WEAR BEHAVIOR OF DRILL BITS IN WOOD DRILLING RESISTANCE MEASUREMENTS

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Abstract. The objectives of this study were to investigate the wear behavior of drill bits in wood drilling resistance measurements and to understand how the blunting of the cutting edges may affect the cutting forces and ultimately the measurement results. Laboratory resistance drilling experiments were conducted using an IML-RESI PD 400 tool (IML Instrumenta Mechanik Labor GmbH, Wiesloch, Germany) and a standard spade-type drill bit. Results were based on 375 drillings made on a 2.58 m long, freshly cut, defect-free yellow birch (*Betula alleghaniensis*) log with an average MC of 55.5%, an average density of 710 kg/m^3, and a total cutting path length (CPL) of 5011 m. With the use of the photographic facilities of the microscope, wear and blunting parameters such as clearance and rake face wear, cutting edge rounding, wear along the bisecting line of the wedge (sharpness) angle, residual microclearance angle, wear area, and drill bit diameter were measured and calculated for initial condition of the drill bit and the conditions at incremental cutting path lengths. The initial geometry parameters of the cutting head of the drill bit had a big impact on tool wear and blunting, which affected the precision of wood density evaluation. Intensive blunting and wear of the cutting edges occurred on the clearance faces and increased proportionally with the total cutting path length. Rounding of the cutting edges and drilling resistance (torque) were relatively constant within the experimental conditions, indicating that resistance drilling measurement in wood was still accurate as the total CPL reached 5011 m (or 375 drillings). Feeding force was found to be affected by the blunting of the cutting tool and may be used to predict the service life of a drill bit.

Keywords: Blunting, cutting path length, drill bit, drilling resistance, feeding force, log, wear.

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INTRODUCTION

Drilling resistance measurement is a quasi-nondestructive method commonly used for wood defect detection (such as decay, insect damage, internal void, internal cracks etc.) and wood density evaluation. A typical resistance drilling tool (also known as Resistograph) is a mechanical drill system that measures the relative density profiles as a rotating drill bit is driven into wood at a constant speed. The technique operates on the principle that the drilling resistance is directly related to the density of the material being tested (Rinn 1996). During the process of a drilling resistance measurement, the drilling forces (torque moment and feeding force) and speed parameters can be measured continuously as a function of drill bit position in the drilling path (Kamm and Voss 1987; Rinn 1996). With the ability to detect internal wood defects and reveal density variations inside a wood member, the drilling resistance method has now been widely adopted for field applications such as tree ring analysis (Rinn 1996; Rinn et al 1996), urban tree decay detection (Mattheck et al 1997; Wang et al 2005; Wang and Allison 2008; Allison and Wang 2015), and condition assessment of existing wood structures (Brashaw et al 2005; Zhang et al 2009; Tannert et al 2014).

Research has been conducted to evaluate the potential of drilling resistance measurement as an indirect method to predict density or specific gravity of dry wood. Some early studies demonstrated that there is a strong linear correlation between the mean drilling resistance and gross density of dry wood (Görlacher and Hättich 1990; Rinn et al 1996). Winistorfer et al (1995) found that the drilling resistance technique provided a good measure of vertical density profiles of wood composite panels. More recent studies on structural wood members also showed moderate to strong relationships between measured drilling resistance values and wood density or specific gravity [$r^2 = 0.67$ reported by Ceraldi et al (2001), $r^2 = 0.44$ reported by Zhang et al (2009), $r^2 = 0.89$ reported by Park et al (2006), $r^2 = 0.93$ reported by Bouffier et al (2008), $r^2 = 0.62$-0.78 reported by Sharapov and Chernov (2014), and $r^2 = 0.71$-0.77 reported by Oliveira et al (2017)]. There is also a growing interest in using drilling resistance for forest genetics field tests (Gao et al 2017). In a tree genetic improvement program, Isik and Li (2003) evaluated the usefulness of the Resistograph tool for measuring the relative wood density of live loblolly pine (*Pinus taeda* L.) trees and for estimating family and individual-tree breeding values. They reported strong correlations between average drilling resistance values and wood density and strong genetic control at the family level; however, individual phenotypic correlations were found to be relatively weak. Similar results have also been reported by Charette et al (2008), Gwaze and Stevenson (2008), and Eckard et al (2010). There were speculations that environmental, operator, and instrument factors may affect the accuracy of wood density prediction (Isik and Li 2003; Ukrainetz and O'Neill 2010). In a study designed to quantify the sensitivity of the drilling resistance tool to various environment and instrument factors, Ukrainetz and O'Neill (2010) found that density index was sensitive to operator movement, tree MC, air temperature, and proximity of the sampling location to knots. Nonetheless, by ensuring that the operator remains steady while drilling, sampling only live trees, testing only when ambient temperature is above freezing, and avoiding knots, measurement error could be minimized.

