

# EVALUATION OF THREE SURFACING METHODS ON PAPER BIRCH WOOD IN RELATION TO WATER- AND SOLVENT-BORNE COATING PERFORMANCE

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(Received October 2007)

**Abstract.** Helical planing, face milling, and sanding were used to surface paper birch wood prior to application of coatings. The surface roughness and wetting properties of the wood were evaluated as well as the pull-off strength of water- and solvent-borne coatings, before and after aging. The specimens surfaced with helical planing produced surfaces with the highest surface roughness, the best wetting properties, no subsurface damage, and good pull-off strength before aging. Those surfaced with face milling generated surfaces with intermediate surface roughness, lowest wetting properties, slight surface and subsurface damage, and good pull-off strength before aging. The sanded samples produced the lowest surface roughness, intermediate wetting properties, the highest surface and subsurface damage, and good pull-off strength before aging. After aging, all samples coated with the same varnish exhibited the same pull-off strength regardless of the surfacing treatment. However, loss in pull-off strength after aging was lower for helical planing than for the others. This suggests that helical planing could produce more suitable surfaces for indoor furniture applications. Finally, the water-borne coating created stronger bonds with the substrate than the solvent-borne coating.

**Keywords:** Sanding, helical planing, face milling, wetting properties, roughness, cell damage, coating adhesion, paper birch.

## INTRODUCTION AND BACKGROUND

The understanding of adhesion mechanisms on wood surfaces is of great interest to extend service life of transparent film-forming coatings. Wettability and roughness analyses provide important information on the adhesion ability of coating films on wood surfaces. Good wetting is essential to adhesion as it provides better mechanical interlocking, molecular-level interactions, and secondary force interactions between the coating film and the wood surface. For any type of coating, good wetting might contribute to good film performance (Wulf et al 1997).

Thus, if a coating cures before complete wetting, a weak boundary layer of entrapped air may be formed at the interface (Lewis and Forrester 1969). An increase in surface roughness enhances wettability by facilitating liquid spreading by capillarity (Garrett 1964; Lewis and Forrester 1969). In addition, a suitable level of roughness provides a greater actual surface available for adhesion mechanisms. The importance of wood surface wettability and roughness on adhesion of polyurethane varnishes has been reported in previous studies (de Moura and Hernández 2005, 2006c).

Sanding is a common practice used to prepare wood surfaces for coating. However, this machining process is one of the most skill-based, time-consuming, and expensive operations in

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the wood industry (Taylor et al 1999). Sanding produces homogeneous surfaces and alters the cellular structure so that no anatomical roughness is detectable (Richter et al 1995). However, sanded wood is characterized by a layer of crushed cells at the surface and subsurface, lumens clogged by fine dust, scratches, and packets of microfibrils torn out of cell walls. Crushing and clogging of cells hinder penetration (Richter et al 1995; de Meijer et al 1998), while fibrillation and scratches accelerate spreading of liquid coatings on sanded surfaces. The benefits of fibrillation for mechanical adhesion of coating films have been shown for sanded wood surfaces (de Moura and Hernández 2005). In searching for methods to reduce the need for sanding, helical planing and face milling processes have been proposed (Stewart and Lehmann 1974; Stewart 1974).

In true helical planing, the knives are mounted onto the periphery of a cutterhead at an angle to the axis of rotation and form a continuous oblique cutting edge (Stewart 1971). Torn grain, raised grain, and chipmarks are reduced in the gradual cutting action of helical planing (Jones 1994). Helical planing performed across the grain appears to have a good potential to reduce dependence on sanding since it improves surface adhesion properties and enhances the performance of coatings. This surfacing method provides surfaces with improved wetting properties, good fibrillation, and virtually no cell crushing (de Moura and Hernández 2006a).

Face milling is generally considered to be the combined cutting action of cutting edges located at the periphery and the face of a cutter to machine a flat surface perpendicular to the cutter axis (Stewart 1974). Stewart (1984) studied the surface quality of several combinations of cutterhead diameter, chamfer angle, and feed position when face milling clear-grained hardwoods. The results showed that these variables had minimal effect on the milling process. However, investigations of other variables of face milling appeared worthwhile. Furthermore, this process typically occurs across the grain; therefore a suitable level of fibrillation should be expected.

