WOOD MACHINING PROPERTIES OF POPLAR HYBRID CLONES FROM DIFFERENT SITES FOLLOWING VARIOUS DRYING TREATMENTS

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Abstract. Planing, sanding, turning, and routing properties of seven hybrid poplar clones from three growing sites were evaluated on kiln-dried specimens following three types of drying schedules, high temperature, elevated temperature, and conventional. Machining tests were performed at 8 and 12% MC according to ASTM D 1666-87. Surface quality was evaluated with qualitative and quantitative methods. Poplar clones performed well for planing, sanding, and routing and poor for turning. In general, machining performance was affected in decreasing order by machining, clones, kiln-drying treatments, and growing sites. The best planing was obtained at a 20° rake angle and at 24 knife marks per 25.4 mm. Better conditions should be obtained at a 17° rake angle and lower feed rates. Conventional drying positively affected planing performance compared with the other two drying processes. Sanding using 180-grit sandpaper performed excellently. Turning was better at 12% MC than at 8% MC. For routing, down-milling mode provided generally better surface quality than up-milling mode. Three clones were selected as more suitable for machining. Generally, denser wood behaved better than light wood for all machining processes. However, correlations between wood density and machining properties were weak. Although selection of best clones for wood density could indirectly help improve wood machining, direct measurement of these properties is preferable. Finally, only a few weak effects of drying and sites were observed on specific conditions of machining, and they were thus considered negligible.

Keywords: Planing, sanding, routing, turning, poplar hybrid, clones, surface quality, surface roughness.

INTRODUCTION

Although poplar species (*Populus* spp.) has long been considered to have low commercial value, it has become an economically important part of Canada's forestry. In Quebec, for instance, annual wood consumption increased from 240 Mm^3 in the 1960s to 5357 Mm^3 in 2004. Economic value of poplar (mainly aspen) has been predominantly created by the pulp and paper and the wood-based panel industries (Ménétrier 2008).

Considering that timber supplies in the future may become scarce, hybrid poplar plantations could play a more important role. In the late 1960s, the Quebec Ministry of Natural Resources and Wildlife initiated an active poplar breeding program. This program, in general, initially emphasized growth rate, bolt form, adaptability, and disease resistance and rapidly

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produced material better adapted to local conditions (Vallée 1995; Hernández et al 1998). High growth rate of genetically improved hybrid poplar clones in eastern Canada can result in trees reaching sawlog size in 15-20 yr with an annual yield of 8-12 m^3/yr/ha. Rotation time in hybrid poplar plantations can be two to three times faster than that of natural stands of poplar (Périnet 1999). However, wood properties from improved and intensively managed trees associated with short-rotation harvest are different and generally contain higher proportion of juvenile wood than that from natural stands (Bendtsen 1978). Juvenile wood has different properties than mature wood, but the range of variation is less in hardwoods than in softwoods (Bendtsen 1978; Mátyás and Peszlen 1997). However, large volumes of tension wood have been observed in juvenile wood of poplar species (Bendtsen 1978). Tension wood shrinks more than normal wood (often causing distortion in lumber during drying), is prone to collapse, and is also more difficult to machine (Clark 1958; Ritter et al 1993).

To use wood more efficiently in value-added products, physical, mechanical, drying, and machining properties must be taken into account. Some poplar tree improvement programs have assessed the main wood properties to pulp and panel industries (Bendtsen 1978; Beaudoin et al 1992; Zhang et al 2003; Pliura et al 2007). Genetic selection of poplar hybrid clones for specific solid wood end-use applications has received some attention (Hernández et al 1998; Koubaa et al 1998a, 1998b; de Boever et al 2007; Kang et al 2007; Kretschmann et al 1999; Peters et al 2002). Machining properties for several wood species coming from different countries have been reported (Mitchell and Lemaster 2002; Malkoçoglu 2007; Ratnasingam and Scholz 2007; Bustos et al 2009). Machining of the more important Canadian woods has also been evaluated (Cantin 1967; Williams and Morris 1998; Lihra and Ganev 1999). All these Canadian studies examined machined poplar wood from natural stands. However, wood from intensively managed stands or hybrid poplar clones has received little attention. Hernández et al (2001) compared wood machining properties of white spruce trees from a natural stand with that from a plantation site. The effect of two drying treatments on machining performance was also studied. Machining properties reported in these studies were fairly variable within the same species. This can be explained by natural variation in wood properties and by qualitative evaluations obtained by visual and tactile stimuli, which are subjected to individual perceptions and may introduce additional variability.

Quantitative assessment of surfaces of solid wood materials is another important criterion affecting secondary manufacturing processes for aesthetic or technical requirements. Surface quality is a function of wood material used, operational parameters, cutting tool geometry (Juan 2000), and engineering quality of equipment (Jackson et al 2002). Several methods and roughness parameters are available to assess quality of machined wood surfaces (Fujiwara et al 2005).

Significant use of *Populus* spp. in the secondary manufacturing sector has been limited because of substantial kiln-drying defects. Adapted drying schedules, modified sawing patterns, or a combination of both approaches for *Populus* spp. have been studied by Mackay (1974), Mackay et al (1977), Beauregard et al (1992), and more recently by Kärki (2002) to minimize lumber drying degrade. Very limited work is available for drying wood of hybrid poplar clones. Kang et al (2007) studied lumber quality variation of five clones following three kiln-drying schedules. Variation in lumber yield and drying quality caused by drying treatments was higher than that associated with the hybrid clone genotype.

This study evaluates machining properties of wood from seven poplar hybrid clones coming from three growing sites. Effect of three drying treatments on planing, sanding, routing, and turning properties was also analyzed. Machining quality was evaluated with qualitative and quantitative methods. The results will provide us with better knowledge about wood machining performance of various poplar hybrid clones prone to be used as raw material for the secondary wood products industry.

MATERIALS AND METHODS

Material for this study came from the experimental sites of Platon, St-Ours, and Windsor, which were established by the Ministry of Natural Resources and Wildlife of Quebec. The sites, originally abandoned agricultural lands, represent typical soil types available for planting hybrid poplar clones in southern Quebec. Detailed description of the experimental sites is given elsewhere (Pliura et al 2007).

Seven clones, each represented by five trees from each site, were selected for this study (Table 1). These clones are mainly recommended for southern Quebec, based on growth rate, bolt form, adaptability, and disease resistance (Vallée 1995). From July to early September 2007, 105 trees were harvested. Trees from St-Ours and Windsor were cut after 15 growing seasons. Trees from Platon were cut after 17 growing seasons, except for those of clone 915508, which were felled after 13 growing seasons. Each tree was cross-cut in three segments: a butt log of 1.50 m followed by two logs of 2.45 m long. Specimens for machining tests were all obtained from the 2.45-m log closest to the butt. Boards of 34 mm thick were sawn with a WoodMizer (Indianapolis, IN) portable bandsaw and stored in a freezer at approximately –4°C before drying.