The accuracy of a drilling resistance tool for wood density prediction can also be affected by the wear and blunting (reduced performance) of drill bits as in the case of any wood-cutting process. Wear of a wood-cutting tool typically refers to loss of material from the surfaces that form the cutting edge, whereas blunting is defined as the change in microgeometry of the edge associated with effects such as increased feeding force and motor power and deterioration of chip or cutting surface (McKenzie and Karpovich 1975). A large body of work has been performed on characterizing wear behavior and blunting of various wood-cutting tools (McKenzie and Cowling 1971; McKenzie and Karpovich 1975; Zotov and Pamfilov 1991; Sheikh-Ahmad and McKenzie 1997; Sheikh-Ahmad and Bailey

1999; Sheikh-Ahmad et al 2003; Porankiewicz et al 2005; Aknouche et al 2009; Ekevad et al 2012); however, very limited information exists regarding the wear behavior of drill bits in wood resistance drilling. Currently, there is great practical interest in knowing the service life of a drill bit with regards to wood density prediction without compromising the measurement accuracy. The objectives of this study were to investigate the wear behavior of drill bits in wood drilling resistance measurements and to understand how the blunting of the cutting edges may affect the cutting forces and ultimately the measurement results.

Figure 1. Drilling resistance measurements on a yellow birch log.

MATERIALS AND METHODS

Materials

A freshly cut defect-free yellow birch (*Betula alleghaniensis*) log was obtained for conducting a series of drilling resistance measurements. The log sample was 2.58m long with a diameter of 35 cm at the large end and 29 cm at the small end. The log had an average MC of 55.5% and an average basic density of 710 kg/m^3, which were determined based on measurements on six disks following the drilling resistance measurements.

Drilling Resistance Measuring Instrument

We used an IML-RESI PD 400 tool to conduct the drilling resistance measurements on the yellow birch log (Fig 1). This resistance drilling tool is equipped with standard spade-type needle drill bits as shown in Fig 2. Because our goal was to investigate the wear behavior of the drill bit and the effect of its blunting on the drilling process, we used a single drill bit throughout the drilling experiments. All drilling resistance measurements were conducted at a fixed feed rate of 0.508 m/min and a fixed rotating speed of 2500 rpm. These speed parameters were selected based on several pretests on the log to prevent overloading during the course of the drilling experiments. All drilling measurements were carried out radially in transverse cross sections, perpendicular to the grain. The resistance profiles obtained from each measurement included a relative resistance curve reflecting the torsion force on the drill bit and a feeding force curve reflecting the pressure put on the tool, both recorded in percentage of the amplitude. The drilling resistance parameters were measured and digitally recorded once every 0.1 mm of drilling depth. The resistance drilling data were saved and processed using the PD-Tools PRO software (IML Instrumenta Mechanik Labor GmbH).

