IMPACT OF THREE ALTERNATIVE SURFACING PROCESSES ON WEATHERING PERFORMANCE OF AN EXTERIOR WATER-BASED COATING

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Abstract. Oblique cutting, face milling, and helical planing were used to surface black spruce wood before application of an exterior acrylic water-based coating. Surface characteristics were assessed using an environment scanning electron microscope, and coating performance was evaluated with pull-off measurements before and after a 3-yr natural weathering exposure. Microscopically, oblique-cut surfaces were smooth with plateau-like areas, had a low level of fibrillation and few open lumens. Face-milled surfaces were characterized by a high level of fibrillation and numerous open lumens that favored coating spreading and penetration. Helical-planed specimens had an intermediate level of fibrillation and a number of open lumens. After coating application, oblique-cut and helical-planed surfaces presented similar overall visual quality, whereas face-milled samples had an irregular appearance that degraded their quality. As a result, the latter were subjected to erosion during weathering exposure, which further degraded their overall quality as well as pull-off strength. More specifically, face-milled samples had a significantly inferior pull-off strength both before and after weathering. Oblique-cut specimens yielded greater initial pull-off strength, but were associated with greater adhesion loss. According to the results, helical planing decreased adhesion loss of the coating studied during a 3-yr exposure, which yielded a superior pull-off strength after weathering. Therefore, surfaces with a certain level of fibrillation still firmly attached to the surface and open lumens were desirable to increase mechanical anchorage of coating on black spruce wood surfaces.

Keywords: Black spruce wood, oblique cutting, face milling, helical planing, water-based coating, adhesion, weathering.

INTRODUCTION

For lumber manufacturers, producing exterior wood siding has been an interesting business strategy to add value to wood. However, the use of wood in this type of application decreased by 39% between 1978 and 1998 because users feel that wood-based products lack in durability (Damery and Fisette 2001). Such a perception is reinforced by the fact that wood requires periodic maintenance compared with plastic-based

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products, stucco, stones, or bricks. As a result, exterior wood siding manufacturers are offering product warranties of 50 yr against wood decay and up to 15 yr on two-coat solid stains. To maximize durability, machining process cutting parameters have to be optimized for specific surface quality and adhesion. Typically, wood surfaces are sawn, sanded, or planed.

In many instances, the sawing process has been used to prepare exterior wood siding. However, this particular process generates important cutting forces that induce an important level of subsurface damage (crushed cells and microruptures) and fibrillation (Singh and Dawson 2006). Microruptures improve coating penetration (Cool and Hernández 2011), but enhanced spread rate is needed to obtain sufficient protection against weathering (Richter et al 1995). The spread rate is further increased when surfaces are characterized with high surface roughness (Richter et al 1995). Richter et al (1995) reported an inverse relationship ($r = -0.78$) between surface roughness and spreading rate of stain on sawn, sanded, and planed surfaces of western redcedar and southern yellow pine. The authors concluded that sanding appeared to be the best machining process because it created uniform wood surfaces that needed little paint coverage due to of little coating penetration. However, many authors observed greater coating adhesion loss after artificial weathering treatment for sanded surfaces because of an important degree of cellular damage (de Moura and Hernández 2006; Hernández and Cool 2008). Results from these studies also indicated that traditional or alternative planing processes offered an interesting alternative to the sawing and sanding processes by better controlling cellular damage as well as adhesion loss. Coating performance is therefore intimately linked to machining processes (Hernández et al 2011) because it affects surface characteristics. Oblique cutting, face milling, and helical planing offer different surface characteristics that yield different coating pull-off strength for an indoor acrylic water-based coating (Cool and Hernández 2011). This study evaluated the effect of these three alternative machining processes in black spruce wood on the performance of an exterior acrylic water-based coating undergoing natural weathering during a 3-yr period. The first objective was to determine what surface characteristics promoted product durability. The second was to link these results with the previous study by Cool and Hernández (2011) to determine how the impact of coating formulation and exposure type affected product durability and performance.

MATERIALS AND METHODS

The factorial experimental design used for this study was created to test two acrylic water-based coatings. The first was formulated for indoor applications such as window frames, glue-laminated structural members, and furniture (Cool and Hernández 2011), whereas the second was formulated for exterior siding applications. As shown in Fig 1, a section from each of the machined black spruce wood samples was used for the first coating and another for the second.

