INFLUENCE OF MACHINING PARAMETERS ON THE STRUCTURAL PERFORMANCE OF FINGER-JOINED BLACK SPRUCE

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ABSTRACT

In Eastern Canada, black spruce (*Picea mariana* (Mill.) B.S.P.) has recently been introduced in the finger-jointing industry. However, little information is available on some of the key manufacturing parameters that influence the finger-jointing process. Therefore, the main objective of this work was to evaluate the effect of wood machining parameters on the ultimate tensile strength (UTS) of finger-joined black spruce in order to optimize the performance of the product. Parameters investigated in this study were the chip-load and the cutting speed. A feather profile was selected with an isocyanate-based adhesive and an end-pressure of 3.43 MPa. A factorial analysis showed a statistically significant interaction between cutting speed and chip-load on the UTS. Within the range of values studied, the cutting speed was the most significant variable affecting finger-joined black spruce. The influence of chip-load on the tensile strength of finger-joints was lower, being apparent only at lower cutting speeds. Results indicated that suitable finger-jointing could be achieved within a range of 1676 m/min and 2932 m/min of cutting speeds with a chip-load between 0.64 mm and 1.14 mm. However, within this range the best result was obtained at 2932 m/min cutting speed and 0.64 mm chip-load. Scanning microscope image analysis of the damaged cells confirmed the effect of cutting speed on the finger-jointing process. In general, the depth of damage was more severe as the cutting speed increased.

Keywords: Wood machining, finger-jointing, structural performance, cutting speed, black spruce.

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INTRODUCTION AND BACKGROUND

A variety of engineered wood products used for structural applications require finger-jointing short pieces of wood together. This process needs special attention owing to the fact that many factors can affect the performance of finger-joined wood products. Machining parameters are some of the key elements that could affect the finger-jointing process and, consequently, the quality of the end product.

The machining of finger-joints is usually performed following recommendations given by tool and machine manufacturers. Poor finger-joints are often associated with inadequate machining conditions. Tear-out, for example, is a common defect caused by either worn knives, high feed speed, inadequate cutting speed, too small feed per knife or chip-load and wrong rake angle (ACEco Precision Wood Tooling 2000). The influence of these parameters on the structural behavior of this product is one of the aspects that have not been studied thoroughly, specifically for black spruce.

Careful machining is essential in order to perform appropriate processing of raw material into products with good surface quality for glue application. To produce a good joint, wood surfaces must be machined with sharp tools, and be essentially free of machine marks, chipped or loosened grain, and other surface irregularities (Selbo 1975). Damaged surface and surface layers owing to machining conditions have been related to inferior adhesive-bonded joint performance (River and Miniutti 1975; Murmanis et al. 1986; Kutscha and Caster 1987; Reeb et al. 1998; Stehr and Östlund 2000; Hernández and Naderi 2001; Hernández and Rojas 2002; Hernández and de Moura 2002; Singh et al. 2002). In order to get a good finish on the wood and to prevent burning of the knives, the chip-load must be within a reasonable range (ACEco Precision Wood Tooling 2000). Chip-load is defined as the amount of material removed by each cutting tooth or edge with each revolution of the spindle. A small chip-load will produce too much heat and will either glaze the wood or burn the knives (Wisconsin Knife Works 2000). If chip-load increases, cutter pressure and heat will increase. Both of these factors will increase the rate of wear on the cutting face of the cutter, thus reducing the operating time between sharpenings (ACEco Precision Wood Tooling 2000).

Little information is available on how machining parameters affect the performance of finger-jointing. Reeb et al. (1998) studied the finger-joint quality after 4, 6, and 32 h of knife wear. Results showed that as knife wear increased, the crushed cell zone in the finger-joints increased in depth. The longer the cutting tools were used, the rougher and more irregular the wood surfaces became. Collins and Walford (1998) evaluated the effects of feed and cutter speeds and the resulting chip loads on radiata pine finger-jointing quality. Machining speeds were found to be not so critical to joint strength although they may affect the joint appearance. Unfortunately, specific information about the machining parameters was not provided. More recently, a preliminary study on wood machining of finger-jointing black spruce was conducted by Bustos et al. (2002) using a polyurethane-based adhesive. Results showed no statistically significant effects of cutting speed and chip-load on the finger-jointing performance of this wood.