Resistance Drilling Parameters

Drilling in wood is a complicated cutting process. The actual forces acting on the drill bit elements are difficult to measure directly or calculate analytically. Drilling resistance measurement is typically limited to determining the integrated indicators of torque moment and axial (thrust) force (Lyubchenko 2004). Torque moment in a drilling process involves a tangential cutting force component (or cutting resistance force in opposite direction) acting on the cutting edges, whereas thrust force (feeding force) acts in the drilling direction. In our drilling experiment, two cutting force components were indirectly measured and recorded: relative drilling resistance (amplitude in percentage) reflecting the torque moment and feeding force

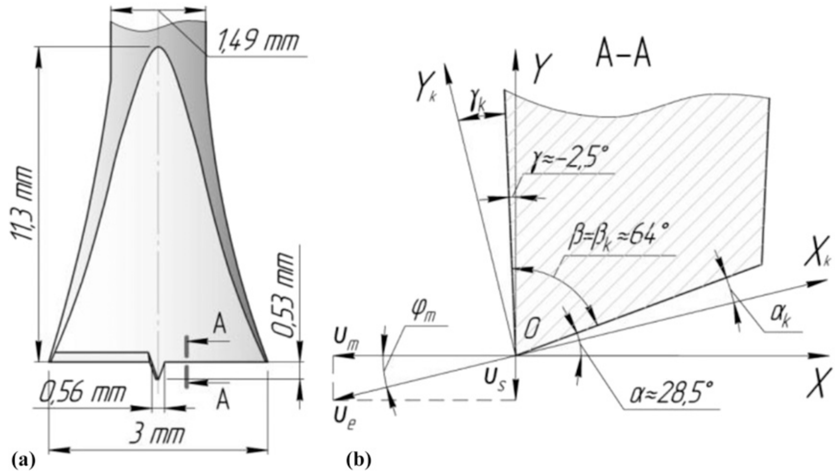

Figure 2. Main geometrical parameters of the spade-type drill bit used in the resistance drilling experiment (approximate values); (a) front view of the drill bit cutting head; (b) side view of the cutting head showing angles and vectors of main movements for the cutting edge in the normal plane (P_n). Cartesian reference system (*XOY*), cutting angles in static: α, clearance angle (degree); β, wedge (sharpness) angle (degree); γ, rake angle (degree); the same in kinematic: α_k, β_k, γ_k; u_s, vector of feeding movement; u_m, vector of cutting movement; u_e, result vector; and ϕ_m, movement angle (Bershadskii and Tsvetkova 1975; Lyubchenko 2004).

(percentage or N) that was actually applied to the drill by the operator.

Drill Bit and its Geometrical Parameters

The spade-type needle drill bit used in this study was 400 mm long with a thin shaft 1.5 mm in diameter and a 3 mm wide triangular-shaped cutting head (Fig 2a). The body of the drill bit was made from a steel grade analogous to EN C80D (AISI 1080), with hard chrome and teflon coating on the cutting head (personal communication with Dr. Tobias Biechele, IML Instrumenta Mechanik Labor GmbH). The flat cutting head of the drill bit had two symmetrical cutting edges that were perpendicular to the shaft (or rotating axis) and a small tip between two cutting edges that rose about 0.53 mm high. It should be noted that the initial geometry parameters of a drill bit cutting head can vary slightly; even the two cutting edges in the same drill bit can be slightly different.

Figure 2b shows various parameters of a cutting edge on the cutting head in a Cartesian reference system, including clearance angle α, wedge (sharpness) angle β, and rake angle γ in static and kinematic conditions.

According to wood-cutting theory, the movement angle ϕ_m (in degrees) of the drilling process is defined by the following equation:

$$\phi_m = \arctan\left(\frac{u_s}{u_m}\right) = \arctan\left(\frac{1000 \cdot u_s}{2 \cdot \pi \cdot n \cdot r}\right) \quad (1)$$

where *r* is distance from the rotating axis to any point on the cutting edge (mm); *n* is rotational speed (rpm); u_s is feed rate (m/min); and u_m is cutting speed (m/s).