The impact of three alternative machining processes, oblique cutting, face milling, and helical planing, was evaluated both qualitatively and quantitatively. Information on feed speed, cutting depth, cutting angles, and cutting direction is detailed in Cool and Hernández (2011) for all three machining processes (Fig 2). In total, nine machining conditions were selected. More specifically, the impact of oblique angle (10, 35, and 60°) in oblique cutting, feed per tooth (FT) (0.26, 0.34, and 0.53 mm) in face milling, and wavelength (1.11, 1.43, and 2.00 mm) in helical planing was assessed in terms of surface quality and coating adhesion. An in-depth discussion on sample surface characterization in terms of surface roughness, wettability, and surface energy was also presented by Cool and Hernández (2011).

Testing Materials

Black spruce wood (*Picea mariana* [Mill.] B.S.P.) was selected for this study. Two hundred and seventy 1.5-m (L) flat-sawn boards were kiln-dried and stored in a conditioning room at 20°C and 40% RH until they reached 10% EMC. After conditioning, all sections were machined

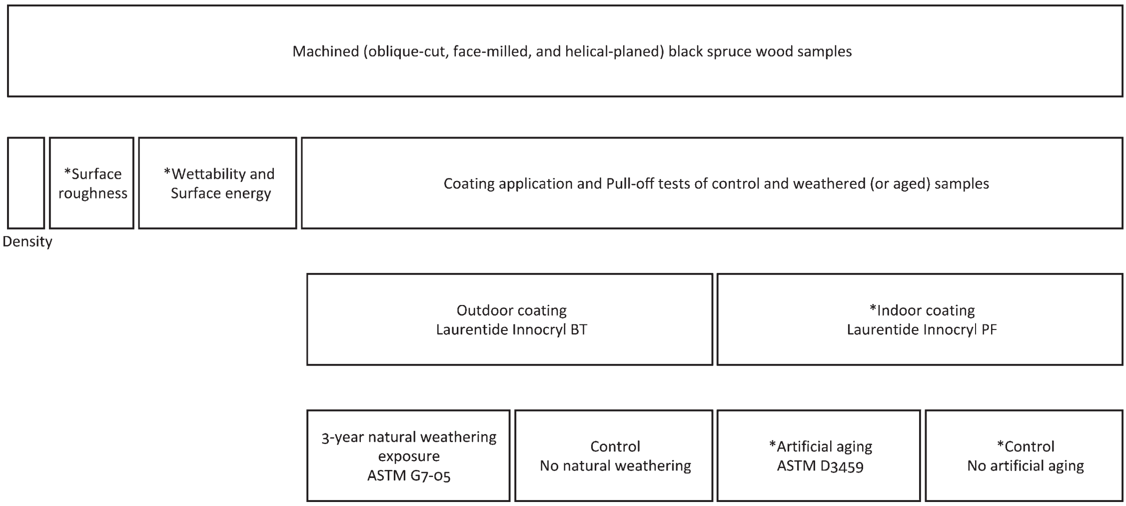

Figure 1. Factorial experimental design. Asterisks indicate data from Cool and Hernández (2011).

to 52 mm (T) width and 22 mm (R) thickness. A 25-mm-long section was crosscut from each specimen to measure average (455 kg/m^3) and standard deviation (35 kg/m^3) of basic density (oven-dry mass divided by green volume). Specimens were then divided into 9 groups of 30 replicates with an average density of 455 kg/m^3 each. Subsequently, each group underwent a surfacing treatment. After surfacing, samples were resectioned to prepare specimens for microscopy (25.4 mm [L]) and exterior coating application (620 mm [L]). After coating, two matched samples were sawn. One sample underwent a 3-yr natural weathering treatment before being submitted to the adhesion test. The other one remained untreated and was stored for the duration of the weathering treatment in a conditioning room at 20°C and 40% RH.

Microscopic Evaluation

Cubes of 10 mm were cut to observe tangential surfaces. Tangential surfaces were used to evaluate fibrillation level and open lumens. All cubes were then desiccated with phosphorous pentoxide for 1 wk and mounted on standard aluminum stubs with silver paint. Environmental scanning electron microscopy (SEM) micrographs were taken for two representative machined samples for each machining treatment.