During visits to five finger-jointing plants in Eastern Canada, it was observed that various cutting speeds and chip-loads were being used to process black spruce lumber. There was no agreement on which of those machining parameters produced the best mechanical performance of finger-joints. The main objective of the present study was to evaluate the effect of cutting speed and chip-load on the finger-jointing process of black spruce, in an attempt to define an operating envelope where good product performance could be achieved.

MATERIALS AND METHODS

Experiments were carried out with 38-mm by 64 mm kiln-dried planed black spruce stud grade lumber obtained from Chibougamau in the province of Quebec, Canada. The boards were placed in a conditioning room at 20°C and 65% relative humidity and allowed to reach a nominal

equilibrium moisture content (EMC) of 12%. Defects were removed from boards by trimming to produce blocks ranging in length between 20 to 91 cm and corresponding to the Canadian National Lumber Grades Authority N° 2 and better grade (NLGA 2000a). The process for eliminating defects was based on NLGA-SPS 1-2000 specifications for structural finger-joined lumber (NLGA 2000b). A Canadian Conception RP 2000 machine provided with a lateral feed system, common in the North American finger-jointing industry, was used. The ends of the blocks were machined across the width in order to obtain horizontal finger-joints. A feather joint configuration was selected owing to its good mechanical performance (Bustos et al. 2003a). The finger-joints were 28.27 mm long, with 0.76 mm tips, and a 6.69 mm pitch. To evaluate the effect of chip-load and cutting speed on the performance of finger-joined black spruce, three chip-loads and three cutting speeds were chosen for this study. Selection was based on the extreme values published by Bustos et al. (2002). The chip-load values were 0.64 mm, 0.86 mm, and 1.14 mm. The cutting speeds were adjusted to obtain 1676 m/min, 2932 m/min, and 3770 m/min. Six sets of knives (bolts) per tool were used for each chip-load condition. These cutting speeds were determined from the outermost position of the knives (267 mm of diameter, corresponding to the tip of the knife). Knives and tools were freshly sharpened and kept in good cutting conditions during the finger-jointing process.

Following finger-jointing, the blocks were glued in keeping with the technical recommendations provided by the adhesive manufacturer. The adhesive was a two-component system consisting of an ISOSET UX-100 polyurethane prepolymer mixed with an ISOSET WD3-A322 emulsion polymer. These two components have to be mixed immediately prior to use. A one-face glue application was used at a spread rate of 110 g/m². The assembled joints were pressed with a constant end pressure of 3.43 MPa for 20 s at 20°C in accordance with previous results reported by Bustos et al. (2003b). The joined pieces were then crosscut to produce 2.44-m-long tension samples. The sample size varied be-

tween 25 to 34 replicates. Specimens were mechanically tested after curing for 24 h at room conditions.

Tension tests were performed in accordance with ASTM D-198 standard (ASTM 1997a) with a Metriguard model 412 machine. Results were evaluated according to NLGA-SPS 1 (NLGA 2000b) specifications for structural finger-joined lumber. Testing and data acquisition were controlled by means of software developed at Forintek Canada Corp. The ultimate tensile strength (UTS) was calculated based on the actual cross section area. Failure modes were examined around the joints and classified in accordance with ASTM D-4688 standard (ASTM 1997b). After each tension test, two samples were cut from each side of the failed joint and moisture content (MC) and density were determined based on ASTM D-2395-93 standard (ASTM 1995). The mean basic density of the specimens was estimated at 437 kg/m³. Since specimens at the time of testing were at 11.6% MC, their volume at the green state was adjusted considering a total volumetric shrinkage of 11.1% and a fiber saturation point of 30%.