Solvent-borne coatings are usually applied in the wood furniture industry. Although these products are efficient, there are efforts to reduce the emission of volatile organic compounds (VOC). Hence, water-borne coating products have been introduced into the market and proved to have reduced VOC emissions up to 60% compared with solvent-borne coatings (Tichy 1997). Rijckaert et al (2001) further observed that water-borne coatings create stronger bonds with the substrate than solvent-borne coatings.

This work evaluated the effect of sanding, cross-grain helical planing, and face milling on the surface quality of paper birch wood for varnish coating. Surface quality was assessed by topography measurements, wetting analyses, and cell damage evaluation. The performance of water- and solvent-borne coating films was assessed by accelerated aging and pull-off tests.

## MATERIALS AND METHODS

### Testing Materials

Paper birch (*Betula papyrifera* Marsh.), a diffuse porous hardwood, was selected for this study. Twenty-six air-dried, flat-sawn boards were stored in a conditioning room at 20°C and 40% relative humidity (RH) until they reached 8% equilibrium moisture content (EMC). After conditioning, each board was crosscut into three matched sections of 390-mm (L) length. All sections were machined to 50-mm (T) width, and 22-mm (R) thickness. Each section underwent a surfacing treatment and was resectioned to prepare specimens for roughness (50 by 25 mm), wetting (50 by 25 mm), and varnishing, accelerated aging, and pull-off adhesion tests (50 by 85 mm). The average and standard deviation of basic density (oven-dry mass to green volume) of the boards were 495 and 35 kg/m<sup>3</sup>, respectively.

### Machining Treatments

The helical planing treatment was performed with a Casadei R63H3 0.61-m planer provided with two freshly sharpened flexible knives. The

rake and helix angles were  $30^\circ$  and  $14^\circ$ , respectively. The specimens were planed across the grain. For this purpose, the boards were butted side-to-side and fed with the grain aligned to a tangent of the helix angle. A jig was built to firmly hold the specimens during cutting. The feed speed was 5.5 m/min, which corresponds to 26 knife marks per 25 mm of length. The depth of cut was 0.6 mm.

The face milling treatment was performed with a Rotoplane 16T planer provided with a disk holding 34 new insert knives having an angle of  $60^\circ$ . The positive axial rake and radial rake angles (according to Stewart 1974) were  $15^\circ$  and  $13^\circ$ , respectively. The boards were fed through the center of the disk and therefore planed nearly to  $13^\circ - 90^\circ$ . A jig was used to firmly hold the specimens during cutting. The depth of cut studied was 0.6 mm, while the feed speed was 7.4 m/min, which corresponds to 0.07 mm of feed per insert knife.

The sanding treatment was performed with a SCM Sandya 20 wide-belt sander provided with open-coat paper-backed sanding belts. The boards were sanded with aluminum oxide sandpaper whose abrasive grains were coated with antistatic zinc stearate. The sanding program was 100–120–150-grit stages. The 100-grit sanding belt was installed onto a drum working with a 0.35-mm removal depth. The second sanding stage was performed with a drum-and-pad combined unit. This unit held a 120-grit sanding belt and was set to remove a depth of 0.15 mm. The 150-grit sanding belt was mounted onto a pad unit removing 0.1 mm of depth. The sanding drums, 172 mm in diameter, were operated at 21 m/s. All sanding units had a 65 SH hardness. Sander feeding was carried out fiberwise with 10 m/min of feed speed. Oscillating blowers performed cooling and cleaning of belts during sanding.

### Surface Topography Measurements

Roughness measurements were carried out on defect-free zones with a Micromasure confocal microscope based on the method described in

Hernández and Cool (2008). The average roughness ( $R_a$ ), the maximum height of profile ( $R_z$ ), the kurtosis ( $R_{ku}$ ), and the skewness of the profile ( $R_{sk}$ ) were determined by using the Mountain software based upon ISO 4287 (ISO 1998). A cutoff length of 2.5 mm combined with a Gaussian filter based on ISO 11562 (ISO 1996) were used for calculations. The surface profile was assessed along and across the grain.

