CHARACTERISTICS OF SUGAR MAPLE WOOD SURFACES PRODUCED BY HELICAL PLANING

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ABSTRACT

In real helical planing, the knives form a continuous oblique cutting edge with an angle to the cutterhead rotation axis. Tool manufacturers affirm that the helical cutterheads produce superior quality surfaces. However, literature on the effect of this cutting geometry on the surface quality of planed wood is scarce. The surface quality of helical-planed sugar maple was evaluated as a function of two planing modes, four feed speeds, and three cutting depths. The helical planing across the grain produced surfaces with higher roughness and improved wetting properties. A slight torn grain was observed in some samples that were helical-planed obliquely to the grain. As feed speed increased, surfaces became rougher and wetting was accelerated. Increasing cutting depth reduced surface roughness, mainly when planing across the grain. Cross-grain helical planing appears to have a good potential to reduce dependence on sanding to improve surface adhesion properties and enhance performance of coatings.

Keywords: Helical, planing, surface, roughness, wetting, sugar maple.

INTRODUCTION AND BACKGROUND

In peripheral planing, the workpiece surface is produced by a successive action of knives installed onto the periphery of a rotating cutterhead (Koch 1964). In conventional straight-knife peripheral planing, the cutting edges of knives are parallel to the cutterhead rotation axis. Given that in some cases this type of planing tends to produce defects on wood surface, an additional sanding process is required in order to obtain a defect-free surface. Furthermore, straight-knife planing is one of the main sources of noise in wood industries (Stewart and Hart 1976). To reduce machining defects and noise level, helical-knife peripheral planing has been proposed. In real helical-knife planing, the knives are mounted onto the periphery of a cutterhead with an angle to the axis of rotation, called the helix angle, and form a continuous oblique cutting edge (Stewart 1971b; Stewart and Hart 1976). The helical geometry provides a gradual cut: only a few peripheral points of the cutting cylinder make simultaneous contact with the workpiece, producing concentrated forces that travel across the workpiece. Therefore, the cutting impact occurs only at one lateral edge of the workpiece as each knife starts to cut (Stewart 1975b). In contrast, in straight-knife planing, the cutting impact takes place simultaneously across the entire workpiece width (Stewart and Hart 1976).

It is generally admitted that torn grain and raised grain are reduced in helical planing, due to a less severe cutting action. The occurrence of chipmarks should also be reduced by this cutting

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geometry, given that chips are easily moved away from the cutting zone during the cutterhead rotation (Jones 1994). Surface quality produced by planing across the grain is approximately the same using either the straight-knife or the helical cutter, but the latter is quieter (Stewart and Lehmann 1974). In addition, feeding the helical cutterhead with the wood grain parallel to the cutting edge reduces the incidence of tearing, mainly around knots or in peculiar grain patterns (York 1975). In tests with a prototype machine, Koch (1976) positioned a helical tool according to this principle. The planing mode suggested by Stewart and Lehmann (1974), York (1975), and Koch (1976) induces a 0°–90° cut. According to Stewart (1975a), this cutting mode provides the best surface quality for planing hardwoods, as it reduces the maximum defect depth.

Manufacturers of wood machinery claim that the helical cutterheads reduce noise and produce better surface quality. The efficiency of the helical geometry on noise reduction has been widely demonstrated in previous works (Stewart 1975b; York 1975; Berolzheimer 1991). However, little literature is available concerning the effect of this cutting geometry on the quality of planed wood surfaces. Therefore, the main objective of this work is to evaluate the surface quality of helical-planed sugar maple wood as a function of planing mode, feed speed, and cutting depth. Surface quality was assessed by roughness measurements, cell damage analyses, and wetting tests. The relationships between surface roughness and wettability are discussed.

MATERIALS AND METHODS

Testing materials

Sugar maple (*Acer saccharum* Marsh.), a diffuse-porous hardwood commonly used for indoor applications, was selected for this study. Commercial air-dried flat-sawn sapwood boards were conditioned at 20°C and 40% relative humidity (RH) until 8% equilibrium moisture content (EMC) was reached. After conditioning, the original group of 2400-mm (L) boards was divided into two independent groups of forty boards each. Each board was crosscut into six matched sections 350 mm (L) in length. These sections were edge-machined to 50-mm (T) width and planed to a thickness of 20 mm (R). These samples underwent a helical planing treatment and were re-sectioned to prepare specimens for roughness and wetting tests. The average and standard deviation of basic density of the boards were 595 and 28 kg/m^3, respectively.

Machining treatments

The helical planing treatments were performed with a Casadei R63H3 24″ surface planer provided with a freshly sharpened flexible knife. This knife was replaced every six treatments to reduce the effect of knife wear on the quality of wood surfaces. The rake and helix angles were 30° and 14°, respectively. Boards from the first group underwent an oblique (76°–14°) peripheral planing. These boards were fed into the planer with the wood grain aligned perpendicularly to the cutterhead rotation axis. Boards from the second group were cross-grain (0°–90°) peripheral planed. For this purpose, the boards were fed with the wood grain aligned obliquely to the cutterhead axis and parallel to the knife edge (as Stewart and Lehmann 1974). Two jig boards were hence built in order to hold samples in an accurate position during feeding and to reduce vibration. For each planing mode, the matched sections were planed at three cutting depths (0.5, 1.0, and 1.5 mm) and four feed speeds (5.5, 7.0, 8.5, and 10.0 m/min). The feed speeds corresponded to 26, 20, 17, and 14 knife marks per 25.4 mm of length, and 0.99, 1.26, 1.53, and 1.80 mm of wavelength, respectively. The lowest feed speed level was the slowest speed of the planer. A helical planing at 0.5 mm of depth was carried out to level samples prior to machining treatment.