Scanning electron microscopy (SEM) evaluations were performed to quantify the damage that occurred in the wood during machining. Three failed tension specimens from each of the nine wood machining conditions studied were randomly chosen to obtain samples for these analyses. UTS values of these specimens were recorded to relate the cell damage with the mechanical performance. Blocks of about 1 cm² transverse area, including the glueline, were removed from the nearest unfailed joint remaining on the tension specimen. The blocks were prepared with a razor blade by carefully cutting the end-grain surface. The blocks were then desiccated with phosphorus pentoxide over two weeks, mounted on a standard aluminum stub with silver paint, redesiccated and coated with gold palladium in a sputter-coater. Electron micrographs of representative sub-surfaces were taken for each of the nine machining conditions. The depth of damage and glueline thickness were evaluated at five systematically chosen points from each SEM micrograph.

A factorial experiment design was used to evaluate the main effects and the interaction between two factors: cutting speed and chip-load on the ultimate tensile strength of finger-joined black spruce (SAS-GLM procedure, SAS Institute 1998). Fisher Protected LSDs multiple comparisons tests were performed to determine differences among means (5% probability level). These comparisons were made with Bonferroni corrections as required. The normality assumption was verified using the Shapiro-Wilk test and the homogeneity of variances by Levene and Bartlett tests. A multiple regression analysis was performed to determine the relationship between cutting speed and wood orientation on depth of damage. For this, the stepwise procedure of SAS was used and the selection or exclusion of the independent variables in the model was set at the 10% probability level. To evaluate the relative importance of each independent variable on depth of damage variation, the regression coefficients were standardized by calculating the beta coefficients.

RESULTS AND DISCUSSION

Effects of wood machining parameters

Mean values and standard deviations of the ultimate tensile strength (UTS) as a function of cutting speeds and chip-loads are given in Table 1. All strength results met the proof tensile strength specifications of NLGA-SPS 1-2000 (NLGA 2000b). In fact, the mean UTS values using different cutting conditions were more than twice those specified in this standard. Moisture content (MC) of the wood averaged about

11.6% with a range of 10% and 12%. Values of UTS were then adjusted to 12% MC as proposed by Kretschmann and Green (1999) in order to facilitate comparisons among the joints tested. ANOVA indicated a statistically significant (P = 0.05) interaction effect between cutting speed and chip-load on UTS. The multiple comparisons showed that there are significant differences among the three cutting speeds for each chip-load condition. In general, lower values of ultimate tensile strength were associated with higher cutting speed (3770 m/min) for each chip-load condition (Fig. 1). This could result from a damage occurring near and at the glued surface as a result of the high speed at which the knives pass through the wood. Results at 0.86 mm of chip-load were not in agreement with a prelimi-
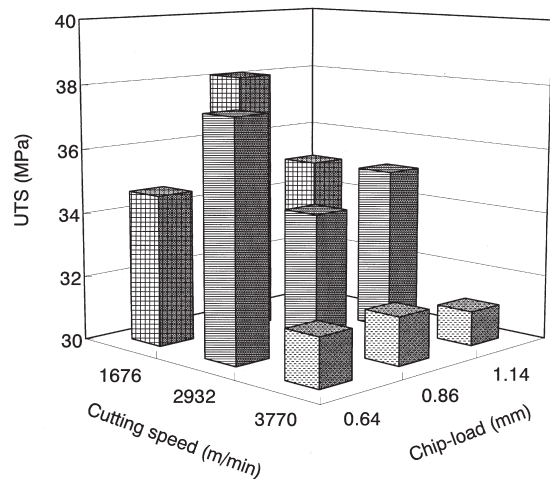

Fig. 1. Influence of cutting speed and chip-load on the ultimate tensile strength (UTS) of finger-joined black

TABLE 1. *Ultimate tensile strength (MPa) of finger-joined black spruce machined at three cutting speeds and three chip-loads.[a]*

| Chip-load(mm) | Cutting speed (m/min) | | | SPS-1 2000 |
	1676	2932	3770	Prooffload tension stress
0.64	34.7 (7.3)[b] Aa[c]	37.4 (5.9) Aa	31.5 (4.7) Ab	
0.86	38.1 (6.7) Ba	34.1 (5.4) Ab	31.5 (4.0) Ab	6.8
1.14	35.0 (6.7) Aa	35.1 (5.6) Aa	31.1 (5.1) Ab	