Given the feed rate of 0.508 m/min, the drill bit rotational speed of 2500 rpm, and the geometry of the drill bit cutting head, the movement angle was in the range of 1.2-6.5 degrees.

The microgeometry and wear parameters of the spade-type drill bit used in this study are characterized using the parameters described in Grube (1971). Figure 3 shows the cutting edge blunting and wear parameters defined in a static rectangular coordinate system: clearance face wear X_1 (μm), rake face wear Y_1 (μm), edge rounding ρ_1 (μm),

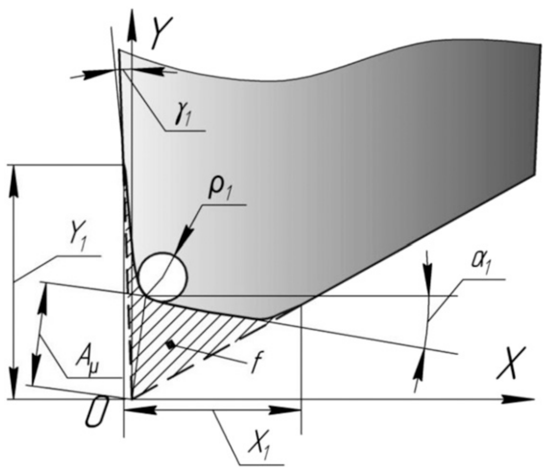

Figure 3. Measured cutting edge blunting and wear parameters: X_1, clearance face wear (μm); Y_1, rake face wear (μm); ρ_1, cutting edge rounding (μm); A_μ, wear along the bisectrix line of residual sharpness angle (μm); α_1, residual microclearance angle (degree); γ_1, residual microrake angle (degree); and *f*, wear area size (μm^2).

wear along the bisecting line of residual sharpness angle A_μ (μm), residual microclearance angle α_1 (deg.), residual microrake angle γ_1 (deg.), and wear area *f* (μm^2). Wear and blunting parameters were measured separately for the left and right cutting edges of the drill bit.

The initial geometry (microgeometry) parameters of the new drill bit used in this study were determined as follows: 1) left edge: $\beta = 64.5$, $\gamma = -2.35$, $\rho_1 = 13.1$ μm, $X_1 = 22.2$ μm, $Y_1 = 26.3$ μm, $A_\mu = 14.8$ μm, and $f = 173.4$ μm^2; 2) right edge: $\beta = 63.7$, $\gamma = -2.25$, $\rho_1 = 9.3$ μm, $X_1 = 28.5$ μm, $Y_1 = 28.8$ μm, $A_\mu = 15.5$ μm, and $f = 212.1$ μm^2; and 3) distance between the two outermost points on the left and right cutting edges was 45 μm.

Drilling Resistance Measurements and Data Processing

Drilling resistance measurements were performed on the yellow birch log at room temperature (about 20°C). The round log was divided into five sections of equal length for sequential drillings. The first sequence was five drillings, one drilling on each section, followed by the second sequence of testing, one on each section. A total of 75 sequences of testing with 375 drilling measurements were conducted in two radial-longitudinal sections along the log length, with a 1- to 1.5-cm spacing between any two neighboring drillings. This testing procedure was designed to minimize the effect of wood property variations along the log. Among all the drilling measurements, 17 discrete drilling resistance data points (no. 1, 4, 7, 14, 24, 34, 44, 59, 79, 99, 119, 149, 200, 250, 300, 350, and 375) were selected for force parameter comparison analysis. Drilling resistance data at these points were downloaded from the instrument through PD-Tools PRO (IML Instrumenta Mechanik Labor GmbH) software and further processed using Microsoft Excel (Microsoft Corporation, Redmond, WA) for graphical presentation and mean value calculations.