Surface wettability tests

It has been previously demonstrated that wetting analysis provides important information on the surface quality for adhesion of coating films (de Moura and Hernández 2005). Wetting analysis was performed within 6 h after machining treatments with a FTÅ D200 imaging goniometer at room conditions of 20°C and 40% RH. Small droplets (6 μl) were added to the machined wood surfaces with an injection microsyringe. A frame grabber recorded the changes in contact angle of droplets during the first 100 s of wetting. All measurements were carried out with a view parallel to the orientation of wood fibers. Distilled water and formamide were used as probe liquids. One test of each liquid was performed on each specimen for a total of 40 measurements for each machining treatment. Contact angle was calculated as an average of both sides of droplets to compensate for horizontality variations. The initial contact angles of water and formamide, recorded immediately after droplet deposition, were used to estimate the wood surface energies by the harmonic mean approach (Wu 1971). To quantify the water spreading and penetration, the k-value proposed by Shi and Gardner (2001) was calculated for each machining condition. The total time taken to wetting and complete penetration was also recorded for water.

Surface topography measurements

Roughness measurements were carried out on defect-free zones with a Hommel T1000 waveline-20 profilometer equipped with a TKL 300L stylus pick-up. The pick-up travel length and cut-off length were set to 20 mm and 2.5 mm, respectively. Measurements were performed at 0.5 mm/s. Roughness parameters were calculated as an average of five consecutive cut-off lengths for each pick-up travel length. The roughness average (R_a) was determined, as well as skewness coefficient (R_{sk}), according to ISO 4287-1 (1984). The surface profile was assessed in the parallel and perpendicular directions to the grain. One pick-up travel length was performed in each direction for a total of 40 for each machining treatment. For torn-grain zones, the maximum defect depth was measured by a MTI Microtrak 7000 laser triangulation sensor. This latter assessment considered a variable number of replicates per treatment, according to the occurrence of defects.

Microscopic evaluation

Small blocks measuring 8 mm^2 on the machined tangential face were cut from boards for scanning electron microscopy (SEM) evaluation. For subsurface cell damage analysis, another group of blocks measuring 8 mm^2 on the transverse face was prepared with a razor blade mounted onto a microtome, by carefully cutting one of the end-grain surfaces. All blocks were then desiccated with phosphorus pentoxide for two weeks, mounted onto standard aluminium stubs with silver paint and coated with gold/palladium in a sputter-coater. Electron micrographs were taken for two representative machined surfaces and subsurfaces for each machining treatment.

RESULTS AND DISCUSSION

Surface topography

The values of roughness average (R_a) measured along and across the grain for three cutting depths, four feed speeds, and two planing modes in helical planing are presented in Table 1.

The helical planing oblique to the grain produced smooth and glossy surfaces (Fig. 1). The appearance of these surfaces was similar to those normally produced by peripheral straight-knife planing at low feed speeds. Surface gloss and smoothness increased at lower feed speeds (Table 1). The roughness averages measured along and across the grain were 1.6 μm and 1.5 μm, respectively (all oblique planing conditions pooled). This roughness level was lower than that obtained in a previous work with peripheral straight-knife planing of sugar maple at 15° rake angle and with 34 knife marks per 25.4 mm of length (de Moura and Hernández 2005).

The helical planing across the grain provided surfaces with higher roughness. This effect was observed in roughness measured along and across the grain (Table 1). For this planing mode, the roughness average was significantly

TABLE 1. *Average of roughness average (R_a) of helical-planed sugar maple surfaces measured along and across the grain for three cutting depths, four feed speeds, and two planing modes.*

Cutting depth (mm)	Feed speed (m/min)	Planing oblique to the grain[1]		Planing across the grain[1]	
		$R_{a//}$[2] (μm)	$R_{a\perp}$[3] (μm)	$R_{a//}$ (μm)	$R_{a\perp}$ (μm)
0.5	5.5	1.3 (0.1)[4] A[5] a	1.5 (0.1) A ab	2.6 (0.3) A a	3.1 (0.2) A a
	7.0	1.6 (0.1) AB a	1.8 (0.3) A a	3.2 (0.3) A ab	3.8 (0.3) A a
	8.5	1.9 (0.2) B a	1.7 (0.1) A a	5.1 (0.4) B b	4.8 (0.3) AB b
	10.0	1.9 (0.1) B a	1.5 (0.1) A a	4.6 (0.4) B b	5.5 (0.3) B b
1.0	5.5	1.3 (0.1) A a	1.7 (0.1) A b	3.8 (0.3) A b	3.7 (0.2) A a
	7.0	1.5 (0.1) AB a	1.4 (0.1) A a	3.8 (0.3) A b	3.4 (0.2) A a
	8.5	1.7 (0.1) B a	1.5 (0.1) A a	2.9 (0.2) A a	4.2 (0.3) A ab
	10.0	1.6 (0.1) AB a	1.3 (0.1) A a	3.0 (0.2) A a	4.3 (0.4) A a
1.5	5.5	1.4 (0.1) A a	1.2 (0.1) A a	2.9 (0.2) A ab	3.3 (0.2) A a
	7.0	1.3 (0.1) A a	1.4 (0.1) A a	2.8 (0.2) A a	3.6 (0.2) A a
	8.5	1.6 (0.1) A a	1.5 (0.1) A a	2.5 (0.2) A a	3.3 (0.2) A a
	10.0	1.7 (0.1) A a	1.6 (0.1) A a	2.7 (0.2) A a	3.7 (0.2) A a

[1] Means of twenty replicates.
[2] Roughness average measured along the grain.
[3] Roughness average measured across the grain.
[4] Standard error of the mean in parentheses.
[5] Means within a column followed by the same letter are not significantly different at the 5% probability level. Uppercase letters are for feed speed comparison, for each cutting depth separately. Lowercase letters are for cutting depth comparison, for each feed speed separately.