Coating Application Procedure

Machined surfaces were coated within 8 h after machining treatments. Before coating, samples were placed face against face to keep contamination at minimum levels. Two coats of a semitransparent acrylic water-based exterior coating, Innocryl BT (Laurentide Industrial, Quebec, Canada), was air-sprayed (150 μm/coat) at room temperature according to the manufacturer's specifications. The coating had a 30% solid content and a viscosity of 69 Kreb units. Each coating layer was cured in an infrared Sunkiss oven (Binks Manufacturing Co., Glendale Heights, IL) following a methodology established with the coating manufacture. The oven was set to 82% of its maximum capacity, and feed speed was 5 m/min. A light hand sanding with a P320-grit sandpaper was performed on samples after the first coating layer had cured to decrease the degree of fuzzy grain surface defect that occurred because of cellular springback (Singh et al 2010) and increase mechanical anchorage of the second coating layer.

Natural Weathering

One set of specimens underwent a 3-yr natural weathering treatment in Quebec City, Canada, (46°49′ N and 71°13′ W) according to ASTM (2005). During that period, specimens faced south

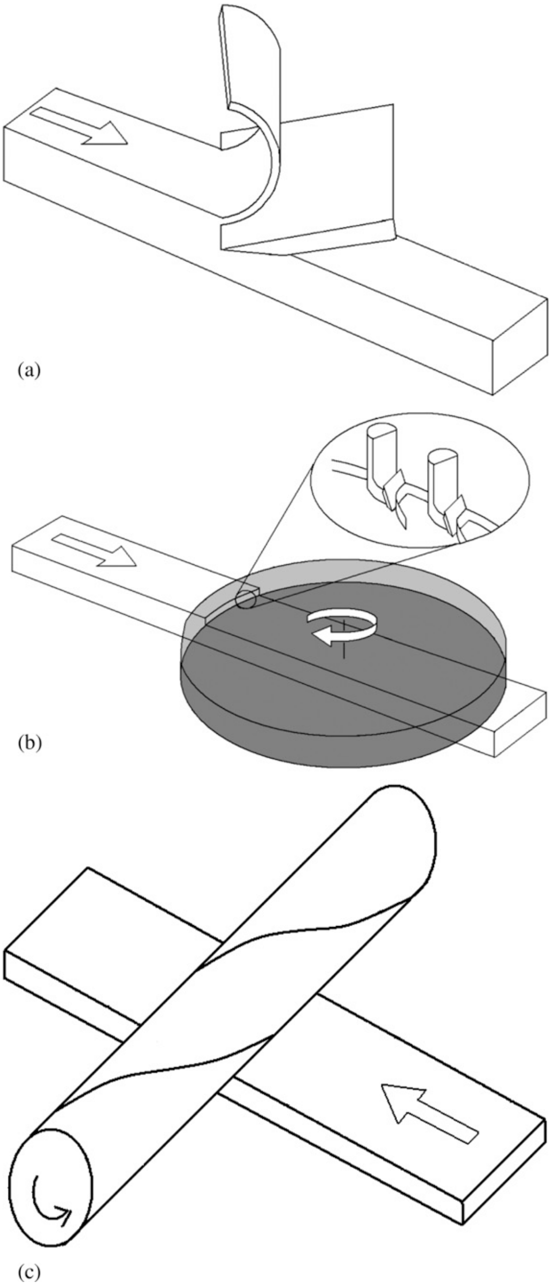

Figure 2. Cutting action for oblique-cutting (a), face milling (b), and helical-planing (c) processes.

Figure 3. Wood samples during weathering.

at a 45° angle from the ground and were located at least 1 m above the ground, which prevented them from being immersed in snow during winter (Fig 3). Mean temperature varied from −18°C in January to 25°C in July, and average yearly rain and snow precipitations were 924 and 3160 mm, respectively.

Adhesion Tests

Adhesion of weathered and unweathered films was evaluated by means of a pull-off test according to ASTM (2002). An MTS QT5 universal testing machine (MTS, Eden Prairie, MN) with a maximum load capacity of 5 kN and ±0.12% precision was used. Small 20-mm-diameter dollies were glued on the film surface with Araldite 2011 two-part epoxy resin (Huntsman International, LLC, Salt Lake City, UT). After 24 h of curing at 20°C and 40% RH, perimeters of the glued dollies were carefully incised to prevent propagation of failures out of the tested area. Pulling was applied at 1 mm/min until separation of the dolly from the substrate. Maximum normal pull strength at rupture was recorded.

