feed speed. Oscillating blowers performed cooling and cleaning of the belt during sanding.

Microscopic Evaluation

Ten-millimeter cubes were used to observe tangential and end-grain surfaces. Tangential surfaces were used to evaluate the level of fibrillation and the openness of cells, principally lumens. End-grain surfaces without adhesive were used to analyze cell damage, and those with adhesive were used to evaluate adhesive penetration. The end-grain surfaces were prepared by carefully cutting with a razor blade mounted on a microtome. All cubes were desiccated with phosphorous pentoxide (P_2O_5) for 1 wk and mounted onto standard aluminum stubs with silver paint. Environmental scanning electron microscopy micrographs were taken for two representative machined samples for each machining treatment.

Other sections of the glued samples were prepared by carefully cutting one of the end-grain surfaces with a razor blade mounted on a microtome. The surfaces were observed with a binocular microscope to evaluate the mean glueline thickness across the width of each glued sample (50 mm T).

Surface Topography Measurements

Roughness measurements were carried out on defect-free zones with a Micromeasure confocal microscope (Stil, Aix en Provence, France) equipped with a 3-mm optical pen fixed at 26.9 mm from the surface. The precision of the pen was 0.4 μm. A surface of 15 mm (L) × 10 mm (T) was analyzed for each sample at 20°C. The data were collected with Surface Map 2.4.13 software using an acquisition frequency of

300 Hz and a scanning speed of 12.5 mm/s. Three-dimensional roughness parameters were determined with Mountain software. A cut-off length of 2.5 mm combined with a Robust Gaussian filter (ISO 2002) was used for calculations. The arithmetical mean deviation of the profile (S_A), root mean square deviation of the profile (S_Q), maximum profile peak height (S_P), and maximum profile valley depth (S_V) were calculated according to ISO 4287 (ISO 1998). The core roughness depth (S_K), reduced peak height (S_{PK}), and reduced valley depth (S_{VK}) were calculated from the Abbot curve according to ISO 13565-2 (ISO 1996).

Gluing Procedure

The machined surfaces were glued within 12 h after the machining treatments, during which time the samples were placed face to face to keep contamination at a minimum. A Type I two-component PVA adhesive (Henkel-Durolok 42.2150) was applied at 300 g/m^2 at room temperature and cold-pressed at 30 kPa for 2 h according to the manufacturer's specifications.

Accelerated Aging

The first set of specimens underwent an accelerated aging treatment, which was adopted from ASTM D3434 (ASTM 2000). A cycle consists of three steps: immersing the specimens for 10 min in boiling water, cooling for 4 min at 23°C, and drying for 57 min at 107°C in an oven. During the first day, the samples were submitted to four cycles and a fifth 10-min immersion in boiling water. Samples were then stored overnight in a conditioning room at 20°C and 40% RH. The following day, the samples were submitted to two more cycles and an eighth 10-min immersion in boiling water. Afterward, specimens were stored in a conditioning room at 20°C and 40% RH until they reached their initial equilibrium moisture content (8%).

A second set of specimens underwent a more severe accelerated aging treatment. The first day, the previously described procedure was used. The second day, the samples were submitted to six cycles, a 10-min immersion in boiling water, and then overnight in a conditioning room at 20°C and 40% RH. The following day, the specimens underwent two more cycles and a fifteenth 10-min immersion in boiling water. Afterward, specimens were stored in a conditioning room at 20°C and 40% RH until they had reached their initial equilibrium moisture content (8%).

Glueline Mechanical Tests

Specimens were evaluated according to ASTM D905 (ASTM 2003) with an RT50 universal testing machine (MTS, Eden Prairie, MN) fitted with a glue shear test fixture and having a maximum capacity of 50 kN and ± 0.18% precision. Load was applied at 5 mm/min until separation of the substrates. Cross-sections of the specimens and load at failure were recorded, and the average glue shear stress was calculated. The fractured surfaces were also evaluated to determine the percentage wood failure (WF), which gives information on bond formation. Low WF indicates that the bond is weaker than the wood, whereas high WF is associated with a bond that is stronger than the wood (Marra 1992). The WF was evaluated through image treatment with Adobe Photoshop CS4 (Adobe Systems, Inc., San Jose, CA). Every specimen was photographed, and the contrast between the adhesive and the wood was amplified for each image. The colors of the adhesive and wood were then modified to black and white, respectively. The WF was easily obtained by counting pixels.