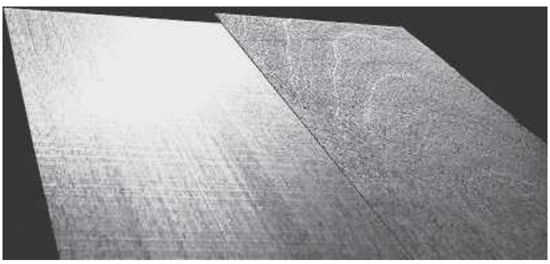

FIG. 1. Macroscopic view of sugar maple helical-planed boards. At the left-hand side, a surface obtained by helical planing oblique to the grain; at the right-hand side, a surface produced by helical planing across the grain.

higher when measured perpendicular to the grain (3.9 μm) than along the grain (3.3 μm, all across-grain planing conditions pooled). The surfaces planed across the grain were generally not glossy (Fig. 1) and presented a tactile roughness very similar to that of sanded surfaces. A slight fuzzy texture occurred occasionally where the grain was uneven. This texture pattern was predominantly observed on earlywood tissues, whilst the thin latewood bands appeared often smoother and glossier (Fig. 1). The higher roughness in earlywood is also attributed to the presence of very small longitudinal grooves, which were absent in latewood.

Roughness of surfaces tended to increase as feed speed increased. This was expected given that faster feed speeds generate deeper and wider knife marks. However, differences in roughness between 8.5 m/min and 10 m/min were not statistically significant, given that the interval of the number of knife marks generated between these two feedings was short (Table 1). Positive correlations were found between feed speed and R_a measured along the grain for helical planing oblique to the grain (Table 2) and between feed speed and R_a measured across the grain for helical planing across the grain (Table 3). In contrast, no correlations were found between these two variables when R_a was measured in the other direction (across the grain, Table 2; along the grain, Table 3). Therefore, the effect of feed speed was apparent only when roughness was measured in the same direction as the planing action (i.e. across the knife marks).

For planing oblique to the grain, the surface skewness coefficient (R_{sk}) became more negative for both directions of measurement as feed speed decreased (Table 4). This indicates that surfaces presented more material on the top of the roughness profile as feed speed decreased, producing smoother plateau-like regions. This

TABLE 2. *Pearson correlation coefficients obtained among machining parameters and surface properties of sugar maple wood after helical planing oblique to the grain.*

Parameter	Wetting time (s)	k-value	Surface energy (dynes/cm)	$R_{a//}$[3] (μm)	$R_{a\perp}$[4] (μm)
Cutting depth	−0.018[1]	−0.016	0.037	−0.044	−0.148
(mm)	0.780[2]	0.810	0.565	0.501	0.022
Feed speed	−0.200	0.135	−0.057	0.306	−0.006
(m/min)	0.002	0.039	0.379	0.001	0.930
Wetting time		−0.528	−0.242	−0.151	−0.061
(s)		0.001	0.001	0.020	0.347
k-value			0.088	0.125	0.058
			0.180	0.056	0.382

[1] Pearson correlation coefficient (r) for 240 replicates.
[2] Prob. > |r| under H_o: $\rho = 0$.
[3] // index for measurement taken along the grain.
[4] ⊥ index for measurement taken across the grain.

TABLE 3. *Pearson correlation coefficients obtained among machining parameters and surface properties of sugar maple wood after helical planing across the grain.*

Parameter	Wetting time (s)	k-value	Surface energy (dynes/cm)	$R_{a//}$[3] (μm)	$R_{a\perp}$[4] (μm)
Cutting depth	0.104[1]	−0.138	0.279	−0.326	−0.240
(mm)	0.107[2]	0.041	0.001	0.001	0.001
Feed speed	−0.170	0.052	0.035	0.100	0.258
(m/min)	0.008	0.441	0.586	0.121	0.001
Wetting time		−0.631	−0.200	−0.355	−0.294
(s)		0.001	0.002	0.001	0.001
k-value			0.066	0.331	0.204
			0.335	0.001	0.002

[1] Pearson correlation coefficient (r) for 240 replicates.
[2] Prob. > |r| under H_o: $\rho = 0$.
[3] // index for measurement taken along the grain.
[4] ⊥ index for measurement taken across the grain.

TABLE 4. *Skewness coefficients measured along ($R_{sk//}$) and across ($R_{sk\perp}$) the grain as a function of the feed speed, for sugar maple surfaces helical-planed oblique to the grain.*

Feed speed (m/min)	5.5[1]			7.0			8.5			10.0		
$R_{sk//}$	−0.92 (0.1)[2]	A[3]	b[4]	−0.80 (0.1)	A	b	−0.60 (0.1)	B	b	−0.44 (0.1)	C	b
$R_{sk\perp}$	−1.77 (0.2)	A	a	−1.21 (0.2)	B	a	−1.22 (0.2)	B	a	−1.02 (0.2)	B	a

[1] Means of sixty replicates (cutting depths pooled).
[2] Standard error of the mean in parentheses.
[3] Means within a row followed by the same uppercase letter are not significantly different at the 5% probability level.
[4] Means within a column followed by the same lowercase letter are not significantly different at the 5% probability level.

could explain the glossier surface observed at lower feed speeds in this planing mode. The R_{sk} of surfaces planed across the grain was not affected by feed speed.

Roughness tended to decrease as cutting depth increased (Tables 1, 2, and 3). This effect was more pronounced in planing across the grain than in planing oblique to the grain. For planing across the grain, the effect of cutting depth on R_a was more prominent at 8.5 m/min and 10 m/min feed speeds (Table 1). From 0.5-mm to 1.5-mm cutting depth, R_a decreased 11% and 25% for planing oblique and across the grain, respectively (feed speeds and directions of measurement pooled). In planing across the grain, the skewness coefficient (R_{sk}) measured perpendicular to the grain became more positive with increasing cutting depth (not shown). This meant that surfaces planed across the grain had a higher concentration of material near the basis of the roughness profile as cutting depth increased.