[a] Number of replicates varied between 25 and 34.
[b] Numbers in parentheses are the standard deviation.
[c] Means within a column or row followed by the same letter are not significantly different at the 5% probability level. Uppercase letters are for chip-load comparison (column) and lowercase letters are for cutting speed comparison (row), for each cutting speed and chip-load separately.

nary study carried out by Bustos et al. (2002). Bustos et al. (2002) worked at the same chip-load with five cutting speeds, also ranging between 1676 m/min and 3770 m/min. Findings from that study indicated that the joint strength was not affected by cutting speed variation. This result could be attributed to the small sample size used in the study. Similar investigations carried out by Collins and Walford (1998) indicated little feed and cutter speed effects and resulting cutter mark spacing on joint strength. However, no details on the machining parameters were given in their work. Collins and Walford (1998) stated that the energy required to cut a joint increases with increased cutting speed and accompanying reduced knife mark spacing.

The highest values of UTS occurred between 1676 m/min and 2932 m/min. The upper value for cutting speed falls within the range given by ACEco Precision Wood Tooling (2000), which indicates that the most commercial cutting speeds for finger-jointing in the USA are between 2512 m/min and 3016 m/min. The lower limit obtained is probably due to the fact that black spruce wood was not taken into account by ACEco Precision Wood Tooling (2000).

On the other hand, Fisher multiple comparisons tests showed few statistically significant differences (P = 0.05) among the three chip-loads used for finger-jointing black spruce (Table 1). These differences were present at 1676 m/min cutting speed, where a chip-load of 0.86 mm performed better than 0.64 mm and 1.14 mm. At a cutting speed of 2932 m/min, differences were not statistically different even though the probability level was close to 0.05 (P = 0.08). For this cutting speed, the higher UTS value was obtained with a 0.64-mm chip-load. The results obtained at 2932 m/min of cutting speed are in agreement with those reported by Bustos et al. (2002). The chip-load values recommended by tool manufacturers, such as ACEco (2000) and Wisconsin Knife Works (2000) vary between 0.38 mm and 0.53 mm, for optimum tool life.

The impact of knife wear on the adherent surfaces of finger-joint specimens was studied by Reeb et al. (1998). They reported that as knife wear progresses, the adherent surfaces become rougher and more irregular. Furthermore, as chip-load decreases, the cutters will rub rather than cut, which produces friction and dulls the cutting edge prematurely, which might possibly burn the wood (ACEco Precision Wood Tooling 2000). This rubbing effect was not studied in the present study.
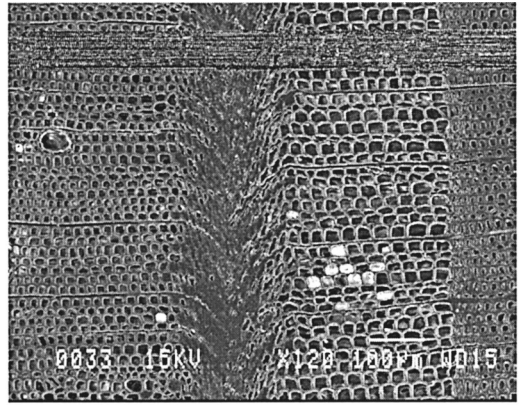
The quality of the glueline was evaluated by the percent wood failure developed in the finger-joint based on the ASTM D-4688 standard (ASTM 1997b). Generally, wood failure was high for all types of finger-joints tested. More than 80% of the specimens failed in modes numbers 3 and 4. Failure mode number 3 occurs mostly along the joint profile but with some failure at the finger roots. Failure mode 4, on the other hand, is associated with wood failure occurring at the joint roots and with high overall wood failure. Such failures are most common in structural finger-joined wood. Almost no glue bond failure was observed, which confirms that the gluing process was adequate.