### Surface Wettability Tests

Wetting analyses were performed with an FTÅ D200 imaging goniometer at  $20^\circ\text{C}$ , with an aqueous glycerine solution (6 mPa·s viscosity) based on the method described in Hernández and Cool (2008). Contact angle was calculated as an average of both sides of the droplet to compensate for any horizontal variations. Also, to quantify the spreading and penetration of the probe liquid, the  $k$ -value was determined according to Shi and Gardner (2001).

### Microscopic Evaluation

To analyze cell damage and coating penetration, 10-mm cubes were prepared with a razor blade mounted onto a microtome by carefully cutting one of the end-grain surfaces. All blocks were then desiccated with phosphorous pentoxide for 1 wk and mounted onto standard aluminium stubs with silver paint. Environmental scanning electron microscopy (ESEM) micrographs were taken for two representative machined subsurfaces for each machining treatment.

### Coating Procedure

The machined surfaces were spray-coated following a typical industrial procedure within 24 h after the machining treatments. During this period, samples were placed face-to-face within black plastic bags to keep contamination at a minimum. Two types of coatings were applied, solvent-borne lacquer (SB) and water-borne varnish (WB). The SB consisted of a *Valspar-Superseal* sealer ( $0.7 \text{ g/m}^2$ ; 10.8 mPa·s) followed by a *Valspar-20 Ultraguard* lacquer (0.6

g/m<sup>2</sup>; 313 mPa•s). The WB consisted of a *Chemcraft-Plastiseal low VOC* sealer (1.1 g/m<sup>2</sup>; 16.3 mPa•s) followed by an UV-cured *Chemcraft-Aquacure* varnish (0.85 g/m<sup>2</sup>; 24.4 mPa•s). A 320-grit sanding was performed manually between the two coats. This sequence is often observed in the Canadian furniture industry for items like bookcases, tables, and chests.

### Accelerated Aging

One-half of the specimens underwent an accelerated aging treatment in a Cincinnati SubZero environmental stimulation chamber (WM-906-MP2H-3-SC/WC) having temperature and RH precision of  $\pm 1^\circ\text{C}$  and  $\pm 3\%$ , respectively. The treatment was based upon ASTM D 3459 (ASTM 1998) and consisted of 2 cycles of 48 h at 50°C and 10% RH followed by 48 h at 50°C and 90% RH. Prior to the treatment, the ends of the specimens were sealed with paraffin to reduce the moisture exchange through the cross-section. After aging, the specimens were conditioned at 20°C and 40% RH until they reached their initial EMC (8%).

### Adhesion Tests

The adhesion of the accelerated aged films as well as those that did not undergo aging treatments was evaluated by means of a pull-off test according to ASTM D 4541 (ASTM 1995). An MTS QT5 universal testing machine having a maximal capacity of 5 kN and  $\pm 0.12\%$  precision was employed. Small 20-mm-dia dollies were glued on the film surface with Araldite 2011 two-part epoxy resin. After 24 h of curing at 20°C and 40% RH, the perimeters of the glued dollies were carefully incised to prevent propagation of failures out of the tested area. Pulling was applied at 7 mm/min until separation of the dolly from the substrate. The maximal normal pull strength at rupture was recorded.

### Statistical Analyses

Surface roughness and wetting properties were analyzed as a randomized block design. The ad-

hesion strength variation was evaluated as a strip-split plot design. Each analysis was done on SAS<sup>®</sup> statistical package, version 9.1 (SAS 2002–2003). Means-difference comparison tests were made when a significant effect was found at the 5% probability level.

## RESULTS AND DISCUSSION

### Surface Topography

No major defects, like torn grain or fuzzy grain, were noted on the surfaces machined for the three surfacing methods.  $R_a$  and  $R_z$  were significantly higher across than along the grain for all surfacing methods (Table 1). The greatest roughness for both directions of measurement occurred in cross-grain helical planing, followed by face milling and sanding. The skewness values ( $R_{sk}$ ) indicate that, compared with sanded surfaces, helical-planed and face-milled surfaces had more material near the top of the roughness profile. The three surfacing treatments tended to produce wide peaks and valleys as indicated by the kurtosis coefficients ( $R_{ku}$ ), which were greater than 3 (Table 1). The maximum height of the profile ( $R_z$ ) was greater for helical planing, followed by face milling, and finally sanding. This could partially indicate the proportion of open lumens, which would affect the actual surface available for mechanical anchorage between coating and wood (Fig 1a, 2a, 3a).