Statistical Analyses

The data followed a factorial experimental design, and results from surface topography, wettability, surface energy, and adhesion tests were analyzed as a one-way analysis of variance following the GLM procedure. Mean difference comparison tests were performed at the 5% probability level when required. Simple correlations between surface quality parameters and adhesion test results were studied using the CORR procedure. Analysis was performed with SAS (2007) Ver. 9.2.

RESULTS AND DISCUSSION

Surface Characterization

After machining, oblique-cut samples were characterized by a glossy surface finish and the presence of torn grain around knots. The glossy aspect of samples was caused by the fact that the knife edge tended to peel cells apart in or close to the middle lamella (Cool and Hernández 2011). As a result, oblique-cut surfaces were smooth with few open lumens and little fibrillation (Fig 4). According to the SEM micrographs, increasing the oblique angle up to 60° enhanced the number of open lumens as well as the level of fibrillation that could be associated with microfuzzy grain, which slightly decreased specimen glossiness. This indicates that cutting dynamics were modified because of an increase in the lateral force component when the oblique angle reached 60°. Correspondingly, incidence of torn grain in black spruce wood also increased when an oblique angle of 60° was used. In combination with grain deviation, this was caused by the higher lateral cutting force component. Similar conclusions were reported by de Moura and Hernández (2007) who observed an increase in surface defects, surface roughness, and lateral force component when increasing the oblique angle from 30 to 50° in 8% EMC sugar maple wood machined using a fixed-oblique knife pressure-bar cutting system. Also, the authors reported that the proportion of excellent and uneven samples increased from 65% to 80% when the oblique angle was decreased from 70 to 30°. These findings are consistent with observations made on oblique-cut black spruce wood samples. Face-milled surfaces did not, however, present any typical surface defects although they were characterized by a significantly greater surface roughness (Cool and Hernández 2011). This was because of the fact that most cell lumens were exposed during planing in addition to a higher level of fibrillation where partial cell wall detachment was observed (Fig 5). The face milling equipment operated according to a 13-90° cutting direction. Therefore, the parallel force component was important and was almost perpendicular to the grain. In combination with the lesser mechanical properties of wood perpendicular to the grain, this produced a greater level of fibrillation in sample surfaces. Helical-planed surfaces had a similar surface roughness to that of oblique-cut samples (Cool and Hernández 2011) (Figs 4 and 6). The 76-0° cutting direction induced a lateral force component sufficient to enhance the number of open lumens, but the gradual cutting action induced a low level of fibrillation (Fig 6). Both the number of open lumens and the level of fibrillation increased for feed speed corresponding to a wavelength of 2.0 mm. Also, helical-planed samples were characterized by the presence of torn grain around knots. The incidence of this surface defect as well as its depth increased with feed speed, as reported in Cool and Hernández (2011). For more details on machined surface characteristics and surface roughness measurements, an extensive discussion was given in Cool and Hernández (2011).

After coating application, oblique-cut and helical-planed samples were visually similar regardless of cutting parameters. Both processes yielded surfaces that were smooth, had a uniform texture, and showed torn grain surface defects around knots. Localized fuzzy grain was also observed in coated oblique-cut surfaces machined with a 60° oblique angle and in helical-planed samples prepared at a feed speed inducing a 2.0 mm wavelength. Although this defect negatively affected visual quality, it was seldom observed. The occurrence of fuzzy grain can be associated with the level of fibrillation, which slightly increased for those specific cutting parameters. Cool and Hernández (2011) even reported a significant increase in S_{PK}, the reduced peak height surface roughness parameter, when machining with the helical planing process at a wavelength of 2.0 mm. In opposition, face-milled samples did not have a uniform texture and were characterized by fuzzy grain that degraded their overall visual quality. Apparently, the axial rake angle used in the experiment (20°) was not the optimum. Use of