### SEM analysis of transverse glueline faces

SEM analyses on transverse sections of specimens showed that the thickness of the glueline was similar for all machining conditions studied. Crushed and collapsed cells, however, were observed near or at the glueline of samples (Fig. 2). Tracheids far away from the glueline had a normal appearance. However, tracheids near and at the glueline were highly compressed. The rays were also distorted. In latewood (LW), damage was less severe than in earlywood (EW), probably owing to the higher density of LW (Fig. 2). The severity of damage was variable within each wood machining condition. Thus, the depth of damage was measured in three typical specimens for each of the nine wood machining conditions (Table 2). Factorial experiment analysis showed no interaction effect between cutting speed and chip-load on the depth of damage. Significant differences were found, however, in the principal effect of cutting speed. In general, surface damage was more severe as cutting speed increased. Results revealed that the highest value of depth
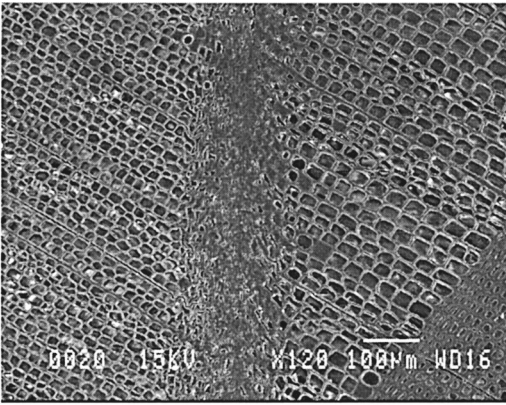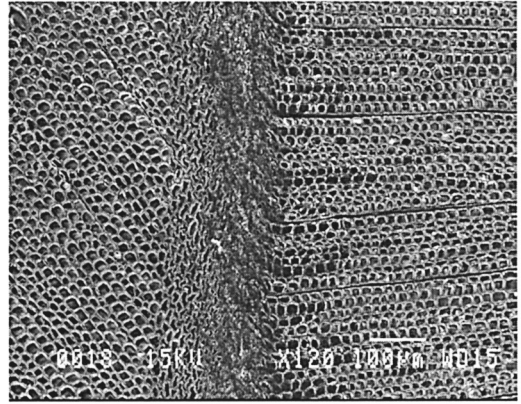
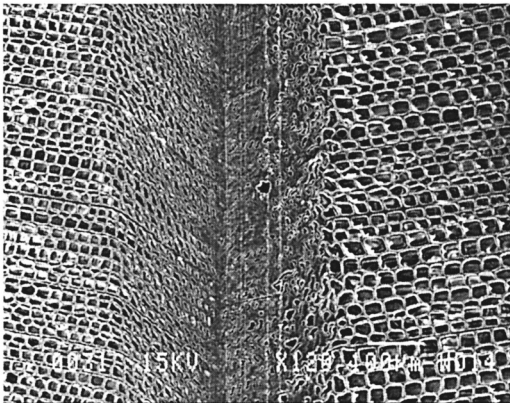Depth of damage = 70 μm (chip-load of 0.64 mm)   A)   Depth of damage = 76 μm (chip-load of 0.64 mm)
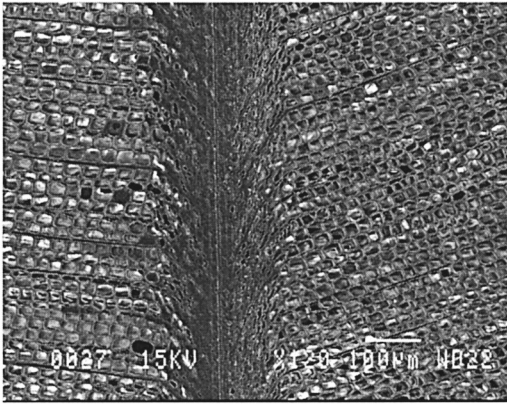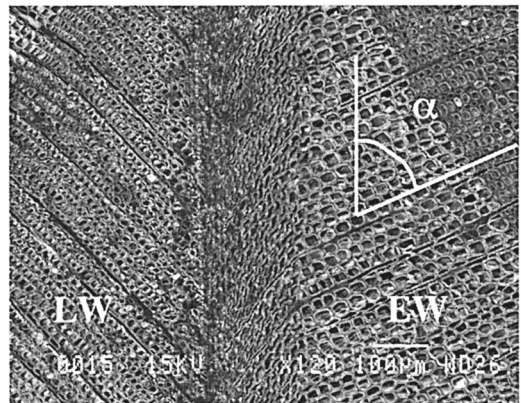
Depth of damage = 115 μm (chip-load of 1.14 mm)   B)   Depth of damage = 108 μm (chip-load of 0.64 mm)