The decrease in surface roughness with increasing cutting depth was induced by a reduction in planing vibration as cutting depth increased. Vibration measurements performed with a laser triangulation sensor on samples during planing confirmed that such parameter decreased as cutting depth increased (not shown). This behavior is explained by the continuous contact of the helical knife with the workpiece during the cut. The length of continuous contact between the knife and the workpiece corresponds to the length of path of knife engagement. This length, which may be calculated by the equation presented by Koch (1964), is strongly increased by increasing cutting depth. In this experiment, the lengths of path of knife engagement were of 8, 11, and 14 mm for the 0.5-, 1.0-, and 1.5-mm cutting depths, respectively (feed speeds pooled). Thus, under the range of cutting depths studied, higher lengths of continuous contact have probably contributed to better stability during planing.

Torn grain was seldom observed, being restricted to regions with severe grain deviations. This defect was virtually only observed on samples that had been planed obliquely to the grain, although their defect-free surfaces were much smoother than those planed across the grain. The average maximum defect depth in this experiment was 219 μm (all oblique planing conditions pooled). The depth and frequency of torn grain tended to increase by increasing feed speed (Fig. 2). This result has been reported also for sugar maple planed with straight knives (Davis 1962; Cantin 1967; Stewart 1971a). For samples machined at 5.5-m/min feed speed, a subsequent sanding with a 0.3-mm removal depth would be sufficient to produce defect-free surfaces (Fig. 2). Otherwise, surfaces obtained at 10-m/min feed speed would require a 0.5-mm removal depth. The maximum individual depth of torn grain produced in planing oblique to the grain was 562 μm. In this experiment, the helical knife worked with a relatively high rake

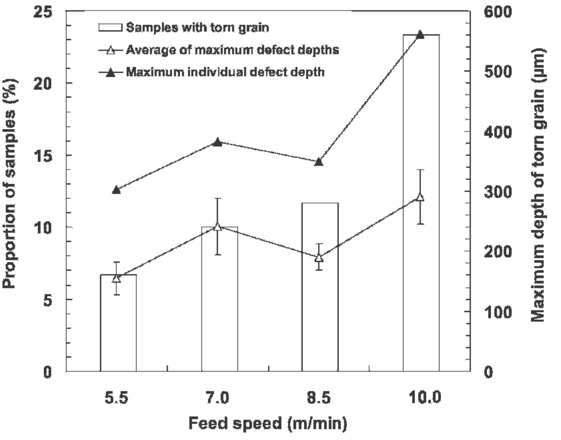

FIG. 2. Proportion of samples with torn grain (left y-axis) and maximum defect depth (right y-axis) as a function of feed speed for helical planing oblique to the grain (cutting depths pooled).

angle (30°), which probably induced high negative normal forces. These upward forces tended to increase the risk of torn grain. Thus, further investigations are required in order to obtain an optimal rake angle for peripheral helical planing.

SEM evaluation

In peripheral straight-knife planing, cutting forces are almost composed only of the normal and parallel components. In helical planing, a lateral force component is also generated. The surfaces produced by planing oblique to the grain presented different levels of detachment of vessel walls, caused by lateral cutting forces (Figs. 3a–b). However, vessels were always open and lumens of fibers and rays were often visible in these surfaces (Fig. 3c). Peripheral straight-knife planed surfaces of sugar maple showed lumens of fibers and rays not frequently opened, while smooth crushed zones were very common (de Moura and Hernández 2005). These smooth zones were also observed after helical planing oblique to the grain, but to a lesser extent (Fig. 3d). This indicates that the helical knife produced less of a crushing effect than the straight knife did. The lateral force component generates a shear stress between cells above and below the cutting plane, occa-