Statistical Analyses

The data followed a randomized block design. Results of the surface topography measurements and mechanical tests were analyzed with a mixed procedure as repeated measures. Simple correlations were calculated among surface roughness, shear strength, and percentage WF using the CORR procedure within the data of each surfacing treatment. Mean difference comparison tests were performed at a 5% probability level when required. The analysis was done on SAS® statistical package, Version 9.2 (SAS 2007).

RESULTS AND DISCUSSION

Microscopy

End-grain surfaces. Oblique-cut samples were virtually free of cell damage (Figs 1a and 2a). Adhesive occasionally penetrated up to the second layer of tracheids when their lumens were open (Fig 2a). The glueline in these specimens was 65 μm thick (Table 1). Conventional-planed specimens showed superficial

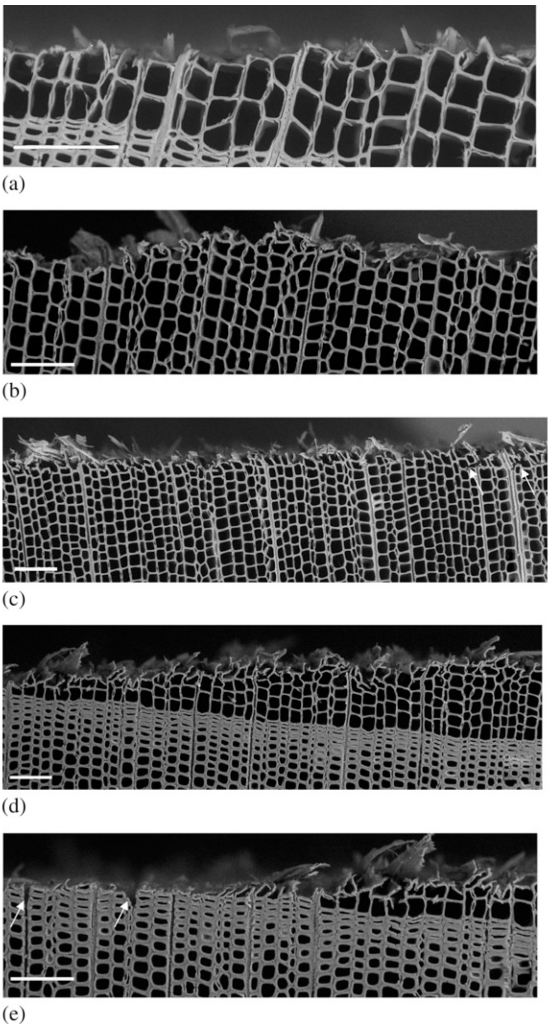

Figure 1. Transverse environmental scanning electron microscopy micrographs of black spruce wood surfaces that were oblique-cut (a), conventional-planed (b), face-milled (c), and sanded (d-e). Arrows show microruptures in face-milled and sanded samples. Scale bars = 100 μm.