ESEM showed superficial cell damage in sanded surfaces (Fig 1b). Tearing and crushing were the main causes of damage in cells at surface and subsurface. Typical scratches produced by the tearing action of the abrasive grains were noted (Fig 1a). The presence of cell damage in sanded surfaces has been reported in earlier studies (Stewart and Crist 1982; de Meijer et al 1998; de Moura and Hernández 2005, 2006b 2006c). This damage is principally caused by normal cutting forces that outweigh the ultimate rupture strength of wood tissues (Stewart and Crist 1982). Lumens were hence covered by cell dust and neighboring cell fractions, which prevents the penetration of coatings into the wood (de Meijer et al 1998) (Fig 1a). In contrast, helical-

TABLE 1. Roughness averages ( $R_a$ ), maximum height of profile ( $R_z$ ), skewness coefficient ( $R_{sk}$ ) and kurtosis coefficient ( $R_{ku}$ ) measured along (||) and across (±) the grain, obtained for three surfacing techniques applied to paper birch wood.

Surfacing method	$R_a$		$R_z$		$R_{sk}$		$R_{ku}$	
		±		±		±		±
Helical planing	6.2 <sup>1</sup> A <sup>3</sup> (0.1) <sup>2</sup>	9.0 A (0.3)	36.3 A (0.7)	59.9 A (1.7)	-0.7 A (0.1)	-1.6 A (0.1)	5.6 A (0.2)	7.2 A (0.3)
Face milling	5.6 B (0.2)	8.1 B (0.3)	32.5 B (0.9)	52.4 B (1.6)	-0.9 A (0.1)	-1.7 A (0.1)	5.8 AB (0.2)	7.4 A (0.3)
Sanding	3.3 C (0.1)	4.7 C (0.1)	21.5 C (0.7)	31.0 C (0.8)	0.1 B (0.1)	-0.4 B (0.1)	6.3 B (0.2)	5.3 B (0.3)

<sup>1</sup> Means of 26 replicates

<sup>2</sup> Standard error of the mean in parentheses

<sup>3</sup> Means within a column followed by the same letter are not significantly different at the 5% probability level.

planed surfaces showed lower superficial cell damage, with relatively more open cells as vessels and fibers (Fig 2a). Similar results were observed in sugar maple surfaces by de Moura and Hernández (2006a). Face milling produced surfaces similar to helical-planed surfaces but with occasional bent rays and fewer open lumens (Fig 3).

All three machining processes generated cell-wall fibrillation on the surface. As indicated previously, fibrillation increases the actual surface available for bonding. Helical-planed samples presented the lowest level of fibrillation (Fig 2a). This surface feature has been observed before for cross-grain helical planing and sanding, but not for the face milling process. In up-milling planing, chip thickness is minimal at the beginning of the cut. As a result, wood cells were more clearly severed and a higher number of lumens were exposed. Face milling produced an intermediate level of fibrillation (Fig 3a). A 15° rake angle typically produced type B chips, with compression and shear failures occurring ahead of the insert knives (Stewart 1979). Fine dust, bent rays, and packets of microfibrils were dragged by the tools and likely clogged open vessels. The sanded samples showed the greatest level of fibrillation (Fig 1a). Type III chips were also formed because of the negative rake angle of abrasive grains. Cell fractions, individual cells, and groups of cells were detached from the surface and filled cell lumens. The parameter  $R_z$  was lower for the sanding process (Table 1). This confirms the fact that sanding makes the surface more uniform and reduces the influence of wood anatomy on the roughness profile. This observation has been reported previously (Richter et al 1995; de Moura and Hernández 2006b).