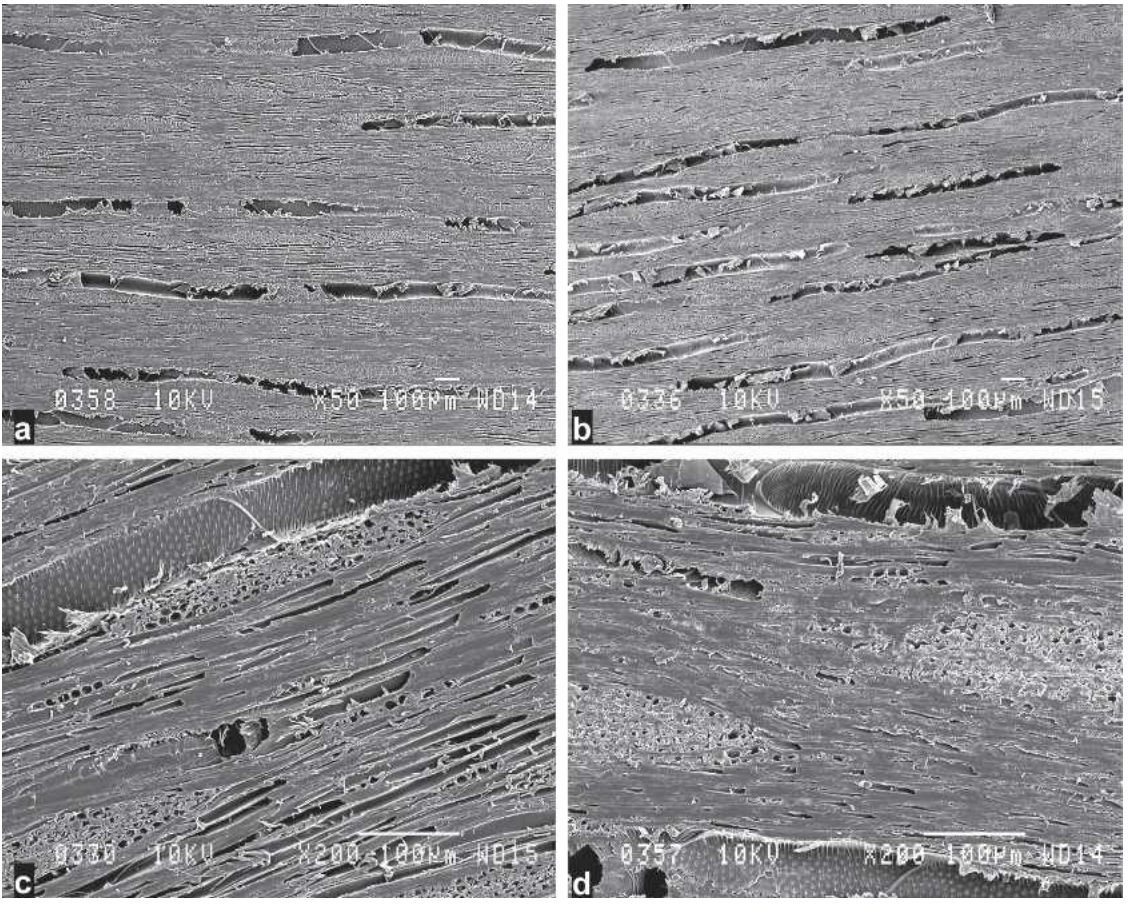

FIG. 3. Tangential surfaces of sugar maple helical-planed oblique to the grain. Low (a) and relatively severe (b) tearing out of vessel walls; sound cut vessels, rays, and fibers (c); predominance of plateau-like zones, torn-out vessel walls, and relatively crushed rays (d).

sionally causing separation of cells from middle lamella. This shear effect was more pronounced at higher feed speeds (Fig. 4).

The surfaces produced by planing across the grain were characterized by the presence of packets of microfibrils, individual cells, and groups of cells torn-out from the workpiece at different levels (Figs. 5a–b). When cutting in the 0°–90° mode, the wood cells were not always sectioned by the knife edge and chips were often removed from the workpiece by pulling out cells from middle lamella (Fig. 6). This surfacing process induces the formation of small longitudinal grooves, left on the surface by pulled-out individual cells or groups of cells. These small valleys accentuate the natural grain texture of wood, being perceptible by careful naked-eye inspection. In rare cases, a large group of cells is pulled out producing a deep valley in the surface, which may be regarded as torn grain. In this study, only three samples planed across the grain presented this defect and were obtained at the highest levels of cutting depth and feed speed. To reduce the risk of large grooves in the surface, the cutting depth should not be much higher than 1 mm when planing across the grain at 8.5 m/min feed speed. If a faster production is required, a 10 m/min feed speed could be used, but cutting depth should be limited to about 0.5 mm.

When planing across the grain, the helical knife attacks rays transversally, with its edge

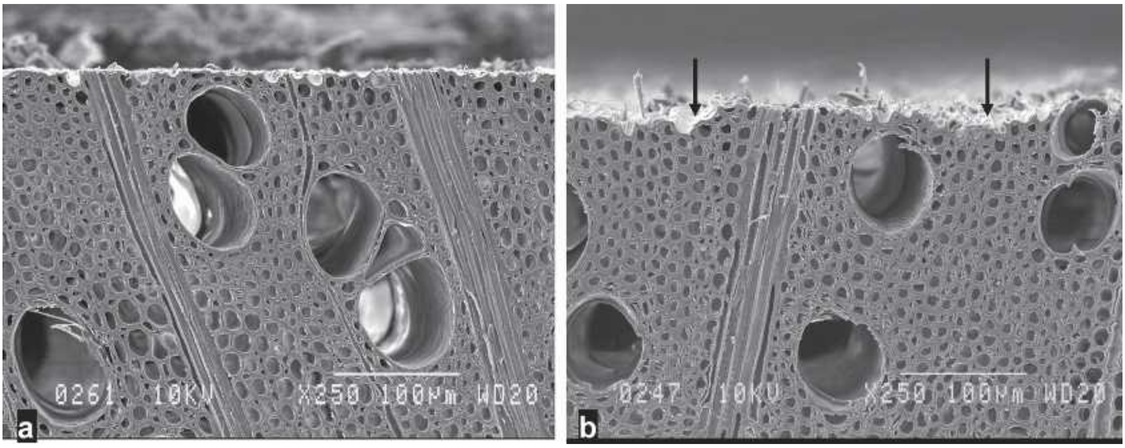

FIG. 4. Transverse SEM micrographs of sugar maple surfaces produced by helical planing oblique to the grain at increasing feed speeds. Smooth surface obtained at 5.5 m/min feed speed (a); higher roughness and slight tearing out of cells (arrows) at 10.0 m/min feed speed (b).

virtually parallel to the height of rays. This cutting situation often facilitated ruptures by bending of rays below the cutting plane. In general, these ruptures were deeper in multiseriate rays than in uniseriate rays (Fig. 7a). At lower feed speeds, rays were often incompletely severed, leaving some uncut cells above the cutting plane (Figs. 5d and 7a). At higher feed speeds, rays tended to be completely removed from the region of rupture. In this latter case, multiseriate rays left deeper valleys than uniseriate rays did (Fig. 7b).

The lateral forces generated in planing across the grain caused severe separation of vessel walls and pushed neighboring cells into vessels (Figs. 5c–d and 7c). At higher feed speeds, the cutting edge tended to completely remove the tissues near vessels, leaving deep valleys (Fig. 7d). This effect was not noticed at lower feed speeds. Thus, for species having large vessels (e.g. oaks), a very low feed speed would be recommended in order to prevent this type of machining defect.

The presence of torn-out fibrils, individual cells, and groups of cells (Fig. 6b) could contribute to a stronger adhesion of film-forming coatings applied on samples planed across the grain. Fibrillation is desirable for adhesion, but it has to be limited to an extent in that it cannot be considered as a machining defect, i.e. fuzzy grain. The importance of torn-out fibrils on mechanical adhesion of a film-forming coating was demonstrated for sanded surfaces of sugar maple in a previous work (de Moura and Hernández 2005). However, sanding produces a superficial layer of crushed cells that hinders coating penetration and may behave as a mechanical weak boundary layer, facilitating cohesive rupture. Otherwise, the cross-grain helical planing provides a high number of anchorage points with virtually no superficial crushing.