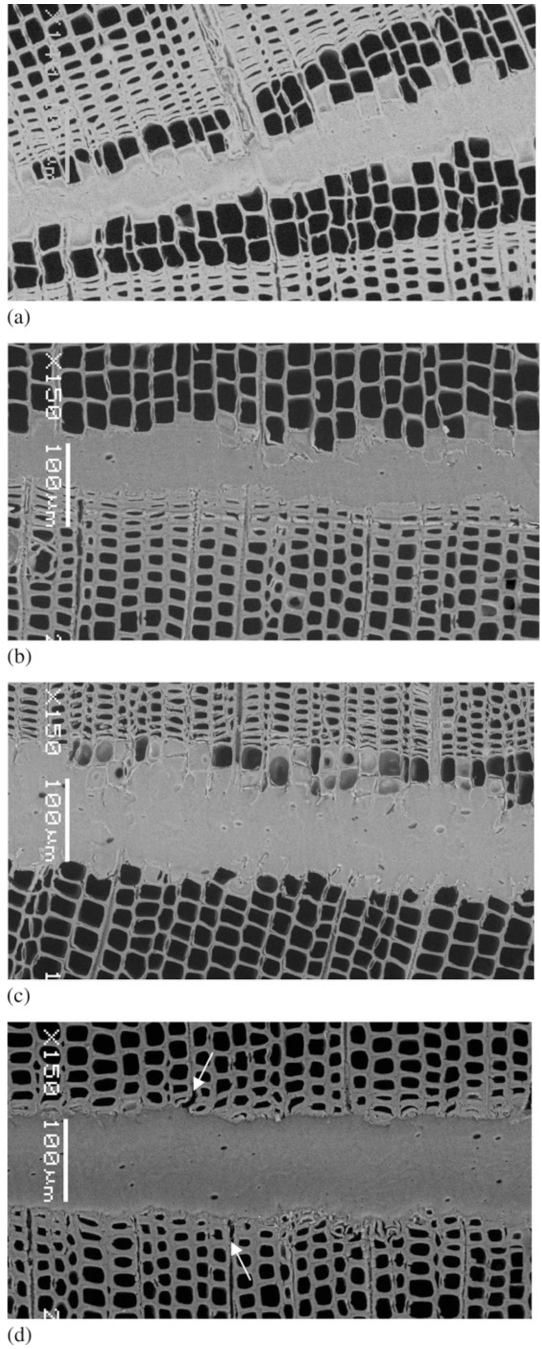

Figure 2. Transverse environmental scanning electron microscopy micrographs of glued black spruce wood surfaces that were oblique-cut (a), conventional-planed (b), face-milled (c), and sanded (d). Arrows show microruptures in latewood of sanded samples, which are unfilled by the adhesive.

Table 1. Glueline thickness of glued black spruce wood specimens prepared with four machining processes and glued with poly(vinyl acetate).

Machining treatment	Glueline thickness (μm)	
Oblique cutting	65[a,b] (6[c])	A
Peripheral planing	81 (6)	AB
Face milling	87 (8)	B
Sanding 80-grit	110 (8)	C

[a] Mean of 20 replicates.
[b] Means within a column followed by the same letter are not significantly different at the 5% probability level.
[c] Standard error of the mean in parentheses.

subsurface damage that occasionally extended down into the first two layers of cells (Fig 1b). The cell walls were lightly deformed and crushed. However, certain zones were sound, similar to those observed in the oblique-cut samples (Fig 1a-b). The mean glueline thickness in planed specimens was 81 μm (Table 1) and was statistically similar to that observed for the oblique-cut samples. Adhesive penetration in earlywood was about two cells deep and appeared to fill the microruptures to this depth. Cell damage in latewood was less than in earlywood and was characterized by slight cell deformation and failures in the middle lamella. The greater strength of the latewood, compared with that of the earlywood, decreased the extent of subsurface damage below the cutting plane. Furthermore, adhesive penetration in latewood was less than in earlywood (Fig 2b). Conversely, face-milled samples showed light damage in the first two layers of cells in earlywood (Fig 1c). Cells deformed along the cutting direction of the knives. Latewood cells were not permanently deformed, and their damage was characterized by microruptures in the middle lamella (not shown). As for the samples prepared by peripheral planing, the higher density of the latewood decreased the extent of damage below the cutting plane compared with earlywood. The mean glueline thickness (including filled lumens) in face-milled samples was 87 μm (Table 1). Adhesive filled up to the first three to four cell layers in the earlywood (Fig 2c). In contrast, a certain level of damage was left unfilled in the latewood because of less penetration. This indicates that when using conventional planing and face milling, minor subsurface damage such as microruptures appears to facilitate the penetration of PVA glue.

Among the four machining processes, sanding produced the most cell damage. Ruptures and cell deformation affected the first three layers of cells in earlywood ($\approx$100 μm) (Figs 1d-e and 2d). Latewood cells were also damaged but to a lesser degree. In the sanded samples, deeper ruptures were present in the rays and the middle lamella of tracheids (Fig 1e). Gluelines of the sanded samples were significantly thicker than for the other machined samples (Table 1). Adhesive remained in the first layer of cells, and the damaged layer was still visible. In contrast to the planed samples, the subsurface damage in the sanded samples did not facilitate adhesive penetration. Thus, the unfilled ruptures in sanded samples could decrease the shear strength after weathering.