During the course of the drilling experiments, the wear and blunting parameters of the cutting edges were also monitored and measured 11 times (initially on the new drill bit, then after 7, 24, 44, 99, 149, 200, 250, 300, 350, and 375 drillings) by taking microscope images of the drill bit cutting edges using an optical microscope (Olympus BX 41 microscope, Olympus Corporation, Tokyo, Japan). The images of the drill bit cutting head were taken in three positions: 1) the cutting head lying flat for measuring the width of the drill bit (with 40× magnification); 2) the cutting head in a vertical position for measuring wear and blunting parameters of the first cutting edge (with 100×, 400×, or 600× magnifications); and 3) the cutting head turned 180 degrees to the opposite vertical position for measuring wear and blunting parameters of the second cutting edge (with 100×, 400×, or 600× magnifications). The microscope images were then loaded into KOMPAS-3D V13 software (ASCON, Saint Petersburg, Russia) and processed as illustrated in Fig 4. The wear and blunting parameters of the two cutting edges were measured using an ocular micrometer in the microscope images.

Throughout the drilling experiment, the drill battery was fully recharged once every 30

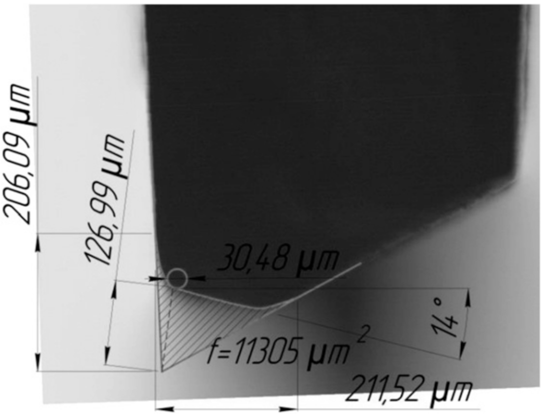

Figure 4. Wear and blunting parameters measured on the microscope image of one of the cutting edges with 100× magnification after 350 drillings (maximum cutting path length: 4691 m). Measurements and calibration were performed using KOMPAS-3D software.

drillings to reduce any possible influence of low battery energy (Ukrainetz and O'Neill 2010). The output amplitude values (in percentage) of the drilling tool can characterize wood density variations along the drilling path, but the exact units for the amplitude measurements were not specified by the tool manufacturer. In this study, we calibrated the feed parameter (percentage) to actual feeding force (N) using a universal testing machine MTS 810 (MTS Systems Corporation, Eden Prairie, MN) with a 1-kN load cell. Because of log diameter variation, the drilling depth of each drilling measurement was different. To better characterize the wear behavior of the drill bit, we used cutting path length (CPL), instead of the number of drillings as a service length indicator that was related to drilling depth, rotating speed and feed rate. The maximum CPL in a drilling process, which corresponds to the outermost corner of the cutting edges traveling in a spiral path, can be determined by the following equation (Bershadskii and Tsvetkova 1975; Lyubchenko 2004):

$$S_{MAX} = \frac{L \cdot n \cdot \pi \cdot D}{1000 \cdot u_s} \qquad (2)$$

where S_{MAX} is the maximum CPL (mm); D is drill bit diameter (width of the drill bit cutting head) (mm); and L is drilling depth (mm).

The nominal feed rate per cutting edge defined by $\Delta = 1000 \cdot u_s/(z \cdot n)$ (z, number of cutting edges) was approximately 0.1 mm.

The center tip between the two cutting edges in the drill bit was designed to stabilize the linear movement of the drill bit during the drilling process. This might have some effects on the drilling resistance and feeding force measurement, but according to Rinn et al (1996), the influence was less than 15%, which is negligible.