Surface wettability

Wetting analysis could easily distinguish between surfaces obtained by helical planing across and oblique to the grain. However, only the total wetting time and the k-value were sensitive enough to differentiate between levels of feed speed and cutting depth. Furthermore, these two wetting parameters were previously shown to be the most significantly related to the pull-off adhesion strength of coating films on wood surfaces (de Moura and Hernández 2005). The results obtained for total wetting time and k-value for all planing conditions are summarized in Table 5.

As seen by the shorter total wetting times observed, surfaces planed across the grain were

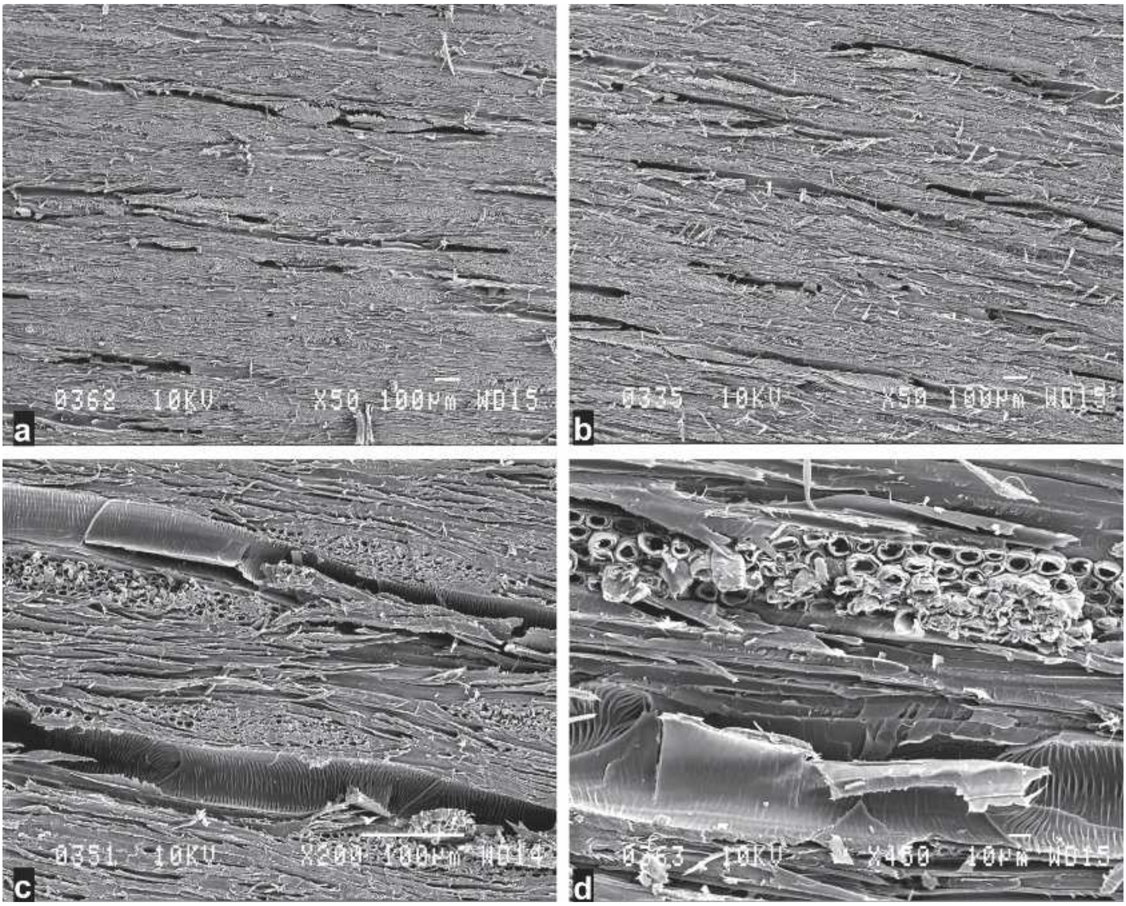

FIG. 5. Tangential surfaces of sugar maple helical-planed across the grain. Low (a) and relatively high (b) levels of fibrillation; neighboring cells pushed into vessels (a–c); severe separation of vessel walls and incompletely severed rays (c–d).

more wettable than surfaces planed oblique to the grain (Table 5). This effect can be attributed to the higher roughness and, as a consequence, higher capillarity of these surfaces. Surfaces planed across the grain offered better conditions for water spreading due to the capillaries left by pulled-out cells (Figs. 6 and 7). This effect was not noticed for surfaces planed oblique to the grain. As a result, the overall average time taken to complete spreading and penetration was considerably less in planing across (168 s) than in planing oblique to the grain (610 s). The statistically significant higher k-values confirm that the cross-grain planing mode provided faster spreading (Table 5).

In helical planing across the grain, roughness was negatively correlated with wetting times and positively correlated with k-values. This indicates that roughness enhanced the wetting properties for this planing mode (Table 3). Other researchers have previously associated better wettability to higher surface roughness (Wenzel 1936; Dolenko et al. 1974; de Moura and Hernández 2005). However, this relationship was not detected with the surfaces planed obliquely to the grain, which is probably due to the low influence of capillaries on wetting (Table 2).