Tangential surfaces. For the oblique-cut samples, the presence of grain deviation caused a light level of fibrillation (Fig 3a), which was not previously observed by de Moura et al (2010). Hence, this machining treatment appears sensitive to grain deviation for this species. Even so, the surfaces obtained were still the smoothest (visually and microscopically) of all surfacing treatments studied. The fibrillation, characterized by partial detachment of tracheids and little crushing, was less than that of other machined surfaces. Pits and even rays were visible on the surfaces, and lumens were free of debris and dust because not much was generated during the process. This should have facilitated adhesive penetration, but unexpectedly, this machining treatment, along with sanding, proved to have the lowest adhesive penetration. Squeeze-out of the adhesive could have been promoted by the smoothness of the surface and lack of debris.

Surfaces prepared by peripheral planing were characterized by open tracheid lumens as well as undamaged rays, which were accessible for adhesive penetration (Fig 3b). As for oblique

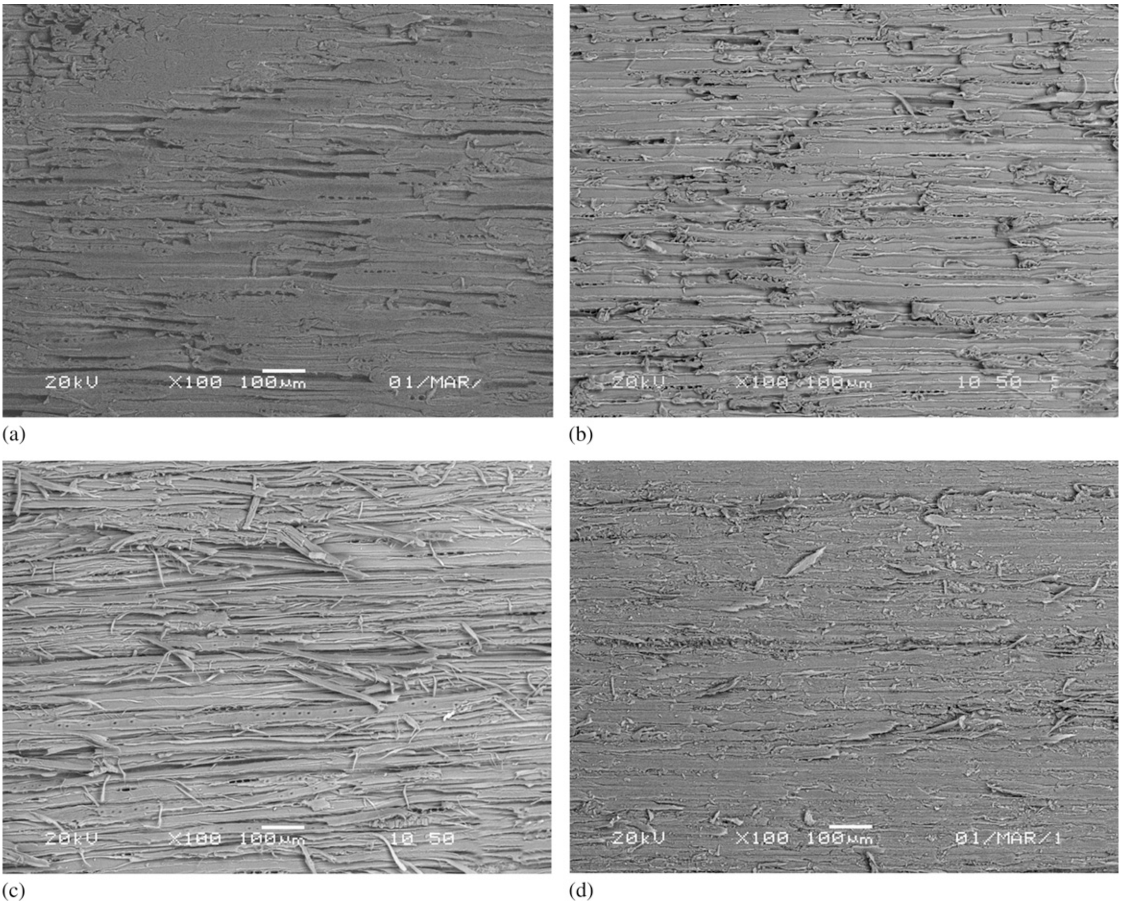

Figure 3. Tangential environmental scanning electron microscopy micrographs of black spruce wood surfaces that were oblique-cut (a), conventional-planed (b), face-milled (c), and sanded (d).