### Surface Wettability

Helical planing showed the fastest wetting, followed by sanding and face milling (Fig 4). The initial wetting for helical-planed surfaces was faster, thus suggesting that the coating should spread easily on the surface and would be able to

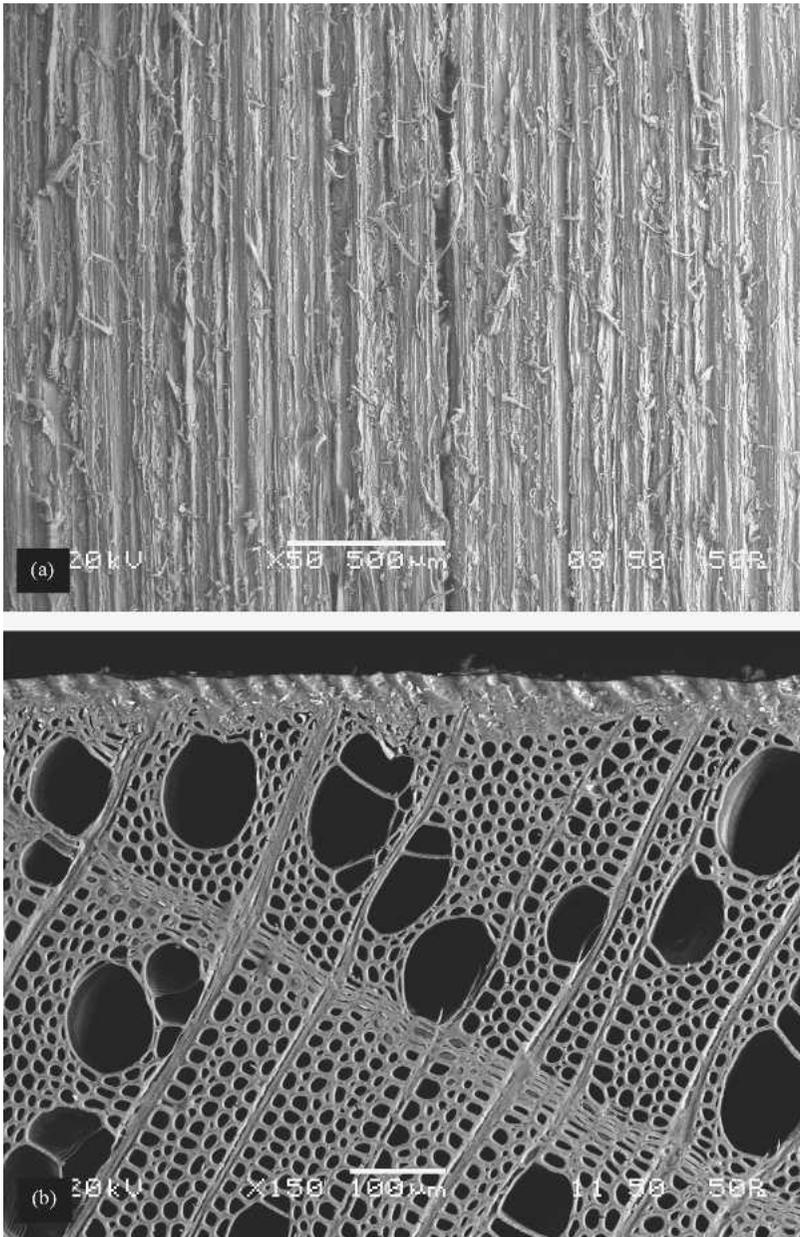


FIGURE 1. ESEM micrographs illustrating (A) top view of an uncoated specimen and (B) transverse view coated with solvent-borne lacquer for a sanded specimen.

fill the asperities properly. ESEM confirmed that up to 2–3 cells were often filled with the coating (Fig 2b). K-values also showed that helical planing induced good penetration and spreading characteristics (Fig 4). Similar trends were reported by de Moura and Hernández (2006c) us-

ing distilled water as a probe liquid. Fibrillation as well as open vessels makes it possible for the coating to spread and penetrate easily into the substrate (Fig 2a). Face milling showed the worst wetting properties (Fig 4). ESEM confirmed that the first row cells were filled with