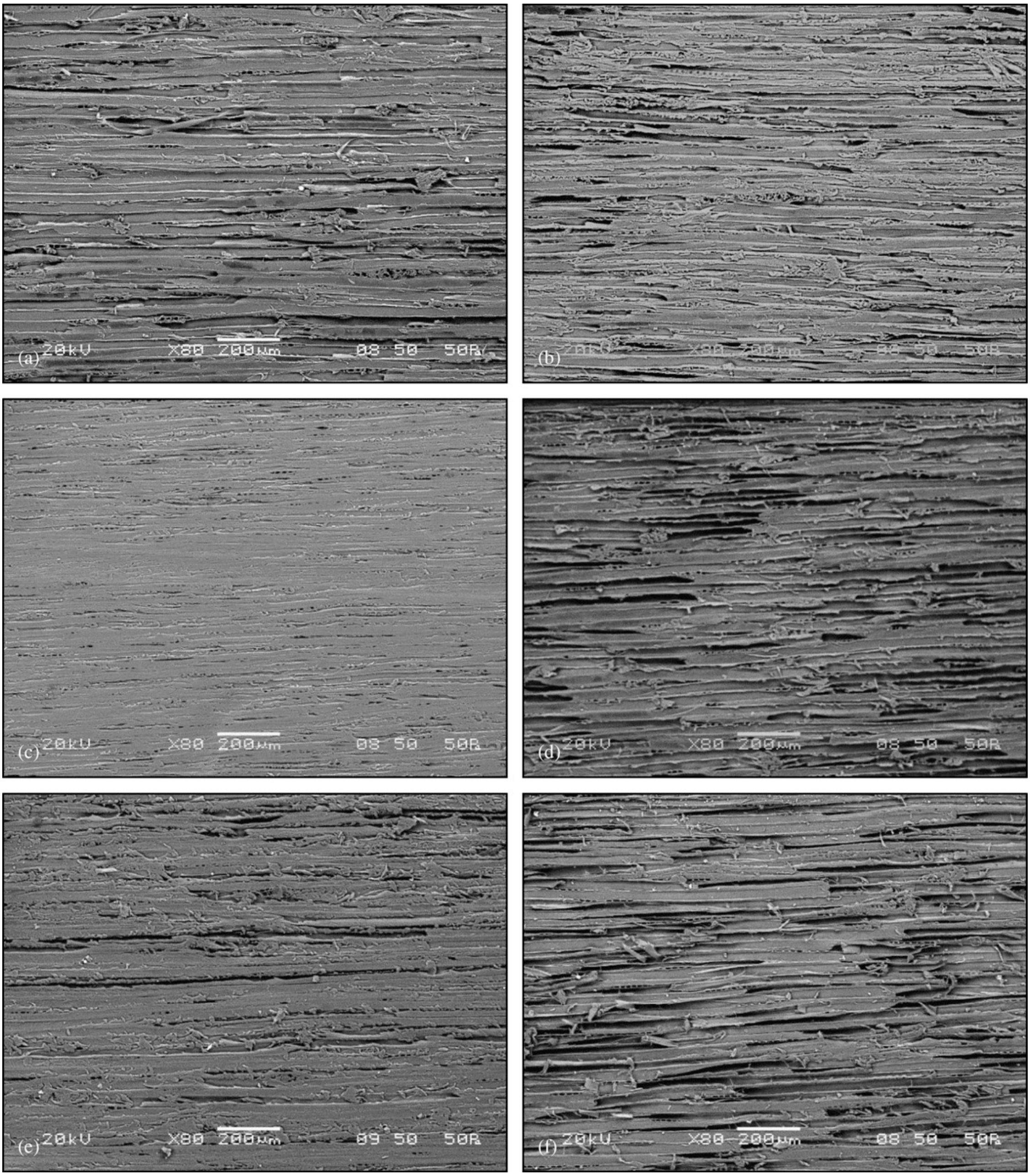

Figure 4. Tangential environmental SEM micrographs of oblique-cut black spruce wood samples cut at oblique angles of 10 (a and b), 35 (c and d), and 60° (e and f).

greater rake angle should give better results for this type of surfacing method. In fact, Stewart and Parks (1980) reported that surface quality increased slightly as rake angle increased from 37 to 60° during milling across the grain. In addition, knife marks were emphasized following the water-based coating application and further degraded the esthetics of face-milled