Table 1. Clones of three poplar hybrids selected for study.

Clone	Hybrid[a]
131	D × N
3230	T × D
3565	D × N
3570	D × N
3586	D × N
4813	D × N
915508	DN × M

[a] D × N: *Populus deltoides* Bartr. ex Marsh × *P. nigra* L.; T × D: *P. trichocarpa* Torr. & Gray × *P. deltoides* Bartr. ex Marsh; DN × M: (*P. deltoides* Bartr. ex Marsh × *P. nigra* L.) × *P. maximowiczii* A. Henry.

To study the effect of three drying schedules on wood machining, the experiment was designed to obtain at least three boards from each tree for a total of 315. Therefore, each tree should be represented by one board within each drying schedule. However, some trees did not have the required dimension or quality to provide adequate boards. A total of 270 boards 34 mm thick, 70-200 mm wide, and 2.45 m long were obtained.

Boards were then dried to a target moisture content of 8% in a 2.5-m^3 experimental kiln using three treatments: a conventional schedule (dry bulb temperature [T_{db}] between 60 and 82°C), an elevated-temperature schedule (T_{db} between 60 and 90°C), and a high-temperature schedule (T_{db} between 90 and 115°C) with top restraint loading (7.5 kN/m^2) in each case. After drying, all boards were evaluated for drying quality, then planed to 25 mm thick, and stored in a conditioning room at 20°C and 40% RH to reach nominal equilibrium moisture content of 8%. This moisture content is suitable for indoor applications. Boards were then used to prepare specimens for different wood machining processes. Given the global quality of boards, machining specimens presented some natural defects such as small knots, slight grain deviations, and discolorations.

Wood Machining Tests

Machining tests were based on ASTM (2004) with some required adjustments. A sample size of five specimens was used for each clone, site, and drying treatment combination. When submitted to the various machining test conditions, samples were randomly selected. Knives were freshly sharpened, and machines used were always kept in good cutting conditions.

Planing tests. Specimens were 19 mm thick, 75 mm wide, and 910 mm long. Before planing, a 25-mm-long section was cross-cut from each specimen to evaluate moisture content and basic density (oven-dry weight to green volume ratio). Seven different planing tests were performed on a Weinig (Mooresville, NC) Powermat 1000 moulder. The top cutterhead was used and set to have only one knife working. Four rake angles (α), 11, 15.5, 20, and 25°, were studied with a feed rate adjusted to produce 20 knife marks per 25.4 mm. Additional tests were made at 20° rake angle and at three other feed rates that produced 12, 16, and 24 knife marks per 25.4 mm. In all cases, clearance angle was 40°, cutting depth was 1.6 mm, radius of the cutting circle was 56.4 mm, and cutterhead speed was 6000 rpm.

Sanding tests. Sanding was performed on a Costa and Grissom (Archdale, NC) Series E Model 36 wide-belt calibrating–sanding machine. Specimens 7 mm thick, 75 mm wide, and 30.5 mm long were prepared from pieces previously used for planing tests. Aluminium oxide sandpapers with abrasive grains coated with antistatic zinc stearate (SIA abrasives, Frauenfeld, Switzerland; TOPTEC series 1919) were used. An initial pass was performed with 80-grit sandpaper to calibrate all specimens to the same thickness. Three sanding programs were then tested: 120-, 120-150-, and 120-150-180-grit stages. Depth of cut was set at 0.2 mm for 120-grit sandpaper and at 0.1 mm for 150- and 180-grit sandpapers. Feeding was carried out in the fiber direction at 6.1 m/min feed speed. Specimens were evaluated after each sanding program.

Routing tests. Routing was conducted with a Pade (Bologna, Italy) Spin 5-axis CNC machine center equipped with a tooling system. Samples 19 mm thick, 75 mm wide, and 305 mm long were machined to the pattern shown in Fig 1 using three passes. The first pass was done with a straight profile knife to obtain the shape shown in Fig 1. A second preliminary roughing pass was done with a knife ground as suggested by ASTM (2004). The finishing cut was then done at 1.6-mm cutting depth. Rake and clearance angles were 20 and 14°, respectively. Cutterhead speed was kept constant at 12,000 rpm with only one knife working. End grain of specimens was machined at 1.25 m/min feed rate. Flat-side grain and curved-side grain edges were machined at 5 m/min feed rate (Fig 1).

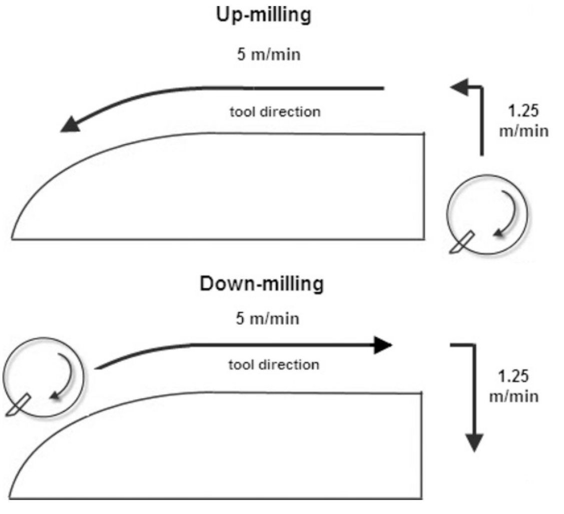

Figure 1. Comparison between up- and down-milling viewed from above.

Given the increasing use of CNC machines, specimens were routed following two modes, up-milling and down-milling. The same specimens were used with up-milling for the first pass and down-milling for the second pass. Routing quality was evaluated separately on each edge (flat-side grain, curved-side grain, and end grain).

Turning tests. Turning was performed with a Locatelli (Alme, Italy) MK-CE 600 lathe at Dynasty Wood Turnings Ltd (St-Marc-des-Carrières, Québec, Canada). A suitable set of two back knives was used to produce the profile suggested by ASTM (2004). Initial dimensions of each specimen were 19 mm thick, 19 mm wide, and 127 mm long. Two moisture contents were studied, 8 and 12%, and spindle speed was kept constant at 3300 rpm.

Qualitative Assessment of Machining Properties

Quality of each machined piece was independently graded by three individuals using ASTM (2004): Grade 1 = excellent or defect free; Grade 2 = good; Grade 3 = fair; Grade 4 = poor; and Grade 5 = very poor. Defect types such as chip marks and loosened, raised, fuzzy, and torn grains and their severity were also recorded. From a practical sense, lower grade numbers describe surfaces that would be acceptable in a manufacturing environment, whereas higher grades require additional rework, resulting in additional production costs.