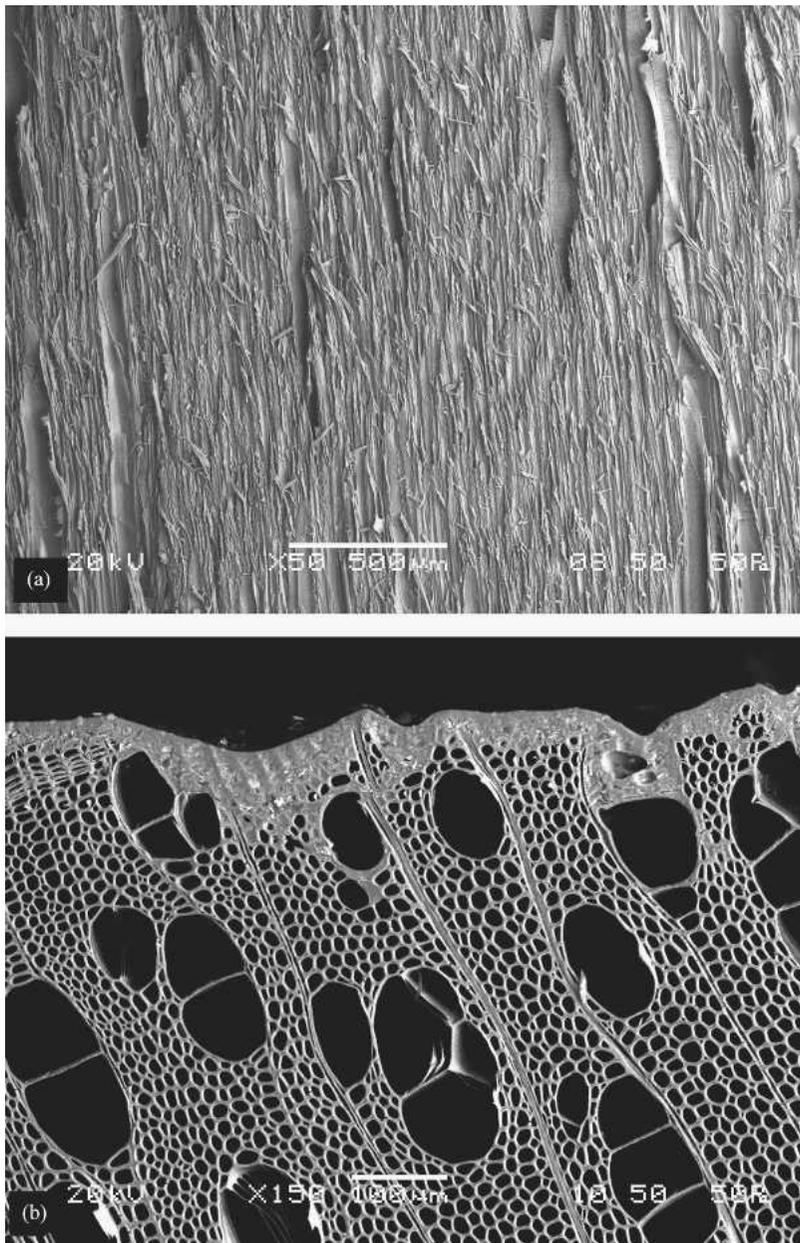


FIGURE 2. ESEM micrographs illustrating (A) top view of the uncoated specimen and (B) transverse view coated with solvent-borne lacquer for a helical planed specimen.

coating and that it rarely penetrated farther (Fig 3b). Sanded specimens had quite good overall wetting properties. The initial wetting was low, but the substrate absorbed the probe liquid constantly (Fig 4). ESEM showed that only the first cells were filled with coating (Fig 1b). Poor pen-

etration and spreading properties are also pointed out by the k-value of sanded surfaces (Fig 4). As noted by de Meijer et al (1998), the damaged layer prevented the probe liquid from penetrating the surface. The higher degree of fibrillation observed on the sanded surfaces