RESULTS AND DISCUSSION

Cutting Path Length

The accumulated maximum CPL after the *n*th drilling was calculated from the drilling distances using Eq 2 and used as a service length parameter in data analysis. Figure 5 shows the theoretical relationships between the maximum CPL of the cutting edges and different combinations of rotational speeds (1500, 2000, 2500, 3500, and 5000 rpm) and feed rates (0.25, 0.5, 1, 1.75, and 2 m/min). Lower feed rate and higher rotational speed resulted in higher CPL. Figure 5 and Eq 2 can be used as a reference for converting specific speed parameters selected in a drilling instrument to total CPL, which was

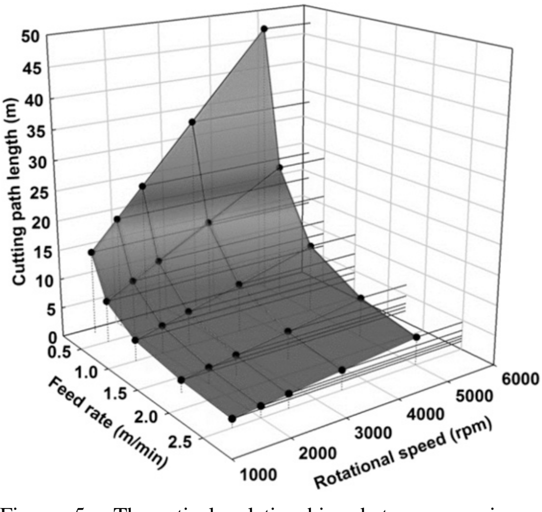

Figure 5. Theoretical relationships between maximum cutting path length (m), drill bit rotational speed (rpm), and feed rate (m/min) for a drilling depth of 250 mm.

analyzed in this study as an indicator of wear and blunting characteristics.

Wear Behavior and Blunting Effect

Figure 6 shows the wear and blunting parameters of the drill bit in relation to CPL for drilling the yellow birch log. Almost all wear and blunting parameters (clearance face wear, rake face wear, and bisector of wedge angle wear) for both cutting edges increased with increasing CPL. The only exception was the edge rounding, which remained relatively constant as the CPL increased to 5011 m. More specifically, the edge rounding only increased slightly at the initial stage of the recession, then remained constant during the course of the drilling experiments. It appeared that with further formation of negative micro-clearance angle, the edge rounding did not reflect the general behavior of metal loss as reported in some research (McKenzie and Cowling 1971; Zotov and Pamfilov 1991). We observed similar wear behavior on the clearance face and the cutting edge (rounding, recession in the direction of the bisector of sharpness angle) in two cutting edges of the same drill bit. However, wear behavior on the rake faces was different. This may have been caused by the initial differences in geometry of the edges, which resulted in uneven feed rates for the two cutting edges and caused uneven recession on the rake faces. The most significant wear (loss of metal) occurred on the clearance faces (Fig 4). The wear on the rake faces was only a small part of the total wear area.

Because more intensive wear occurred on the clearance face and because chip thickness (feed rate per cutting edge in drilling) had more impact on rake face recession, which is negligible compared with the total wear, CPL can be used as a parameter to characterize the service life of drill bits.

The geometry differences between the two cutting edges of a drill bit could affect the actual cutting forces. The resulting differences in the cutting forces can create additional torsion moment, which can change the linear direction of drill bit penetration (Fig 8) and, thus, affect the accuracy of resistance measurements. The subsequent tool wear can aggravate this negative effect. Formation of negative microclearance angles was optically visible when CPL reached 590 m (total drilling depth 12.7 m, $u_s = 0.508$ m/min, and $n = 2500$ rpm). The microclearance cutting angles of the left and right cutting edges were: $-16.75°$ and $-14.23°$, respectively, when CPL reached 5011 m. The diameter (D) of the cutting head in the drill bit was measured using both a caliper and an optical method. During the