Proportion of acceptable pieces. Three evaluations were used to attribute the final surface grade to each machined piece. A piece was considered acceptable when at least two of the three individuals graded it as acceptable. Otherwise, the piece was classified as defective. This permitted us to estimate average proportion of acceptable pieces for each machining test following a binary distribution (acceptable or reject) based on performance criteria described in Table 2. This approach also allowed comparing results with those previously reported. However, this raised some problems of nonconvergence when applying analysis of variance (ANOVA) procedures in SAS (2004).

Index of surface quality. An index of surface quality (ISQ) was calculated by averaging the grades of three individuals for each piece. A mean ISQ of 1 indicates that pieces were excellent, whereas higher ISQs indicate lower quality. This index provided a higher degree of data separation among clones, drying treatments, and site effects, avoiding nonconvergence issues during ANOVA procedures.

Quantitative Assessment of Machining Properties

Roughness measurements were carried out with a Micromeasure confocal optical profiler (Stil, Aix-en-Provence, France). A surface (3D) of 12.5 × 12.5 mm was measured per sample for planing and sanding tests. For routing tests, one profile (2D), 15 mm long, was evaluated on the end-grain, flat-side grain, and curved-side grain edges. Profile and surface data were acquired with SurfaceMap Version 2.4.13 software using an acquisition frequency of 300 Hz. Digitizing steps for 3D data were 20 μm parallel to the grain and 250 μm perpendicular to the grain. The digitizing step for the 2D data was 5 μm following the cutting direction. Average roughness for planed and sanded surfaces (S_a) and for routed profiles (R_a) were determined with MountainsMap® Topography XT Version 4.1.2 software based on ISO (1997). A cutoff length of 2.5 mm combined with a robust Gaussian filter (ISO/DTS 2002) was applied.

Table 2. Performance criteria used to define pieces with acceptable surface quality for each machining test.

Machining test	Performance criteria (grade)
Planing	1
Sanding	1 and 2[a]
Routing	1 and 2
Turning	1, 2, and 3

[a] ASTM (2004) defines acceptable pieces classified as grade 1 for sanding. However, pieces of grade 2 presented very light fuzzy grain with no impact to further process such as varnishing. They were hence classified as acceptable.

Statistical Analysis

Machining tests were carried out as a split-split-plot experimental design. ANOVAs were performed using the SAS (2004) MIXED procedure. MIXED provides parameter estimates for generalized linear models including both fixed and random factors in the same model. Clones and growing sites were considered fixed effects, whereas drying treatments and other sources of variation were considered random effects. Assumptions of normal distribution of residuals and variance were tested using SAS UNIVARIATE procedure. The repeated instruction from SAS MIXED procedure was used to test homogeneity of variances. When statistically significant effects ($p < 0.01$) were found, least-squares means multiple comparison tests were performed using the least significant difference option from the LSMEANS function within the SAS MIXED procedure. A SAS macro pdmix800. sas was also used to convert mean separation output to letter grouping (Saxton 1998). Student t tests were used to determine if basic density was significantly different ($p < 0.01$) between samples graded as acceptable and those rejected for each machining test. Pearson correlation tests were also performed between basic density, ISQ, and roughness parameters for each machining test ($p < 0.01$).

RESULTS AND DISCUSSION

Means of proportions of acceptable pieces and ISQ for machining properties of each clone are shown in Tables 3 and 4 (with values of the different sites and drying treatments pooled).

Planing Properties

With respect to all planing conditions, clones, drying treatments, and sites studied as a whole, poplar hybrid clones showed a somewhat high proportion of defect-free pieces (72%; Table 3). This proportion is higher than that obtained for trembling aspen (*Populus tremuloides*) by Cantin (1967) and Lihra and Ganev (1999), although wood density of these hybrids was lower than that for aspen. The proportion of defect-free pieces was also higher than that reported for black cottonwood (*Populus trichocarpa*) by Williams and Morris (1998). However, trembling aspen planed by Williams and Morris (1998) behaved better than the hybrid poplar clones studied here. The means of each clone showed that clone 131 produced the lowest proportion (58%) of defect-free pieces and clone 3570 the highest (85%).

Table 3. Proportion of acceptable pieces for machining properties of seven poplar hybrid clones (all sites and drying treatments were pooled).

								Turning[d]	
			Sanding[b] grit size			Routing[c]		Moisture content	
Clone	Basic density (kg/m^3)	Planing[a] (%)	120 (%)	150 (%)	180 (%)	Up-milling (%)	Down-milling (%)	8% (%)	12% (%)
4813	360 A[e]	76	22	50	100	94	98	54	53
3565	348 B	68	15	34	98	89	97	25	50
915508	324 C	69	13	51	95	70	85	3	0
3570	321 C	85	35	75	100	86	98	30	17
131	321 C	58	23	42	90	86	97	3	21
3586	316 C	73	2	41	93	84	97	7	16
3230	315 C	70	13	38	95	73	92	8	6
Average	329	72	20	47	96	83	95	19	23

[a] Proportion of pieces that were graded excellent; average of seven cutting conditions.
[b] Proportion of pieces that were graded good or excellent.
[c] Proportion of pieces that were graded good or excellent; average of three edge surfaces.
[d] Proportion of pieces that were graded fair, good, or excellent.
[e] Means within a column followed by the same letter are not statistically different at the 1% probability level.

Table 4. Means of index of surface quality (ISQ) for machining properties of seven poplar hybrid clones (all sites and drying treatments were pooled).

								Turning	
			Sanding grit size			Routing[b]		Moisture content	
Clone	Basic density (kg/m^3)	Planing[a]	120	150	180	Up-milling	Down-milling	8%	12%
4813	360	1.28	2.65	2.14	1.43	1.78	1.56	3.30	3.20
3565	348	1.37	2.72	2.12	1.49	1.86	1.63	3.64	3.37
915508	324	1.37	2.79	2.09	1.38	2.19	1.87	4.32	3.92
3570	321	1.22	2.60	1.98	1.27	1.84	1.51	3.69	3.59
131	321	1.49	2.73	2.17	1.56	1.96	1.63	4.07	3.65
3586	316	1.33	2.68	2.16	1.58	1.98	1.63	3.95	3.61
3230	315	1.34	2.71	2.17	1.59	2.14	1.81	4.13	3.89
Average	329	1.34	2.70	2.12	1.47	1.97	1.66	3.87	3.60

[a] Average of seven planing conditions.
[b] Average of three edge surfaces.