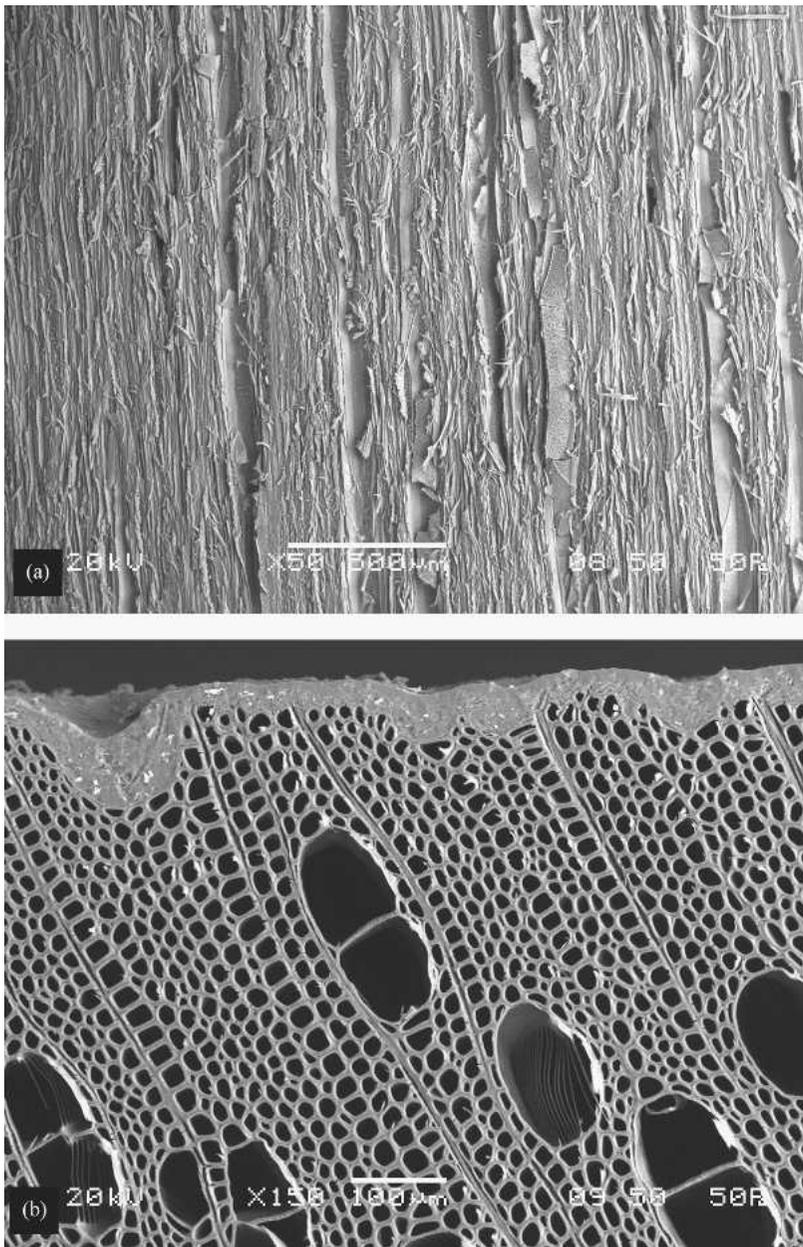


FIGURE 3. ESEM micrographs illustrating (A) top view of the uncoated specimen and (B) transverse view coated with solvent-borne lacquer for a face milled specimen.

could also have slowed the process at the initial steps of wetting.

ESEM analysis also showed that surfaces offering more paths for penetration tended to have thinner films. The average film thickness was 23

$\mu\text{m}$  for helical planing, 25  $\mu\text{m}$  for face milling, and 27  $\mu\text{m}$  for sanding (two coatings pooled). These penetration values were consistent with those of the wetting analysis obtained using a glycerine solution as a probe liquid. Viscosity of the glycerine solution and the sealers used were

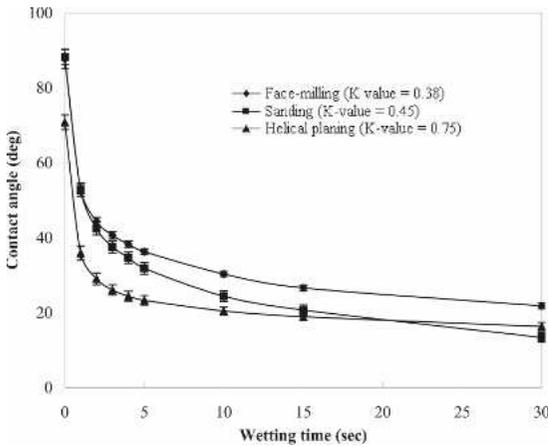


FIGURE 4. Contact angle evolution with wetting time for all treatments.

quite similar. It is recognized that viscosity strongly affects the dynamic wettability of porous surfaces like wood (Liptáková et al 2000; Stehr et al 2001). Thus, the glycerine wetting process observed on the three machined surfaces could correspond with that produced by the sealers during finishing. However, further research is needed to confirm these inferences.