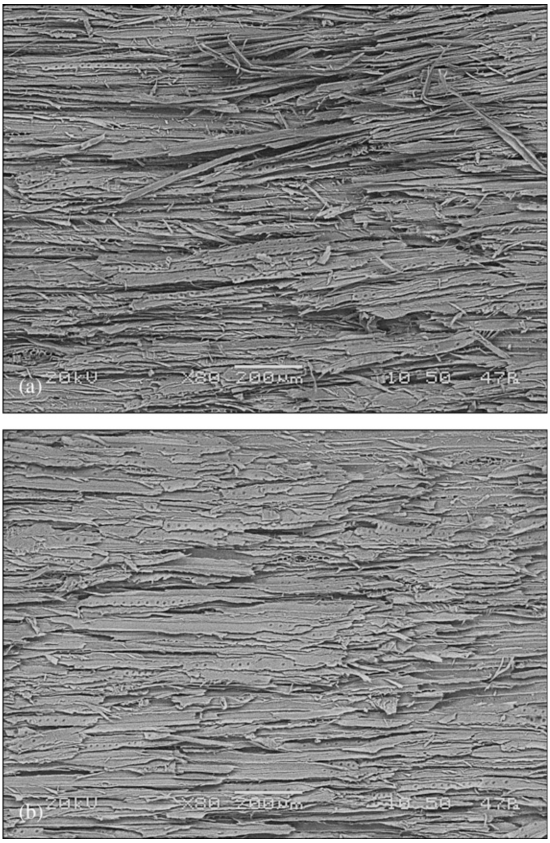

Figure 5. Tangential environmental SEM micrographs of face-milled black spruce wood samples showing different levels of fibrillation in earlywood (a) and latewood (b).

samples. It was expected that the surface roughness would somewhat conceal any surface defects that could result after coating application. However, the amount of subsurface damage, ie cell crushing, cell wall deformation, and microruptures, induced cellular springback after application of the water-based coating. Singh et al (2010) referred to this phenomenon as grain raising in radiata pine weatherboards. Because of the different type of subsurface damage observed in these samples, the cellular springback effect was not uniform throughout sample surfaces. As a result, face-milled surfaces differed from that typically seen in eastern Canadian siding, for which sawn or roughly planed wood surfaces show uniform surface characteristics.

Qualitative observations showed that, after a 3-yr exposure, samples were free of mildew, cracking, and flacking. However, coating color was modified during the natural weathering process. This was expected and was probably caused by exposure to sunlight, which principally degrades lignin, the major constituent responsible for the yellowing of wood (Feist 1983; Williams et al 2000). Also, most samples were characterized by coating erosion over the knots. Because grain orientation of knots differs from that of surrounding wood, cutting direction is locally affected. Cutting direction of knots is approximately 90-90°. In orthogonal cutting, Woodson and Koch (1970) reported that parallel and normal cutting force components were both more important in magnitude when machining in a 90-90° cutting direction compared with that of 90-0° and 0-90°. In their experiments, the authors observed poor surface quality and splits following the grain in samples. It is known

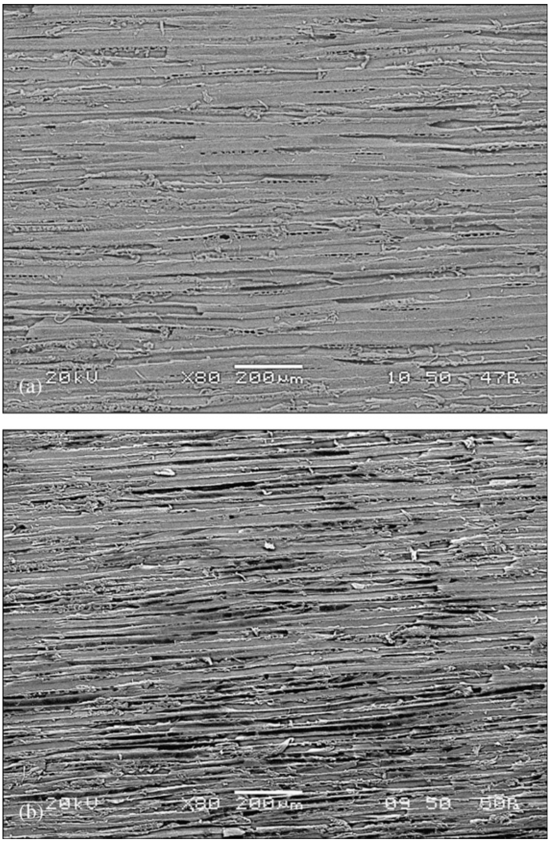

Figure 6. Tangential environmental SEM micrographs of helical-planed black spruce wood samples for 1.43 mm (a) and 2.0 mm (b) wavelength.