The overall mean of ISQ of poplar hybrid clones for planing was also good to excellent (1.34; Table 4). ANOVA showed that ISQ was significantly affected by feed speed and rake angle used for planing and by the different kiln-drying treatments of boards. Again, clone 131 produced the worst quality (1.49) and clone 3570 the best (1.22). However, effects of clones and growing sites on ISQ were not statistically significant.

The main defects observed after planing were fuzzy and raised grains, which were more frequent at 10° rake angle. Other defects such as torn and chipped grain were seen at 25° rake angle. Severity of these defects increased at 20° rake angle and 12 knife marks per 25.4 mm. Cantin (1967), Williams and Morris (1998), and Lihra and Ganev (1999) observed the same type of defects when planing trembling aspen.

Effect of feed rate on planing quality. At 20° rake angle, the four feed rates studied produced significantly different means of ISQ. As expected, ISQ improved as feed rate decreased. The best visual planing quality was obtained at the lowest feed rate (Table 5).

Results also indicated that rate of positive changes in planing quality decreased as feed rate decreased (Fig 2). However, Fig 2 shows that planing quality could be further improved by decreasing feed rate more than 24 knife marks per 25.4 mm of cutting length.

Results of surface roughness confirmed all observations noticed from the ISQ analysis. Surface roughness statistically differed among the three feed rates studied (Table 6). The best quality (lowest S_a) was also obtained at the slowest feed speed. This speed minimized visible defects in the specimens as well as produced the smoothest surfaces.

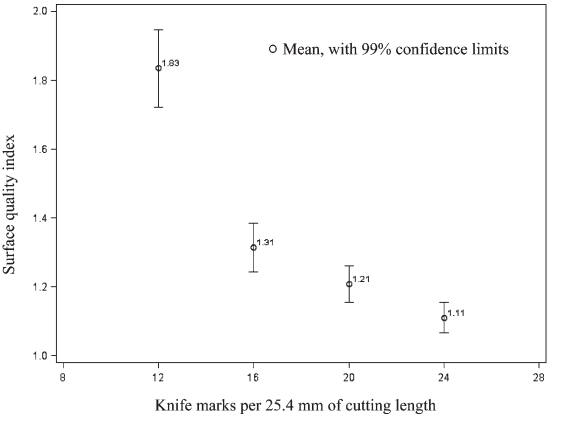

Figure 2. Effect of number of knife marks per 25.4 mm of cutting length on overall mean index of surface quality for all seven poplar hybrid clone specimens. Planing performed at 20° rake angle and 1.6 mm cutting depth.

Table 5. Comparison of index of surface quality means for significant feed rate, rake angle, and kiln-drying treatment effects for planing.[a]

Feed rate effect (knife marks per 25.4 mm of cutting length)				
Rake angle constant (α = 20°)				
	12 marks	16 marks	20 marks	24 marks
Mean	1.83 A	1.31 B	1.21 C	1.11 D
N	270	270	270	270
Rake angle (α) effect				
Feed rate constant (20 knife marks per 25.4 mm of cutting length)				
	α = 11°	α = 15.5°	α = 20°	α = 25°
Mean	1.32 A	1.25 B	1.21 C	1.35 D
N	270	270	270	270
Kiln-drying effect				
	High temp.	Elevated temp.	Conventional temp.	
Mean	1.33 A	1.32 A	1.21 B	
N	352	336	392	

[a] Means within a row followed by the same letter are not significantly different at the 1% probability level.

Table 6. Comparison of surface roughness (S_a, μm) means for feed rate and clone effects for planing.[a]

	Feed rate effect (knife marks per 25.4 mm of cutting length)		
	12 marks	16 marks	24 marks
Mean	11.4 A	10.2 B	6.6 C
N	270	270	270

Clone effect							
Clone	3230	915508	3586	131	4813	3570	3565
Mean	10.1 A	10.1 A	9.8 AB	9.5 ABC	8.8 BC	8.8 C	8.5 C
N	117	117	132	93	108	120	123

[a] Means followed within a row by the same letter are not significantly different at the 1% probability level.

Effect of rake angle on planing quality. The four rake angles produced significantly different means of ISQ. The best results were obtained with 20° rake angle (Table 5). Surface quality decreased slightly for the other angles studied. Fuzzy or raised grains were present at 15.5° and more frequently at 11° rake angles. Surface quality also decreased at 25° rake angle because of torn grain and chip marks.

Rake angle is an important parameter affecting type of chip formation, which influences surface quality (Mackenzie 1960; Koch 1964; Stewart 1977). Small rake angles contribute to formation of type III chips, which are often associated with fuzzy or raised grains. Large rake angles generally produce type I chips, which are often related to torn grain. In general, results appeared to indicate formation of type III chips at 11 and 15.5° rake angles and type I chips at 25° rake angle. An angle between 15.5 and 20° appeared suitable for producing type II chips, resulting in excellent surfaces when planing hybrid poplar clones (Fig 3). A quadratic regression analysis estimated optimum rake angle at 17.5 ± 0.6° (99% confidence level). Cantin (1967) observed that planing of trembling aspen improved when rake angle changed from 30-15°. In contrast, no difference in quality was found by Lihra and Ganev (1999) when planing the same wood between 20 and 12° rake angle.

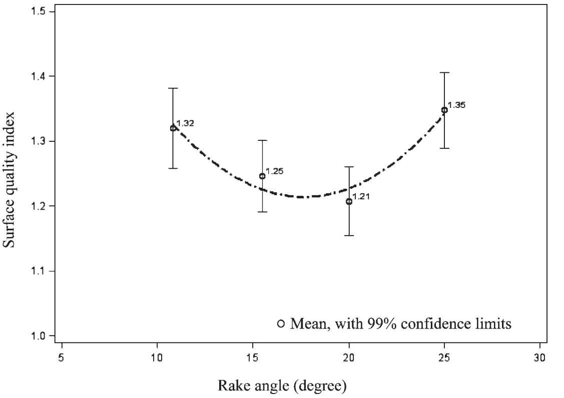

Figure 3. Effect of rake angle on overall mean of index of surface quality for all seven poplar hybrid clone specimens. Planing performed at 20 knife marks per 25.4 mm of feed speed and 1.6-mm cutting depth.

Effect of drying treatments and clones. Drying treatments of boards affected ISQ variation differently. Boards kiln-dried by the conventional schedule were better planed than those kiln-dried by high-temperature and elevated-temperature schedules (Table 5). Occurrence of collapse caused by drying could explain this behavior. In fact, higher proportions of collapsed pieces were found after drying by high-temperature (28%) and elevated-temperature (24%) schedules than by a conventional drying schedule (4%). Different effects of kiln-drying treatments on mechanical properties of wood could have also contributed to this result. However, effect of drying on machining was only noted for visual evaluation (ISQ) and not for roughness values (S_a).