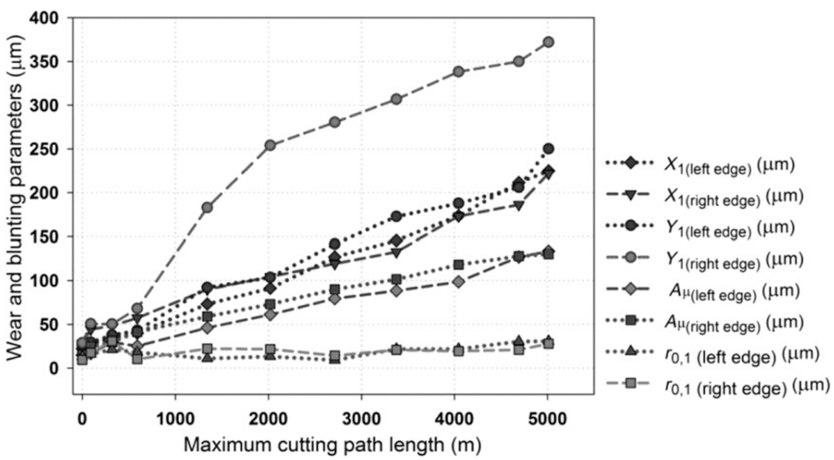

Figure 6. Relationships between wear and blunting parameters of the two cutting edges of a spade-type needle drill bit and maximum cutting path length (m) for resistance drilling of a green yellow birch (*Betula alleghaniensis*) log.

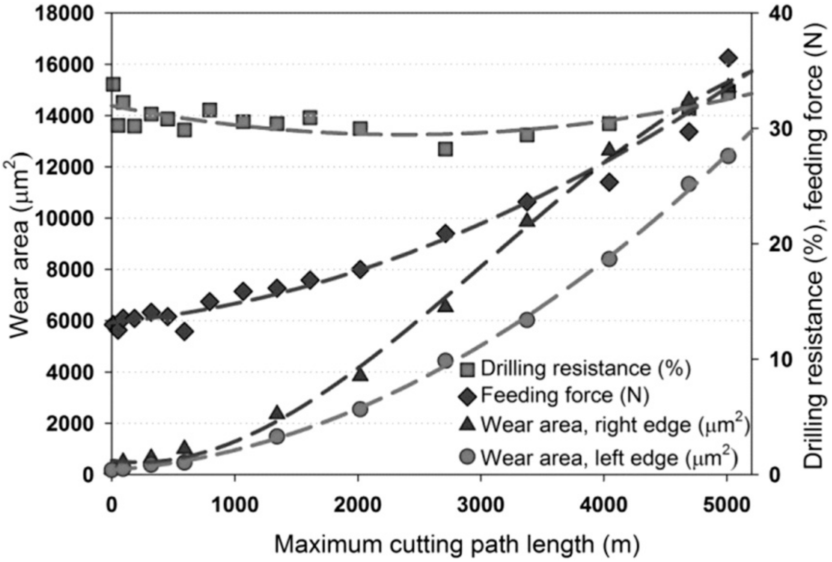

Figure 7. Data and regression models showing relationships between wear area (μm^2) of the cutting edges of a spade-type needle drill bit, drilling resistance (%), feeding force (N), and maximum cutting path length (m) for resistance drilling of a green yellow birch (*Betula alleghaniensis*) log.

drilling experiment, *D* measured using a caliper decreased 3.7% as a result of metal loss, whereas *D* measured using the optical method, decreased nearly 6%. This indicates that more intensive recession occurred when it got closer to the cutting edges, which is not possible to measure using a caliper.