**Adhesion Tests**

The pull-off strength was statistically similar for the two coatings before the aging treatment. After the aging treatment, the WB coating performed better than the SB lacquer regardless of the surfacing process (Table 2).

The helical-planed surfaces showed slight lower pull-off strength before the aging treatment for

both types of coatings (although not statistically significant). However, after aging, the WB coating lost up to 13% and the SB coating lost up to 37% of the pull-off strength (Table 2). This loss in adhesion was significantly lower than those produced by the surfaces machined by face milling or sanding (Table 2). A larger difference in adhesion loss among the surfacing treatments could have been detected had the aging treatment been more severe. Thus, it is possible to affirm that better long-term bonds were created with helical planing. Because lower superficial cell damage was observed for helical planing, a better mechanical adhesion likely took place. This adhesion was a result of the good wetting properties and the best quality of the fibrillation produced by this technique.

The sanded and face-milled samples experienced similar aging effects (Table 2). The higher loss in strength resulted from greater surface and subsurface damage. During the aging process, damage cells shrank and swelled more, causing microruptures in the coating-substrate interface. The cell-wall fibrillation on the surface could also have shrank and swelled through the aging process, which also weakened bonds.

Pull-off strength measured for paper birch wood was similar than that obtained for beech and oak woods (Liptáková and Kúdela 2002), and lower than for sugar maple wood (de Moura and Hernández 2006c). This can be explained by the variable basic properties of the substrates, as well as those of the varnishes used for the experiments.

TABLE 2. Pull-off adhesion strength for a water-borne (WB) and a solvent-borne (SB) coating applied to paper birch wood machined by three surfacing methods.

Surfacing method	Pull-off adhesion before aging (MPa)		Pull-off adhesion after aging (MPa)		Lost in adhesion (%)	
	WB	SB	WB	SB	WB	SB
Helical planing	5.1 <sup>1</sup> A <sup>3</sup> a <sup>4</sup> (0.2) <sup>2</sup>	4.6 Aa (0.3)	4.4 Aa (0.2)	2.9 Ba (0.2)	13	37
Face milling	5.9 Aa (0.2)	5.4 ABa (0.4)	4.3 Ba (0.3)	2.7 Ca (0.1)	27	50
Sanding	5.5 Aa (0.3)	5.4 Aa (0.3)	4.2 Ba (0.2)	3.0 Ca (0.1)	24	44

<sup>1</sup> Means of 26 replicates.

<sup>2</sup> Standard error of the means in parentheses.

<sup>3</sup> Means in a row followed by the same uppercase letter are not significantly different at the 5% probability level.

<sup>4</sup> Means in a column followed by the same lowercase letter are not significantly different at the 5% probability level.

### CONCLUSIONS AND RECOMMENDATIONS

Although all three surfacing techniques generated samples with the same coating performances, helical planing had a lower pull-off strength loss after the aging treatment. Thus, helical planing showed the best potential for long-term utilization since the coating-substrate bond created was of better quality. Good cell-wall fibrillation, no subsurface damage, and high wetting properties seemed to be the best combination to obtain good and long-term coating performance. Also, the water-borne coating proved to have better adhesion strength than the solvent-borne.

Further research needs to be done to determine the optimal level of cell-wall fibrillation, and how to qualify and quantify it. Also, good wetting properties are essential to achieve good wood-coating adhesion strength but more research is needed to determine what parameter would describe it best. Face milling and helical planing may not have been performed under their optimal cutting conditions. For instance, the optimal rake angle of both machining techniques was not determined. Once all cutting parameters are optimized, the helical planing and face milling should yield even better results.

### ACKNOWLEDGMENTS

The authors thank Luc Germain and Jean-François Mercier for valuable assistance, as well as Meubles Laurier and Forintek Canada Corp. for technical support during coating and sanding tests, respectively. This research was supported by Développement Économique Canada.

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