Conversely, means of ISQ for the seven clones studied were not statistically different. Clones could not be differentiated by the presence and/or severity of defects such as torn, fuzzy, and raised grains. However, means of surface roughness (S_a) of the seven clones were found to be statistically different. Thus, surfaces of clones 3565, 3570, and 4813 were smoother than those of clones 3230 and 915508 (Table 6). Optimal rake angle for the three best performing clones was estimated to be 17° by a quadratic regression analysis. Two of these better clones (3565 and 4813) had the highest basic density, whereas clone 3230 had the lowest (Table 3).

Overall, results obtained for planing show that clones 3565, 3570, and 4813 should be preferred for the three growing sites studied. Wood of these clones should be kiln-dried following a conventional temperature schedule. For these clones, planing should be performed at 17° rake angle and 24 knife marks per 25.4 mm of cutting length or higher.

Sanding Properties

All pieces sanded with 120-grit sandpaper presented some level of fuzzy grain that contributed to their overall fair performance. However, if occurrence of fuzzy grain was light (grade 2), it would not affect any further finishing application such as sealing or varnishing. Acceptable performance was then calculated including proportion of pieces graded 1 and 2. Overall proportion of acceptable pieces was 20% for 120-grit sandpaper (Table 3). This proportion is lower than those observed by Williams and Morris (1998) for trembling aspen and black cottonwood. Lihra and Ganev (1999) reported only 4% of defect-free pieces (grade 1) for trembling aspen. However, proportions of good pieces substantially increased up to 47 and 96% when using 150- and 180-grit sandpapers, respectively (Table 3).

Overall behavior of poplar hybrid clones was on average good to fair (ISQ 2.70) with a 120-grit sandpaper, good (ISQ 2.12) with a 150-grit sandpaper, and excellent to good (ISQ 1.47) with a 180-grit sandpaper (Table 4). Fuzzy grain contributed to downgrade sanded pieces. Occurrence and severity of fuzzy grain decreased significantly when finer sandpapers were used. ANOVA applied on ISQ data indicated three significant double interactions: sandpaper grit and drying treatment; site and drying treatment; and sandpaper grit and clone (Table 7). Analysis of individual sources of variation showed that sandpaper was by far the variable that most affected ISQ variation followed by clone, drying treatment, and, finally, site factors.

ANOVA applied on average surface roughness (S_a) data for the sanding process also revealed a significant interaction between the two more significant sources of variation: sandpaper grit and clones (Table 8). Sites and drying treatments did not play a significant role on S_a variation.

Sandpaper grit and drying treatment interaction. ISQ means for the three sandpapers were all statistically different within each drying treatment (Table 7). The 180-grit sandpaper performed the best in all cases. Compared with conventional drying, high-temperature drying negatively affected sanding, but only for 120-grit sandpaper. Drying treatments did not affect ISQ differently when sanding was performed with finer sandpapers (150- and 180-grit).

Site and drying treatment interaction. Within drying treatments, ISQ obtained for the Windsor site was significantly lower than that from the Platon site for the elevated-temperature drying schedule (Table 7). There was no difference in ISQ among sites for the high-temperature and conventional drying schedules. Conversely, for the Platon site, significant differences in ISQ between the elevated-temperature and conventional drying treatments existed. Within the St-Ours and Windsor sites, no significant differences in surface quality were found among the three drying treatments.

Sandpaper grit and clone interaction. ISQ means obtained for the three sandpapers were all statistically different within each clone (Table 7). The 180-grit sandpaper performed the best within each clone. ISQ means slightly varied among clones, although this variation depended on the sandpaper grit used. For the best performing 180-grit sandpaper, ISQ of clone 3570 was significantly lower than ISQs

Table 7. Comparison of index of surface quality means for significant sandpaper grit and drying, site and drying, and sandpaper grit and clone interactions for sanding.[a]

	High temp.	Elevated temp.	Conventional temp.
Sandpaper grit × drying treatment interaction			
120-grit sandpaper			
Mean	2.75 A a	2.71 AB a	2.63 B a
N	88	84	98
150-grit sandpaper			
Mean	2.08 A b	2.15 A b	2.13 A b
N	88	84	98
180-grit sandpaper			
Mean	1.48 A c	1.46 A c	1.47 A c
N	88	84	98

	Elevated temp.	High temp.	Conventional temp.
Site × drying treatment interaction			
Platon			
Mean	2.21 A a	2.08 AB a	1.99 B a
N	75	81	93
St-Ours			
Mean	2.11 A ab	2.07 A a	2.11 A a
N	90	93	99
Windsor			
Mean	2.01 A b	2.16 A a	2.12 A a
N	87	90	102

Clone	915508	131	3565	3230	3586	4813	3570
Sandpaper grit × clone interaction							
120-grit sandpaper							
Mean	2.79 A a	2.73 AB a	2.72 AB a	2.71 AB a	2.68 AB a	2.65 AB a	2.60 B a
N	39	31	41	39	44	36	40
150-grit sandpaper							
Mean	2.09 AB b	2.17 AB b	2.12 AB b	2.17 AB b	2.16 AB b	2.14 AB b	1.98 B b
N	39	31	41	39	44	36	40
180-grit sandpaper							
Mean	1.38 AB c	1.56 A c	1.49 AB c	1.59 A c	1.58 A c	1.43 AB c	1.27 B c
N	39	31	41	39	44	36	40

[a] Means within a row followed by the same uppercase letter are not significantly different at the 1% probability level. Means within a column followed by the same lowercase letter are not significantly different at the 1% probability level for each interaction separately.

for clones 3586, 3230, and 131. Sanding behavior of other clones was quite similar.

Within each clone, surface roughness means obtained with the three sandpapers were all significantly different (Table 8). Surfaces were smoother when sanding with 180-grit sandpaper. Performance of clones in terms of surface roughness depended on the sandpaper grit used. For the most effective sandpaper (180-grit), clone 4813 produced the smoothest surfaces among all clones studied.

Finally, taking into account qualitative and quantitative evaluations, results showed that sandpaper grit was by far the factor that most affected sanding quality. One hundred eighty-grit sandpaper is most appropriate. Clones 3570 and 4813 are preferred among the seven clones studied. The minor effects of sites and drying treatments on sanding were negligible given that they were observed for specific cases.