cutting, peripheral planing seemed sensitive to grain deviation, resulting in clusters of fibrillation. Located in the lumens, the debris looked more or less attached to the surface and could decrease adhesive spreading. The penetration, however, was not decreased by the level of fibrillation but instead was promoted by the open rays and tracheids. Lumens of the face-milled surfaces were also exposed by the machining process (Fig 3c). Moreover, the level of fibrillation was more important than that generated by the other planing processes. In certain areas, cells were torn and the fibrillation corresponded to portions of cell walls. The thin cell walls in earlywood were easy to tear from the surface. Conversely, the latewood areas had a lower level of fibrillation than earlywood areas and the fibrils seemed to be better attached to the surface and resembled what was reported for sugar maple and paper birch wood (Hernández and Cool 2008a, 2008b; de Moura et al 2010). Although gluelines in samples prepared by peripheral planing and face milling were thick, adhesive penetrated more in those treatments than for oblique-cut specimens. This suggests that a combination of open lumens and fibrillation is desirable to promote adhesive penetration and diminish squeeze-out.

Sanded surfaces presented a light level of fibrillation (Fig 3d) and did not show open lumens. These cavities were often filled with dust, which decreased adhesive penetration. Frihart (2005) reported that PVA adhesives showed good flow into exposed cell lumens but their high molecular weight prevented cell wall penetration. Additionally, the pits of black spruce wood are usually aspirated during kiln drying, which further limits adhesive penetration. Compared with sanding, planed samples had a thinner glueline. Open tracheid and ray lumens favored adhesive penetration in the wood prepared with peripheral planing and face milling, whereas debris as well as fibrillation decreased squeeze-out.

Surface Topography

No major defects such as torn grain or fuzzy grain were noted on the oblique-cut, face-milled, or sanded surfaces. Only the peripheral planing caused light torn grain. The three planing processes generated surfaces with greater roughness parameters than the sanded surfaces (Table 2).

The mean surface roughness parameters (S_A and S_Q) and S_K, which is related to the machining process (Fujiwara et al 2005; Gurau et al 2005), were generally higher for the face-milled and conventional-planed surfaces. Face milling produced a high level of fibrillation in which packets of microfibrils or portions of cell walls were partially torn from the surfaces (Fig 3c). In face milling, knives attack the wood perpendicular to the grain. Cutting forces are lower when machining across the grain (0-90°) than when planing along the grain (90-0°) (Stewart 1975; Stewart and Parks 1980), but face milling increases the level of fibrillation. The open tracheid lumens were also clearly visible (Fig 3c) and further increased the surface roughness. Means of S_A, S_Q, and S_K of the peripheral-planed samples were statistically similar to those of the face-milled samples because of the amount of open tracheid lumens and the level of fibrillation (Fig 3b). In contrast, surfaces prepared by the oblique cutting process were smoother (Fig 3a); fewer lumens were open and a lower level of fibrillation was observed. Conversely, sanded surfaces presented a certain level of fibrillation without open lumens (Fig 3d). As reported by Richter et al (1995) and Hernández and Cool (2008b), sanding produces homogeneous surfaces and alters the cellular structure in such a way that no anatomical roughness is detectable. This resulted in the lowest mean surface roughness measured for the black spruce wood samples.

Some authors use the S_{PK} factor to study sanded surfaces because it is related to fuzzy grain (Fujiwara et al 2005; Gurau et al 2005; Khazaeian 2006). In this study, none of the samples presented that defect visually, although they were all characterized by a certain degree of fuzziness at the microscopic level (Fig 3). According to values presented in Table 2, the three types of planed surfaces were defined by a higher level of fibrillation than the sanded ones. As mentioned previously, the sanded surfaces were more uniform because of the combination of cellular damage and dust filling the lumens.