Depth of damage = 281 μm (chip-load of 0.64 mm)   C)   Depth of damage = 142 μm (chip-load of 0.86 mm)

FIG. 2.   SEM micrographs of finger-joined black spruce transverse sections, machined at a cutting speed of A) 1676 m/min, B) 2932 m/min, and C) 3770 m/min, showing surface damage occurred during machining.

TABLE 2. *Depth of damage measured from SEM images and corresponding ultimate tensile strength (UTS) of finger-joined black spruce machined at three cutting speeds.*

	Cutting speed (m/min)		
	1676[a]	2932	3770
Depth of damage (μm)	77.3 (31.3)[b] A[c]	86.2 (39.2) A	133.8 (63.4) B
UTS (MPa)	39.3 (9.5)[b] A[c]	34.6 (7.3) A	25.6 (3.7) B

[a] Number of replicates is 9, values of three chip-loads were pooled because no significant differences were observed among them.
[b] Numbers in parentheses are the standard deviation.
[c] Means followed by the same letter are not significantly different at the 5% probability level.

of damage (134 μm) was reached at 3770 m/min of cutting speed, which is 73% higher than the damage obtained at a cutting speed of 1676 m/min (77 μm). Therefore, it could be concluded that as cutting speed increases, more damage is produced at the surface and subsurface of the fingers. Damage in the surface and subsurface of the cells during machining could have been magnified by the end-pressure applied, but the end-pressure applied to assembly blocks in the finger-jointing process was kept constant for all cutting conditions (3.43 MPa). This pressure was selected in accordance with a previous work by Bustos et al. (2003b). The factorial experiment analyses performed on the UTS values did not show any interaction between cutting speed and chip-load on specimens used for SEM analysis. Failure to observe the same pattern of interaction between the two machining factors for cell damage as observed for UTS might have resulted from the different sample sizes used in the analyses. There were, however, significant differences in the principal effect of cutting speed on the depth of damage (Table 2). As cutting speed increased, the surface damage increased, and consequently the gluing process was negatively affected, and as a result, the mechanical performance decreased. Singh et al. (2002) reported that extensive damage to wood cells is responsible for the inferior glue bonding with dull knife-planed wood surfaces. In our case, a reduction of 35% was observed in UTS when going from a cutting speed of 1676 m/min to 3770 m/min (chip-load values pooled). The effect of cutting speed on UTS could have been even more pronounced after accelerated aging of specimens (Jokerst and Stewart 1976; Caster et al. 1985; Hernández 1994). Therefore, SEM analysis con-

firms the effect of the cutting speed on the UTS variation in finger-joined black spruce.