Given that sanding is one of the most expensive operations in the wood industry besides being a

Table 8. Multiple comparisons of surface roughness (S_a, μm) means for significant sandpaper grit and clone interaction for sanding.[a]

	Clone code						
Clone	915508	3230	3586	131	3570	4813	3565
	120-grit sandpaper						
Mean	10.0 A a	9.5 AB a	9.4 AB a	9.3 AB a	9.1 B a	9.0 B a	8.9 B a
N	39	39	44	31	40	36	40
	150-grit sandpaper						
Mean	6.1 A b	5.8 ABC b	5.8 AB b	5.6 BC b	5.4 CD b	5.2 D b	5.6 BC b
N	39	39	44	31	40	36	40
	180-grit sandpaper						
Mean	4.3 A c	4.1 A c	4.3 A c	4.3 A c	4.2 A c	3.8 B c	4.1 AB c
N	39	39	44	31	40	36	40

[a] Means within a row followed by the same uppercase letter are not significantly different at the 1% probability level. Means within a column followed by the same lowercase letter are not significantly different at the 1% probability level.

health hazard (d'Errico et al 2009), attempts should be made to replace it partially or totally. Planing instead of sanding could lower production costs and increase air quality in wood processing plants. Surface quality produced by planing was equivalent to that obtained by sanding, especially for the three best performing clones (3565, 3570, and 4813). Sanding with 180-grit sandpaper produced overall mean values of 1.41 for ISQ and 4.0 μm for S_a for these clones. Corresponding values were 1.07 for ISQ and 6.4 μm for S_a at 20° rake angle and 24 knife marks per 25.4 mm of cutting length for boards kiln-dried at conventional temperature. Thus, depending on the solid wood end-use applications, planing shows potential as an alternative to sanding.

Routing Properties

Routing tests produced a high proportion of good or excellent pieces. Routing by down-milling mode produced more acceptable pieces than routing by up-milling mode (Table 3). The overall proportion of acceptable pieces for down-milling was higher than those reported for trembling aspen by Cantin (1967) and Lihra and Ganev (1999). Williams and Morris (1998) also obtained a high proportion (98%) of acceptable pieces when routing trembling aspen. As discussed subsequently, clones 3230 and 915508 generally performed badly compared with others. Excluding these two clones from results, overall proportions of acceptable pieces went from 83-88% for up-milling and 95-97% for down-milling.

Overall means of ISQ of poplar hybrid clones for routing were also as good for down-milling as for up-milling (Table 4). ISQ values also showed that wood of clones 3230 and 915508 produced the worst quality among those studied. As indicated previously, routing properties were evaluated separately on three different grain surfaces of specimens.

In general, torn, fuzzy, and raised grains were the defects observed for all grain surfaces and milling modes. Torn grain was more frequent and severe for up-milling than for down-milling. Severity and frequency of defects were less on the flat-side grain followed by end grain and finally on curved-side grain. However, feed rate was four times lower when routing the end-grain surface (1.25 m/min) compared with side-grain surfaces (5 m/min). For end grain, raised and fuzzy grains occurred in both cutting modes, but there was a significant decrease in torn grain when routing by down-milling. For flat-side grain, torn grain was more frequent in up-milling than in down-milling, but severity was similar in both cutting modes. Although raised and fuzzy grains were less frequent in up-milling, they were more severe than in down-milling. Finally, for curved-side grain, presence of raised and fuzzy grains was similar in both cutting modes. Torn grain incidence was lower in down-milling than in up-milling.

Flat-side grain surface. ANOVA showed that ISQ was significantly affected by the cutting mode × drying treatment interaction and by the clones studied. Cutting mode was by far the variable that most affected ISQ variation followed by drying treatment and, finally, by clones. For high- and elevated-temperature schedules, down-milling performed better than up-milling (Table 9). However, characteristics of down-milling and up-milling were similar when wood was kiln-dried by the conventional schedule. Moreover, for up-milling, conventionally dried specimens were routed better than those dried by the other two drying treatments. Within the down-milling mode, there were no significant differences among kiln-drying treatments. These results appear to recommend routing by down-milling and selecting any of the three drying schedules for working flat-side grain surfaces of poplar hybrid clones. Routing by up-milling appeared to be sensitive to the temperature used for drying specimens. However, this cutting mode gave similar results to those expected with down-milling if wood was conventionally dried.

Significant differences in ISQ attributable to clones were found. Clones 3565, 3570, and 4813 performed better than clone 915508 for the flat-side grain surface.

A significant effect of clones on profile roughness (R_a) was also observed for flat-side grain surfaces (Table 10). Effects of sites, kiln treatments, and cutting modes were not statistically different. Comparison of means indicated that routed surfaces of clone 3565 were smoother than those of clones 131, 3230, and 3586.

Curved-side grain surface. ANOVA showed that ISQ was also significantly affected by the cutting mode × drying treatment interaction and by the clones studied. Cutting mode was again the variable that most affected ISQ variation followed by drying treatment and, finally, by clones. For the high-temperature schedule, down-milling performed better than up-milling (Table 9). Quality of down-milling and up-milling was equivalent when wood was kiln-dried by conventional and elevated schedules. For up-milling mode, conventional and elevated-temperature dried specimens were better routed than those dried by high-temperature treatment. For down-milling mode, no differences in surface quality were found among the three drying treatments. Results also suggest using the down-milling mode for curved-side grain surfaces because of its equal behavior for the different drying treatments. Up-milling mode gave similar results if wood was dried following conventional and elevated-temperature schedules. Clones also had a significant effect on ISQ of curved routed surfaces. Clones 131, 3565, 3570, 3586, and 4813 performed better than clones 3230 and 915508.

Roughness measured on curved-side grain surfaces showed that cutting mode and clones had significant effects on this parameter (R_a) (Table 10). Again, down-milling produced smoother profiles than up-milling. Neither site nor kiln treatment effects were found to be significant. R_a values for clones 3565, 3570, and 4813 were lower than those for clones 3230 and 915508.

End-grain surface. ANOVA showed that ISQ was significantly affected by the cutting mode × clone interaction. The major source of variation was cutting mode followed by clones. Down-milling mode produced better ISQ than did up-milling within each clone (Table 9). For both cutting modes, clones 3565, 3570, 3586, and 4813 produced better surface quality than clones 3230 and 915508. Roughness of end-grain surfaces was also significantly affected by the cutting mode × kiln-drying interaction as well as by site variation (Table 10). Cutting mode was by far the variable that most affected roughness variation followed by drying treatment and, finally, by sites. As for ISQ, down-milling mode produced significantly smoother profiles than did up-milling mode. For both modes of routing,

Table 9. Comparisons of index of surface quality means of routing properties measured in the flat-side grain, curved-side grain, and end-grain surfaces of specimens.[a]