Table 2. Three-dimensional surface roughness parameters (μm) of black spruce wood specimens prepared with four machining processes.

Machining treatment	S_A		S_Q		S_K		S_P		S_V		S_{PK}		S_{VK}	
Oblique cutting	6.3[a,b] (0.4)[c]	B	8.4 (0.5)	B	17.9 (1.1)	B	29.0 (1.7)	B	42.2 (2.3)	B	6.6 (0.3)	B	12.7 (0.7)	B
Peripheral planing	8.2 (0.3)	C	10.5 (0.4)	C	24.5 (1.0)	C	32.2 (1.0)	B	46.0 (1.9)	B	7.6 (0.3)	C	13.6 (0.7)	B
Face milling	8.0 (0.4)	C	10.9 (0.4)	C	22.1 (1.1)	C	30.6 (1.0)	B	56.3 (1.7)	C	6.3 (0.3)	B	17.2 (0.6)	C
Sanding 80-grit	3.6 (0.1)	A	4.7 (0.2)	A	11.0 (0.3)	A	19.7 (0.8)	A	22.7 (1.1)	A	3.7 (0.1)	A	5.8 (0.4)	A

[a] Mean of 20 replicates.

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

[c] Standard error of the mean in parentheses.

S_A, arithmetical mean deviation of the profile; S_Q, root mean square deviation of the profile; S_K, core roughness depth; SP_p, maximum profile peak height; S_V, maximum profile valley depth; S_{PK}, reduced peak height; S_{VK}, reduced valley depth.

Conversely, tracheid lumens were easily seen on the planed surfaces. This could have amplified the peaks and the value of S_{PK} by lowering the mean line of the profile. It is therefore suggested that the S_{PK} factor be used to compare surfaces coming from only one machining process; that is, surfaces having similar features.

The parameter S_{VK}, which is related to anatomical features (Fujiwara et al 2005), suggests that lumens should be more visible for the three planing processes compared with the sanded (Table 2). The clogged cells contributed to the uniformity of the sanded surfaces and lowered the value of S_{VK}. For samples prepared by oblique cutting and conventional planing, S_{VK} mean values were statistically similar (Table 2). The resemblance between both surfaces was obvious (Fig 3a-b). Lumens were partially visible, and surfaces were characterized by plateau-like regions. The oblique-cut process took place by cell detachment in, or close to, the middle lamella, which implies that the lumens were not very exposed (de Moura et al 2010). For the face-milled specimens, Fig 3c clearly illustrates the difference compared with the other machining processes. Most lumens are exposed, and the level of fibrillation is the most important. This certainly contributed to a significant increase in the S_{VK} parameter by raising the mean line of the profile.

Adhesion Tests

Means of the glueline shear strength were statistically similar for the four machining treatments before the specimens were submitted to the aging treatments (Table 3). The initial WF indicated that failure occurred mainly in the wood (mean of 84%; Table 3), which shows that the gluing procedure was carried out efficiently and that this species is relatively easy to glue. However, the aging treatments had a significant effect on the shear strength and WF of glued samples machined by the four processes. Although the first aging caused a significant 25% loss in both shear strength and WF, the machining treatments generated surfaces yielding similar behaviors (Table 3). The aging treatment had a significant impact on the glue joints but was not sufficient to generate differences among the four machining treatments. After aging, the failure was still mainly located in the wood (mean of 63%).

The more aggressive aging treatment decreased shear strength of oblique-cut specimens by 38% compared with initial measurements. After this aging treatment, the oblique-cut samples had significantly lower shear strength than face-milled specimens. The samples prepared by face-milling, peripheral planing, and sanding were all characterized by the presence of microruptures (Figs 1 and 2). These microruptures could act as discontinuities during the swelling–shrinkage cycles of cell walls caused by weathering. Adhesive penetration and the level of fibrillation could also have decreased the impact of the weathering treatment in face-milled samples (23% loss in adhesion). Face-milled samples showed the deepest adhesive penetration as well as important fibrillation (Figs 2c and 3c). Adhesive penetration and fibrillation both increased the contact surface between the adhesive and cell walls, thus enhancing the mechanical anchorage and the resulting adhesion.