The average initial contact angle for water was significantly higher in surfaces planed oblique to the grain (57.9°) than in those milled across the grain (51.0°). The former surfaces

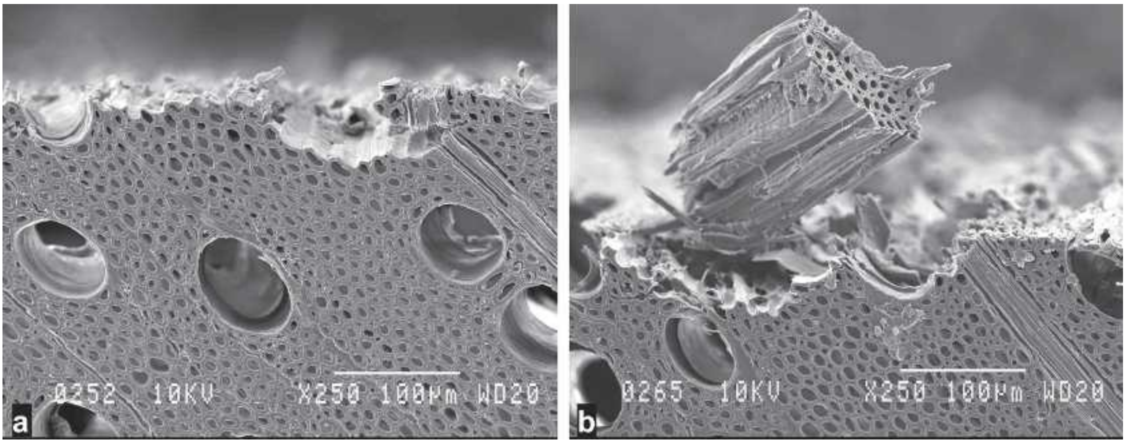

FIG. 6. Transverse SEM micrographs of sugar maple surfaces produced by helical planing across the grain. Valley left by a group of fibers torn-out from middle lamella (a); group of torn-out fibers remaining attached to the workpiece (b).

also presented a lower average surface energy (45.8 dynes/cm) than the latter surfaces (50.4 dynes/cm). In this study, measurements of the initial contact angle were carried out at 0.1-s intervals. Therefore, initial contact angles were recorded before they were significantly affected by surface profile (i.e. with negligible roughness hysteresis). As a result, no correlations between initial contact angle and surface profile parameters were found. In fact, at the beginning of wetting, the surface voids are still filled with air and the real initial contact angle can be measured (Liptáková and Kúdela 1994). Furthermore, the coefficient of variation was much higher in surface profile assessments (e.g. 59%, for $R_{a\perp}$) than in initial contact angle measurements (13%, for all machining variables pooled). These results could indicate that machining treatments had much more effect on surface profile than on initial contact angles. The deviations in initial contact angle and surface energy could hence be attributed to slight chemical variations on surfaces.

The total time taken to complete wetting and penetration by water tended to decrease by increasing feed speed for the two planing modes (Tables 2 and 3). However, this effect was statistically significant only at the 0.5-mm cutting depth, for both planing modes (Table 5). In planing oblique to the grain, a significant reduction in total wetting time was noticed only for the highest level of feed speed, whereas in surfaces planed across the grain this reduction was observed from the 8.5 m/min feed speed (Table 5). This acceleration of wetting is associated to the increase in surface roughness as feed speed increases (Table 1).

Cutting depth presented significant correlations with k-value for planing across the grain only (Table 3). The k-value tended to be reduced by increasing cutting depth, although no differences were detected between averages (Table 5). The pooled average of k-values for planing across the grain at 1.5-mm cutting depth (0.459) was significantly lower than the pooled average of 0.5-mm and 1.0-mm cutting depths (0.609) (feed speeds pooled). This tendency of reduction in k-values was probably associated to the decrease in surface roughness as cutting depth increased (Tables 1 and 3). Otherwise, surface energy was improved by increasing cutting depth in planing across the grain (Table 3). As mentioned above, surface energy was not affected by surface profile and its variations are likely caused by variations in chemical characteristics of surfaces. The friction between the chips and the knife rake face becomes higher as cutting depth increases. As a result, higher temperatures may have been generated during deeper cuts,