Flat-side grain surface							
Cutting mode × drying interaction							
		Elevated temp.		High temp.			Conventional temp.
Up-milling							
Mean		1.44 A a		1.42 A a			1.33 B a
N		84		88			98
Down-milling							
Mean		1.30 A b		1.19 A b			1.28 A a
N		84		88			98
Clone effect							
Clone	915508	3586	3230	131	3565	4813	3570
Mean	1.50 A	1.40 AB	1.37 AB	1.32 ABC	1.26 BC	1.24 BC	1.18 C
N	78	88	78	62	82	72	80
Curved-side grain surface							
Cutting mode × drying interaction							
		High temp.		Conventional temp.			Elevated temp.
Up-milling							
Mean		2.48 A a		2.15 B a			2.04 B a
N		88		98			84
Down-milling							
Mean		2.05 A b		2.11 A a			2.06 A a
N		88		98			84
Clone effect							
Clone	915508	3230	3565	3586	131	3570	4813
Mean	2.37 A	2.36 A	2.12 B	2.11 B	2.10 B	2.01 B	1.97 B
N	78	78	82	88	62	80	72
End-grain surface							
Cutting mode × clone interaction							
Clone	915508	3230	131	3586	3570	3565	4813
Up-milling							
Mean	2.61 A a	2.54 AB a	2.30 BC a	2.19 C a	2.19 C a	2.10 C a	2.04 C a
N	39	39	31	44	40	41	36
Down-milling							
Mean	1.82 A b	1.84 A b	1.63 AB b	1.62 B b	1.48 B b	1.61 B b	1.60 B b
N	39	39	31	44	40	41	36

[a] Means within a row followed by the same uppercase letter are not significantly different at the 1% probability level. Means within a column followed by the same lowercase letter are not significantly different at the 1% probability level for each interaction separately.

wood kiln-dried by high temperature produced smoother profiles than that obtained by the two other kiln-drying treatments. Furthermore, average wood R_a from the Platon region was significantly lower than for the Windsor area. For this grain, wood of different clones showed similar behaviors.

Feed direction in relation to direction of cutterhead rotation had the most significant effect on routing quality. In general, down-milling provided smoother and better surface quality than up-milling and, therefore, is preferred. Mitchell and Lemaster (2002) reported similar results when routing flat-grain surfaces of soft maple. This appears to contradict Koch (1964) who suggests up-milling for planing wood parallel to the grain. However, operational parameters used in this study were very different, producing significant geometric

Table 10. Comparison of roughness (R_a, μm) means of routing properties measured in the flat-side grain, curved-side grain, and end-grain surfaces of specimens.[a]

Flat-side grain profile							
Clone effect							
	3586	131	3230	915508	4813	3570	3565
Mean	10.3 A	10.1 AB	10.0 AB	9.5 ABC	8.9 ABC	8.5 BC	8.1 C
N	88	62	78	78	72	80	82
Curved-side grain profile							
Cutting mode effect							
				Up-milling			Down-milling
Mean				8.9 A			7.9 B
N				270			270
Clone effect							
Clone	3230	915508	3586	131	3570	3565	4813
Mean	9.3 A	9.0 AB	8.5 ABC	8.3 BCD	8.0 CD	7.8 CD	7.7 D
N	78	78	88	62	80	82	72
End-grain profile							
Cutting mode × drying interaction							
			Conventional temp.		Elevated temp.		High temp.
Up-milling							
Mean			11.3 A a		10.1 A a		7.7 B a
N			98		84		88
Down-milling							
Mean			9.0 A b		8.6 A b		5.8 B b
N			98		84		88
Site effect							
			Windsor		St-Ours		Platon
Mean			9.7 A		8.6 AB		8.0 B
N			186		188		166

[a] Means within a row followed by the same uppercase letter are not significantly different at the 1% probability level. Means within a column followed by the same lowercase letter are not significantly different at the 1% probability level for each interaction separately.

differences in average chip thickness, wavelength height, and cutting length path between up-milling and down-milling. Routing parameters selected for this study did not provide any significant geometric advantage toward one cutting method. As reported by Juan (2000), the working cycle between the two cutting methods was quite different. According to Juan (2000), during down-milling parallel to the grain, material is always in compression favoring type III chip formation. In up-milling parallel to the grain, a cutting cycle is divided into three stages, in which normal cutting forces change from negative (pushing action) to positive (pulling action). Transitions among type III, II, and I chips can occur, which mainly depends on rake angle used. However, results show that differences between down-milling and up-milling were more important for end-grain surfaces. The cutting situation in this case is related to a 90-90° orthogonal cutting action.

Turning Properties

Overall behavior during turning wood of poplar hybrid clones was poor (Table 3). The main defects observed were torn grain and fuzzy grain and were generally so severe that they could not be entirely removed by sanding. Therefore, overall proportion of excellent to fair pieces was very low (21%) compared with that observed by Cantin (1967) (89%). Turning tests by Cantin (1967) were performed at a spindle speed of 1500 rpm instead of 3300 rpm suggested by the standard, which could

Table 11. Comparison of index of surface quality means for significant wood moisture content and clone effects for turning.[a]

Wood moisture content effect							
			8% MC				12% MC
Mean			3.87 A				3.60 B
N			257				265
Clone effect							
Clone	915508	3230	131	3586	3570	3565	4813
Mean	4.13 A	4.01 AB	3.86 BC	3.78 BC	3.64 CD	3.51 DE	3.25 E
N	75	75	59	86	80	78	69

[a] Means within a row followed by the same letter are not significantly different at the 1% probability level.

have contributed to obtaining better quality. Williams and Morris (1998) and Lihra and Ganev (1999) used simpler specimen profiles and different types of lathes, which makes comparisons difficult.

ISQ values also showed a fair to poor turning performance (Table 4). ANOVA indicated that moisture content and clones significantly affected ISQ variation. Although final moisture content influenced turning performance, no significant difference was found among the three kiln-drying treatments used. Also, there was no significant effect of sites on turning quality. Turning performance was better at 12% MC than at 8% MC (Table 11).

Wood from clones 3565 and 4813 turned better than wood from clones 3586, 131, 3230, and 915508 (Table 11). However, even the best clones showed quite high ISQ. Decreasing the lathe spindle speed could improve this process (Cantin 1967). Better control of cutting depth would also be useful. Additional work is therefore required to optimize turning of the more efficient clones.