Table 3. Glueline shear strength (S) and percentage wood failure (WF) of black spruce wood prepared with four machining processes and glued with poly(vinyl acetate).

	Before aging				After aging treatment #1 (total of 6 cycles)				After aging treatment #2 (total of 13 cycles)			
Machining treatment	S (MPa)		WF (%)		S (MPa)		WF (%)		S (MPa)		WF (%)	
Oblique cutting	11.6[a,b] (0.4)[c]	A	84 (2)	A	8.5 (0.4)	A	62 (3)	A	7.2 (0.5)	B	44 (2)	B
Peripheral planing	11.6 (0.3)	A	86 (2)	A	8.9 (0.2)	A	63 (3)	A	8.0 (0.5)	AB	45 (2)	B
Face milling	11.0 (0.3)	A	81 (3)	A	8.3 (0.4)	A	61 (3)	A	8.5 (0.5)	A	49 (3)	AB
Sanding 80-grit	10.9 (0.4)	A	85 (3)	A	8.5 (0.3)	A	67 (2)	A	8.0 (0.5)	AB	52 (2)	A

[a] Mean of 20 replicates.
[b] Means within a column followed by the same letter are not significantly different at the 5% probability level.
[c] Standard error of the mean in parentheses.

Although adhesive penetration and fibrillation were lower for the peripheral-planed and sanded than the face-milled samples, the losses in adhesion during the weathering treatment were slightly higher (31 and 27%, respectively). In contrast, the oblique-cut specimens were characterized by the absence of microruptures, low adhesive penetration as well as little fibrillation (Figs 1a, 2a, and 3a). The low mechanical anchorage of adhesive on the surface of oblique-cut specimens combined with the natural shrinkage–swelling movements of cell walls had a greater impact on the shear strength during weathering (38% loss in adhesion) compared with other treatments.

As for shear strength, WF was further decreased with the second aging treatment by another 25%. Thus, chemical links within the adhesive could have been broken with the number of weathering cycles. It is known that the catalyst used in the two-component PVA adhesive allows a certain degree of crosslinking, which increases its resistance to moisture and temperature compared with regular PVA (Frihart 2005). Even with this crosslinker present, this adhesive will soften when exposed to moisture. The oblique-cut and peripheral-planed specimens had a significantly greater decrease in WF (about 47%) than sanded and face-milled samples (about 39%) (Table 3). The increased fibrillation and quantity of microruptures may have limited the extent of the weathering effect in the sanded and face-milled samples.

The analysis shows that all four machining treatments yielded quite similar results in terms of gluing performance before weathering. Weathering caused a slightly higher loss in adhesion for the samples machined by oblique cutting compared with those face-milled. However, oblique-cut samples behaved similarly to peripheral-planed and sanded samples in terms of shear strength and were statistically equal to the peripheral-planed and face-milled samples in terms of WF (Table 3). Therefore, differences among them can be considered negligible. These minor differences among the machining treatments indicate that black spruce wood was easily glued with PVA. Considering the shear and WF values, the analysis shows that the four machining processes yielded surfaces with similar gluing behavior. The quality of all surfaces was satisfactory, and the microscopic and topographic differences observed among the machining treatments were not sufficient to generate significant differences in terms of glueline shear strength.

CONCLUSIONS AND RECOMMENDATIONS

The analysis showed that a higher level of fibrillation of black spruce wood surfaces appeared to decrease adhesive squeeze-out and that open lumens and rays promoted adhesive anchoring in the surfaces. Both peripheral-planed and face-milled samples had those features and showed better adhesive penetration as well as moderate adhesive thickness compared with oblique-cut and sanded samples. The surface roughness parameters S_A, S_Q, and S_K were related to the machining process as well as to the anatomical features of wood. The parameters S_V and S_P both gave more information on how cutting tools interact with the wood. The functional parameters S_{PK} and S_{VK} could be used to compare surfaces defined by similar features or prepared by the same machining process. Means of shear strength and percentage WF were statistically similar for surfaces prepared by the four machining treatments before the samples were aged. Although weathering had a significant negative effect on glued samples, all four machining treatments had similar strength and percentage WF after weathering. Considering productivity, peripheral planing and face milling should be better alternatives. To select the best machining process, future research should also take into account wear phenomena of cutting tools.

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