that spruce knots have a density 1.5 times higher than that of surrounding wood (Boutelje 1966). Because knot cell walls are thicker than that of surrounding wood, it is expected that subsurface damage would be associated with cell wall deformation and crushing. This could have hindered coating penetration in knots. Furthermore, resin content in knots is approximately five times greater than that of surrounding wood (Boutelje 1966), which makes them more hydrophobic and can negatively affect coating adhesion. With a lower coating penetration, knot protection against weather was therefore probably insufficient. To improve coating adhesion on knots, Williams (1999) suggested sealing knots before coating application. Nonetheless, the great number of knots in eastern Canadian black spruce wood makes this an important issue that will need to be analyzed thoroughly in a future study. Furthermore, erosion was observed on samples in which resin exudation had occurred. The presence of resin locally lowered coating adhesion, and coating erosion was observed as early as in the first year of exposure in some samples. It can be expected that eroded areas could get bigger if not repaired and would be susceptible to decay. Resin exudation may have been prevented by crystallizing resin (ie pitch setting) during drying. According to Simpson (2001), this can be achieved by drying at a minimum temperature of 80°C. However, duration is not specified and depends on wood species. Black spruce wood samples used in this study were dried at 80°C for more than 30 h, but apparently, this was not sufficient to crystallize resin for this particular wood species because leaching of resin still occurred when samples were heated by sunlight. Also, face-milled samples were characterized by a greater level of coating erosion than that of oblique-cut and helical-planed samples. This was because samples were characterized with greater surface roughness and a higher level of fibrillation (Fig 5) as well as more knife marks. Cool and Hernández (2011) reported that coating penetration was deeper for face-milled samples when using a water-based acrylic coating for indoor purposes than those prepared by oblique cutting or helical planing. It is assumed that the coating used in this study behaved similarly. Therefore, the combination of greater surface roughness and coating penetration resulted in a thinner film protecting wood surfaces against weathering. Face-milled samples were thus more likely to undergo erosion than were oblique-cut and helical-planed samples.

Adhesion Tests

Significant impacts of machining parameters were detected on pull-off strength before and after weathering as well as on adhesion loss (Table 1). These results differ from Cool and Hernández (2011) who reported statistically similar water-based interior coating adhesion regardless of machining processes before aging, but were able to discriminate performing processes using pull-off strength after aging as well as calculating the loss in adhesion. Although samples from both studies were matched, no correlations were detected among pull-off strength and adhesion loss values (not shown). This was because the two water-based acrylic coatings differed in pigments, solid, and volatile organic content contents. It also needs to be emphasized that accelerated aging treatments used in both studies varied greatly.

Before weathering, significant impacts of machining parameters were detected on pull-off strength (Table 1). According to the data, oblique-cut samples machined using an oblique angle of 10 and 35° were characterized by significantly superior pull-off strength compared with that of samples prepared by helical planing at a wavelength of 1.11 mm and by face milling at an FT of 0.34 and 0.26 mm. Generally, greater initial pull-off strength was obtained from smooth samples with little fibrillation or microfuzzy grain. This observation is supported by surface roughness measurements (Cool and Hernández 2011). However, no correlations were detected among adhesion test values and surface roughness parameters, surface wettability, or surface energy components (not shown).

After weathering, helical-planed samples prepared at a wavelength of 1.43 mm performed

Table 1. Pull-off strength before and after natural weathering and adhesion loss for black spruce wood specimens prepared with oblique cutting, face milling, and helical planing.

		Pull-off strength (MPa)		
Oblique cutting	Oblique angle (°)	Before weathering	After weathering	Adhesion loss (%)
	10	4.7[a] (0.2)[b] A[c]	3.2 (0.1) AB	32 B
	35	4.7 (0.2) A	3.2 (0.1) AB	32 B
	60	4.5 (0.2) AB	3.2 (0.1) AB	29 AB
Face milling	FT (mm)			
	0.53	4.2 (0.2) ABC	2.8 (0.1) C	33 AB
	0.34	4.0 (0.2) BC	2.8 (0.1) BC	31 AB
	0.26	3.9 (0.2) C	2.9 (0.1) BC	27 AB
Helical planing	Wavelength (mm)			
	2.00	4.3 (0.2) ABC	2.9 (0.1) BC	33AB
	1.43	4.5 (0.2) AB	3.2 (0.2) A	27 AB
	1.11	4.1 (0.2) BC	3.2 (0.1) AB	22 A