Effect of Clones and Basic Density on Wood Machining Properties

Some clones machined better than others for the different machining processes studied. Selection of clones for a given machining process is certainly possible but is not necessarily practical. An overall analysis showed that euramericana clones (*P. deltoides* × *P. nigra*) 3565, 3570, and 4813 performed the best for most of the machining processes. The interamericana clone (*P. trichocarpa* × *P. deltoides*) 3230 as well as the clone (*P.* × *euramericana* × *P. maximowiczii*) 915508 performed the worst for most of the machining processes. Therefore, variation in machining properties appears to be related to interclone variation as well as to the type of hybrid. Analysis also showed that variation in wood density among clones was statistically significant (Table 3). Two of the best performing clones (3565, 4813) had dense wood, whereas those that machined worst (3230, 915508) had less dense wood. Although euramericana clone 3570 had the same density as the less performing clones, it machined favorably. Pearson correlations tests were performed to determine relationships between wood density and machining properties. Correlation coefficients were calculated between machining properties (ISQ and roughness parameters) and basic density by pooling values of drying treatments and sites together (Table 12).

Correlations between ISQ and basic density were not statistically significant for planing, sanding, and down-milling routing. In contrast, significant negative weak correlations were found between basic density and ISQ for up-milling routing and for turning. Thus, dense specimens should perform better than light specimens for these two processes. The effect of density on turning has been reported in previous studies (Cantin 1967; Williams and Morris 1998; Hernández et al 2001).

Table 12. Pearson correlation coefficients between basic density of specimens and their machining properties (with sites and drying treatments pooled).

Machining properties	N	Index of surface quality	R_a or S_a
Planing			
10°, 20 knife marks	270	$-0.03^{n.s.}$	n.a.
15°, 20 knife marks	270	$0.09^{n.s.}$	n.a.
20°, 20 knife marks	270	$0.04^{n.s.}$	n.a.
25°, 20 knife marks	270	$0.11^{n.s.}$	n.a.
20°, 12 knife marks	270	$0.08^{n.s.}$	–0.24**
20°, 16 knife marks	270	$0.05^{n.s.}$	–0.24**
20°, 24 knife marks	270	$0.10^{n.s.}$	$-0.11^{n.s.}$
Sanding			
120-grit	270	$0.10^{n.s.}$	–0.21**
150-grit	270	$0.10^{n.s.}$	–0.27**
180-grit	270	$0.05^{n.s.}$	$-0.13^{n.s.}$
Routing			
Down-milling			
Flat-side grain	270	$-0.06^{n.s.}$	$-0.09^{n.s.}$
Curved-side grain	270	$-0.15^{n.s.}$	–0.27**
End grain	270	$-0.16^{n.s.}$	$0.01^{n.s.}$
Up-milling			
Flat-side grain	270	$-0.04^{n.s.}$	$-0.09^{n.s.}$
Curved-side grain	270	–0.20**	–0.34**
End grain	270	–0.35**	$-0.06^{n.s.}$
Turning			
At 8% MC	265	–0.37**	n.a.
At 12% MC	257	–0.39**	n.a.

N = Number of specimens; R_a = means profile roughness; S_a = means surface roughness; n.s. = not significant at the 1% probability level; n.a. = means not applicable

** Significant at the 1% probability level.

Surface roughness appeared more affected by basic density than did ISQ (Table 12). Thus, denser specimens should produce smoother surfaces than light specimens during planing at high feed rates or during sanding with coarser sandpapers. This effect of density was weak, and it was removed when parameters of machining were set to produce smoother surfaces (the lowest feed rate for planing and the finer sandpaper for sanding). Dense woods also should route better than light woods, especially in curved surfaces. The practical implication of these results is that, as a first approach, it should be possible to select trees with high density that could have better machining performance. However, this would be at the expense of radial growth because there is a negative correlation between both traits (Beaudoin et al 1992). Given that these relationships are weak, there are exceptions, or correlation breakers, which in clonal forestry may be exploited. Thus, it is possible to simultaneously achieve gains in growth rate, wood density, and machining properties.

It is therefore apparent that, apart from wood density, other attributes of clones could be involved in machining performance. Tension wood occurs in large proportions in juvenile wood of poplar species, in particular when growth is accelerated (Bendtsen 1978). According to Clark (1958), presence of tension wood contributed to production of fuzzy grain on planed surfaces of eastern cottonwood. An analysis was performed with data on proportion of gelatinous fibers extracted from a parallel study carried out with the same poplar hybrid clones. ANOVA showed that proportions of gelatinous fibers for clones 3565 (44%) and 4813 (44%) were significantly higher than those for other clones. As indicated previously, these two clones machined better than other clones with lower amounts of gelatinous fibers. For balsam poplar, Ritter et al (1993) reported that only a few zones of highly gelatinous fibers could result in major machining defects. Other surfaces poorly machined were free of gelatinous fibers. Thus, other materials or factors must contribute to machining difficulties. Direct measurement of machining properties is therefore recommended because no important predictor variable has been identified.

CONCLUSIONS AND RECOMMENDATIONS

Planing, sanding, and routing properties of the seven hybrid poplar clones studied were comparable with or better than those of native poplar species grown in Canada. However, performance of these clones during turning was lower. In general, machining performance of the poplar clones was influenced in decreasing order by machining, clones, kiln-drying treatments, and sites.

The best planing condition was obtained at feed rate of 24 knife marks per 25.4 mm with a 20° rake angle for all clones. A higher number of knife marks in conjunction with a 17° rake angle should produce even better quality and smoother surfaces. Wood for planing should be dried following a conventional schedule. Sandpaper grit size was critical to obtain excellent quality during sanding. One hundred eighty-grit sandpaper is recommended to minimize frequency and severity of fuzzy grain. For this grit size, kiln-drying schedules and wood density variation did not affect surface quality differently. Other minor effects of sites and drying schedules on wood sanding were considered negligible given that they were observed for specific cases. Turning performance was poor because of severe torn and fuzzy grains. Wood turned better at 12% MC than at 8% MC. Effects of cutting speed and cutting depth should be studied to improve the turning process of more efficient clones. Feed direction in relation to cutterhead rotation direction had the most significant effect on routing performance. In general, down-milling mode provided smoother and better surface quality than up-milling. Up-milling only showed similar behavior when routing flat-grain surfaces that had been kiln-dried by conventional drying. The difference in performance between both modes of routing was more important when milling end-grain surfaces. These surfaces routed better when they were previously kiln-dried using a high-temperature schedule. Conventional kiln-drying resulted in less downgrading caused by collapse compared with high- and elevated-temperature schedules.

Results also showed that Euramericana clones (*P. deltoides* × *P. nigra*) 3565, 3570, and 4813 performed best for most machining processes. The interamericana clone (*P. trichocarpa* × *P. deltoides*) 3230 as well as clone (*P.* × *euramericana* × *P. maximowiczii*) 915508 performed worst for most machining processes.

Finally, some correlations between wood density and machining properties were significant but weak. Apparently, selection of clones strictly on the basis of basic density is not appropriate. Therefore, more research is needed to identify other descriptors for tree selection that could lead to better machining performance. For now, direct measurements of machining properties are required because no significant predictor variable has been identified.

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