Observations of SEM samples indicated that the depth of damage appears to be affected by the orientation of rays within the sample with respect to the glueline (α). In general, more significant damage was observed when rays were not at a right angle to the glueline. When the angle formed between the rays and the glueline is about 90°, the ray walls seem to resist and counteract the action of the knives during machining. When the angle is about 45°, the cutters press on the tracheids and the rays directly, which provokes more distortion. A multiple stepwise regression analysis was performed in order to describe the depth of damage measured in the worst damaged side of the glueline as a function of the ray orientation and the cutting speed. The following equation resulted:

$$D = -29.77 + 0.023\ V + 0.68\ \alpha$$

where:
D = depth of the worst surface damage side of the glueline (μm)
V = cutting speed (m/min)
α = ray orientation with respect to the glueline (from 0 to 90°)

Although the model was statistically significant, it explained only 33% of the total variation in D with a coefficient of variation (COV) of 46%. The high COV indicates that this equation cannot be used for predictive purposes. The depth of damage (D) was positively affected by the cutting speed (V) and by the orientation of the rays (α). The cutting speed was the most significant parameter affecting the depth of damage. The standard estimates of the regression

coefficients (beta coefficients) indicated that the effect of this variable accounted for about 60% of the D variation explained by the regression equation.

Therefore, under conditions given in this study, it is possible to identify certain optimal machining values suitable for finger-jointing black spruce wood. Cutting speeds higher than 2932 m/min must be avoided since they give the lowest tensile strength performance observed. A range of cutting speed between 1676 m/min and 2932 m/min appears to produce satisfactory finger-joined black spruce for all chip-loads studied. The feed speeds used under these conditions vary between 7.7 m/min and 24 m/min (Table 3). The highest UTS value was obtained at 1676 m/min of cutting speed and 0.86 mm of chip-load (Fig. 1). Given that 1676 m/min was the minimum cutting speed evaluated, it is not clear if a lower cutting speed could have produced better results. This is an important factor that needs to be further investigated. In addition, although there were not significant differences in UTS at 2932 m/min among the three chip-loads studied, the probability level was close to 0.05 (P = 0.08), and the higher UTS value for this cutting speed was obtained at 0.64 mm chip-load. The corresponding feed speed at this point (13.4 m/min) is 30% higher than the highest condition at 1676 m/min and 0.86 mm chip-load (10.3 m/min) (Table 3). The selection of higher feed speeds has obvious implications on the productivity of the finger-jointer. Thus, the 2932 m/min of cutting speed with 0.64 mm of chip-load would produce 30% more fingers than the 1676 m/min of cutting speed with 0.86 mm of chip-load. Both yield virtually the same tensile strength. Higher feed speeds (18 m/min and 24

m/min) can be obtained at 2932 m/min cutting speed with 0.86 mm and 1.14 mm chip-load, respectively. However, the UTS at these conditions could be reduced by 8.8% and 6.2% with respect to the UTS value at 2932 m/min cutting speed and 0.64 mm chip-load, respectively. Therefore, the latter wood machining condition could be considered as the optimum for finger-jointing black spruce lumber. Moreover, the optimal range of values of cutting speed and chip-load found for finger-jointing black spruce using sharpened knives will eventually be affected by the wear of cutting tools. Further investigation on how wear affects the process is needed. Varying the rake angle and diameter of the cutting circle are other parameters that need to be considered as well.

CONCLUSIONS

Black spruce wood has a good potential in finger-joined structural applications. The tensile strength of all finger-joints fabricated using various chip-loads and cutting speeds met requirements of the Canadian National Lumber Grades Authority (NLGA) SPS 1-2000. Within the range of values studied, cutting speed was the most significant machining parameter affecting the strength of finger-joined black spruce. The influence of chip-load on the tensile strength of finger-joints was less pronounced i.e., it was significant only at lower cutting speeds. Results indicated that suitable finger-jointing could be achieved within a range of 1676 m/min and 2932 m/min of cutting speed with a chip-load between 0.64 mm and 1.14 mm, but a cutting speed of 2932 m/min and a chip-load of 0.64 mm appear to be the optimum condition for finger-jointing black spruce. The results also showed that finger-joints of high tensile strength can be produced with the isocyanate adhesive used in the study.

TABLE 3. *Feed speeds (m/min) required to produce the three cutting speeds and three chip-loads studied in this experiment.*

	Cutting speed (m/min)		
Chip-load (mm)	1676	2932	3770
0.64	7.7	13.4	17.3
0.86	10.3	18.1	23.2
1.14	13.7	24.0	30.9

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