[a] Mean of 30 replicates.
[b] Standard error of the mean in parentheses.
[c] Means within a column followed by the same letter are not significantly different at the 5% probability level.

significantly better in terms of pull-off strength than helical-planed samples prepared at a wavelength of 2.00 mm and face-milled specimens (Table 1). An intermediate level of fibrillation appeared to be desirable to maximize adhesion throughout weathering. This was probably caused by the increased surface available for mechanical anchorage that strengthened the wood–coating interface. These results are somewhat similar to those reported by Cool and Hernández (2011). In both cases, face-milled samples were associated with lower pull-off strength after undergoing the aging treatment, and helical planing at a wavelength of 1.43 was among the machining processes that yielded superior pull-off strength values. This suggests that an important level of fibrillation could hinder coating durability in long-term applications because fibrils are not firmly attached to the wood surfaces (Feist et al 1985). This is in agreement with Ratnasingam and Scholz (2006) who reported a lower coating adhesion with increasing surface roughness of rubberwood. As a result, weaknesses are introduced in the wood–coating interface, which could promote coating failures. It was therefore unexpected that oblique-cut samples prepared with an oblique angle of 10 and 35° would have undergone great adhesion loss (Table 1). These samples had a significantly greater adhesion loss compared with helical-planed samples machined at a wavelength of 1.11 mm. Similar to maximizing pull-off strength after weathering, an intermediate level of fibrillation also appeared desirable to preserve adhesion during the 3-yr outdoor exposure. These results contradict those of Cool and Hernández (2011) who concluded that a smooth surface was necessary to minimize adhesion loss for an interior water-based coating.

In conclusion, different types of surfaces should be favored according to applied coatings and end-use applications. In the case of black spruce wood, indoor and outdoor acrylic water-based coatings performed better when, respectively, applied on smooth surfaces (Cool and Hernández 2011) and surfaces with an intermediate level of fibrillation.

CONCLUSION

Oblique cutting and helical planing generated surfaces with similar features such as low levels of fibrillation and cellular damage. Face-milled surfaces were rougher both in appearance and surface roughness and were characterized by a high level of fibrillation where partial cell wall detachment was observed as well as cellular damage in the form of microruptures and cell wall deformation and crushing. Because cellular damage was nonuniform through earlywood and latewood areas of black spruce, the samples could have undergone a nonuniform springback after the water-based coating application. As a result, face-milled surfaces were not visually appealing compared with those obtained from oblique cutting and helical planing. In addition, the roughness of face-milled samples was associated with an accelerated coating erosion during the 3-yr weathering exposure. These observations were supported by pull-off strength measurements that revealed poor coating adhesion before and after weathering. Adhesion test results also showed that helical-planed surfaces machined at a wavelength of 1.11 mm underwent less adhesion loss during a 3-yr weathering treatment than that of oblique-cut specimens prepared at an oblique angle of 10 and 35°. Consequently, a certain level of fibrillation (microfuzzy grain) and amount of open lumens are desirable to maximize durability of an acrylic water-based coating used in exterior wood siding. More specifically, a high level of fibrillation and large amount of open lumens were associated with deep coating penetration that left only a thin layer of film protecting wood surfaces against erosion. Pull-off strength values were, in those cases, significantly inferior. However, when fibrillation and amount of open lumens were low, mechanical anchorage of coating was insufficient to maintain long-term adhesion. Indeed, in those cases, adhesion loss values were significantly greater. According to the results, helical planing at a wavelength of 1.11 mm yielded the best weathering performance for exterior coating black spruce wood with a 22% adhesion loss after a 3-yr natural weathering.

Coating erosion was also observed in knots. It was hypothesized that low knot adhesion was caused by differences in grain direction and density that lowered mechanical anchorage of coating as well as the higher resin content that contributed to increased hydrophobicity to the disadvantage of adhesion. To improve durability of coated black spruce wood, future studies need to focus on enhancing coating adhesion in knots. Black spruce wood has numerous knots and their poor coating adhesion negatively impacts its potential to be used in high-quality exterior wood siding. To decrease coating erosion on black spruce surfaces, a drying schedule is needed that effectively eliminates resin exudation. Because subjecting black spruce to a 30-h medium-temperature drying schedule did not eliminate resin exudation, it is hypothesized that using a high-temperature (above 95°C) drying schedule may be more effective. However, pitch setting has to be done without inducing too much warp or negatively affecting surface adhesion and appearance.

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