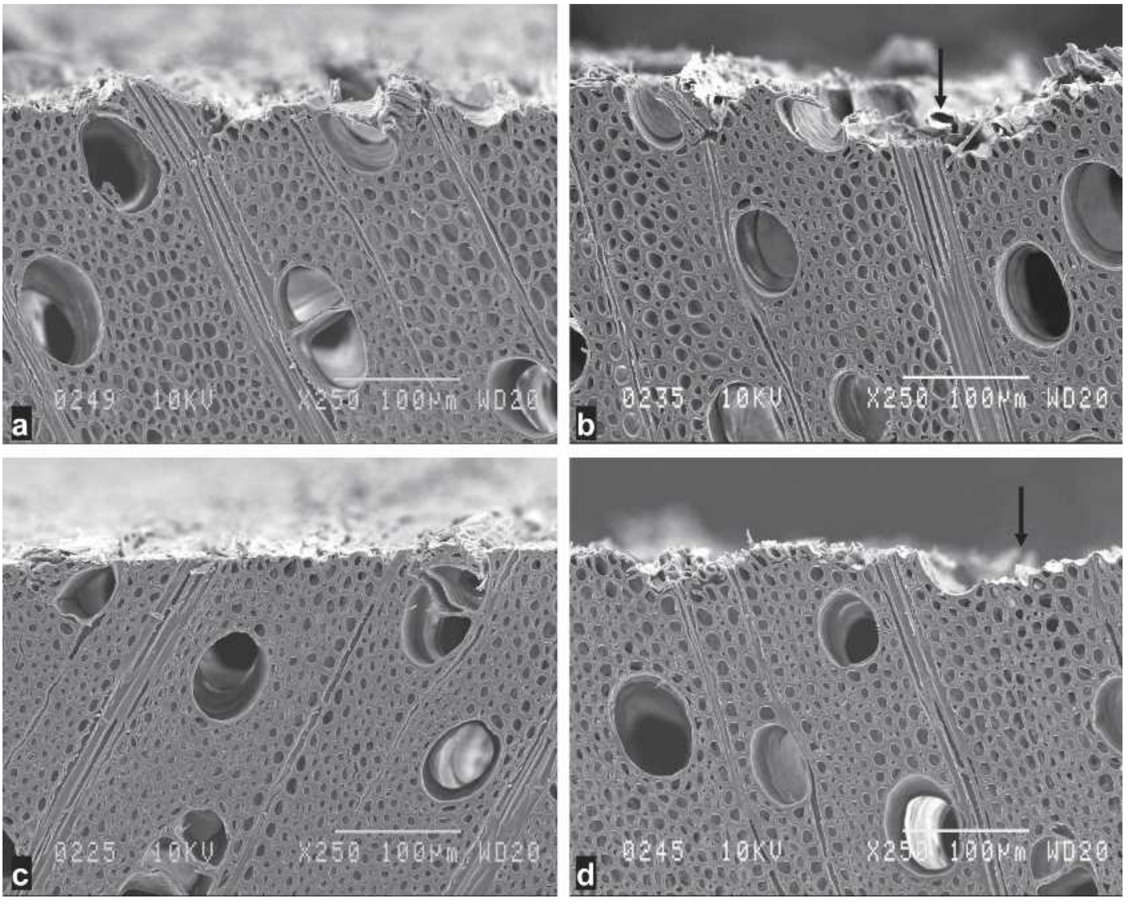

FIG. 7. Transverse SEM micrographs of sugar maple surfaces produced by helical planing across the grain. Rays presenting ruptures by bending below the cutting plane (a–b); multiseriate ray with rupture deeper than in uniseriate ray (a); arrow indicates a multiseriate ray and neighboring cells completely removed from the surface at the highest feed speed (b). Neighboring cells pushed into vessels at the lowest feed speed (c); arrow indicates tissues completely removed near a vessel at the highest feed speed (d).

which could accelerate oxidation at the wood surface. The increase of wood surface energy by means of oxidation has been previously reported (Gray 1964; Wålinder 2000).

The total time taken to complete wetting was negatively correlated with surface energy (Tables 2 and 3). This indicates that wetting time was influenced not only by capillarity forces, provided by roughness, but also by surface energy. For all machining treatments pooled, the roughness average measured across the grain and the surface energy accounted for 49% and 8% of the total variation in wetting time, respectively.

CONCLUSIONS AND RECOMMENDATIONS

Surfaces produced by helical planing oblique to the grain were smoother and glossier than those produced by straight-knife planing in a previous work. These surfaces were characterized by slow liquid spreading and low number of anchorage points for mechanical adhesion of coating films. In planing across the grain, chip formation takes place predominantly by pulling out cells or groups of cells from middle lamella. Due to its particular mechanism of chip formation, helical planing across the grain produces surfaces with higher roughness and accentuated

TABLE 5. *Total wetting time and k-value, using water as probe liquid, for sugar maple surfaces helical-planed at three cutting depths, four feed speeds, and two planing modes.*

Cutting depth (mm)	Feed speed (m/min)	Planing oblique to the grain[1]						Planing across the grain[1]					
		Total wetting time (s)			k-value			Total wetting time (s)			k-value		
0.5	5.5	654 (27)[2]	B[3]	a	.088 (.012)	A	a	258 (30)	B	b	.476 (.096)	A	a
	7.0	627 (35)	AB	a	.144 (.019)	A	a	193 (35)	AB	a	.613 (.087)	A	a
	8.5	646 (22)	AB	a	.103 (.014)	A	a	100 (20)	A	a	.686 (.095)	A	a
	10.0	520 (50)	A	a	.108 (.014)	A	a	104 (16)	A	a	.622 (.085)	A	a
1.0	5.5	651 (32)	A	a	.089 (.009)	A	a	164 (26)	A	a	.601 (.096)	A	a
	7.0	592 (46)	A	a	.167 (.030)	AB	a	144 (16)	A	a	.627 (.092)	A	a
	8.5	635 (32)	A	a	.077 (.006)	A	a	151 (26)	A	a	.618 (.098)	A	a
	10.0	583 (38)	A	a	.141 (.026)	A	a	145 (22)	A	ab	.631 (.084)	A	a
1.5	5.5	642 (29)	A	a	.067 (.008)	A	a	161 (19)	A	a	.466 (.089)	A	a
	7.0	636 (35)	A	a	.123 (.029)	AB	a	239 (34)	A	a	.454 (.089)	A	a
	8.5	603 (40)	A	a	.082 (.015)	A	a	173 (19)	A	a	.437 (.101)	A	a
	10.0	535 (48)	A	a	.161 (.017)	B	a	188 (25)	A	b	.477 (.076)	A	a

[1] Means of twenty replicates.
[2] Standard error of the mean in parentheses.
[3] Means within a column followed by the same letter are not significantly different at the 5% probability level. Uppercase letters are for feed speed comparison, for each cutting depth separately. Lowercase letters are for cutting depth comparison, for each feed speed separately.

grain texture. The evaluation of roughness and wetting properties indicates that surfaces produced by helical planing across the grain have a good potential for adhesion. Moreover, these latter surfaces presented virtually no cell crushing. Under this context, we hypothesize that cross-grain helical planing could effectively be an alternative treatment to sanding in preparing surfaces for coating.

The surface roughness and the occurrence of torn grain were increased with increasing feed speed. Torn grain was virtually only observed in planing oblique to the grain. Further research is required in order to set an optimum rake angle for helical planing of sugar maple. Some samples helical-planed across the grain might occasionally present abnormally large surface grooves when feeding is too fast and cutting is too deep. When planing across the grain, the cutting depth should not be much higher than 1 mm, and the number of knife marks per 25.4 mm of length should not be lower than 17, in order to obtain good wetting properties with low risk of large grooves in the surface. If a faster production is required, a feed speed set to achieve 14 knife marks per 25.4 mm of length could be used, but cutting depth should be limited to about 0.5 mm.

In this experiment, the length of boards was limited by the cutterhead length when planing across the grain. This problem could be solved by inclining the cutterhead arbor so that the knives attack with their edges parallel to the wood grain. This modification would allow to perform cross-grain helical planing with no limitation in board length and no need to adapt feed direction. The present study was carried out with thin flexible knives, which are highly susceptible to edge deformation by knots. Further studies with more wear-resistant material would be very important. Moreover, additional research should be developed to optimize the cross-grain helical planing for softwoods and ring-porous hardwoods.

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