Experimental data on wear areas of both cutting edges, average drilling resistance, and feeding force are plotted in Fig 7. The dashed lines show the regression curves for the relationships between wear area, drilling resistance, feeding force and the maximum CPL. Regression models for wear area, feeding force, and drilling resistance were fitted using SigmaPlot 12.5 software (Systat Software Inc., San Jose, CA) and are provided in

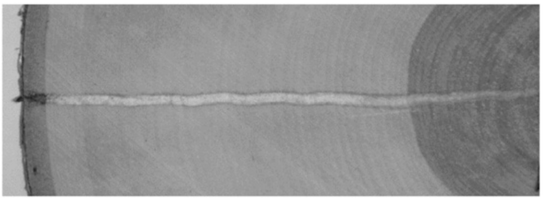

Figure 8. Bore channel observed in one of the drillings made on a green yellow birch (*Betula alleghaniensis*) log.

Table 1. Generally, wear behavior of the left and right cutting edges were similar, and wear area increased exponentially as CPL increased. The different wear area values of the two cutting edges can be explained by the differences in rake face recession, as shown in Fig 6. It was also found that feeding force can be a good indicator of the cutting edge condition. When CPL reached 5011 m, the average value of feeding force increased by 178% compared with the new drill bit.

The sensitivity of feeding force to edge blunting can be seen in Fig 9. Figure 9a shows the results of the drilling resistance measurement using the new drill bit, and Fig 9b shows the results of the drilling resistance measurement at a close location but using the used drill bit (CPL = 5011 m). It is clear that feeding force increased significantly for the used drill bit. One of the main reasons for the feeding force increase was the formation of negative microclearance angles on the cutting edges and the appearance of movement angle in the drilling process, which increased the perpendicular component of the cutting force.

Conversely, drilling resistance (torque moment) showed very small variation during the course of

Table 1. Empirical regression models for relationships between wear area of the cutting edges of a drill bit, feeding force, drilling resistance, and maximum cutting path length.[a]

Parameter, $f(x)$	Regression model	R^2	SEE	F-Ratio	P-Value
Wear area (left edge) (mm^2)	$180.76 + 0.358x + 0.0004x^2$	0.99	134.78	5773	<0.0001
Wear area (right edge) (mm^2)	$551.88 + 0.0016x^2 - 1.6857E{-}007x^3$	0.99	340.9	1004.6	<0.0001
Feeding force (N)	$13.19 + 6.1001E{-}007x^2$	0.97	1.138	277.6	<0.0001
Drilling resistance (%)	$31.96 - 0.0021x + 4.4458E{-}007x^2$	0.5	1.0299	7.0129	<0.0078

[a] Variable x, maximum cutting path length (0-5011 m); R^2, coefficient of determination; SEE, standard error of estimate; F, ratio of the model mean square to the error mean square. Insignificant coefficients are not included in the regression models.

the drilling experiment. Drilling resistance decreased slightly as CPL increased from 0 to about 2500 m, then increased slowly as CPL continuously increased to 5011 m. At the end of the drilling experiment (CPL = 5011 m), the drilling resistance changed by 1.9% (maximum difference in data were 16.6% at 2712-m CPL) compared with the reading from the new drill bit.

Our findings in this study generally agreed with previous investigations (McKenzie and Franz 1964; McKenzie and Karpovich 1975) and showed that the perpendicular cutting force component (feeding force in the drilling process) was more sensitive to tool blunting than the tangential (principal) cutting force component. The special design of the drill bit cutting head also contributed to the relatively consistent resistance readings obtained in the study. Figure 10 shows two scanning electron microscopic images of the drill bit cutting heads showing contrast of the microgeometry between new and used drill bits (after CPL reached 5011 m). Clearly, the wear of the cutting edge was not uniform along the length, and this was caused by the variations in cutting speed, CPL, working angles, and possible changes in temperature along the edges.

The side surfaces of the new drill bit cutting edges had a negative rake angle as shown in Fig 10a, which increased the friction with the drilling surfaces and cut off chips. The subsequent wear on the side surface (Fig 10b) reduced drilling resistance, which is a counter effect compared with the cutting edge blunting, resulting in relatively consistent drilling resistance values (Fig 7). Further increase in drilling resistance could have been the result of blunting of the cutting edges. It is expected that with further increasing

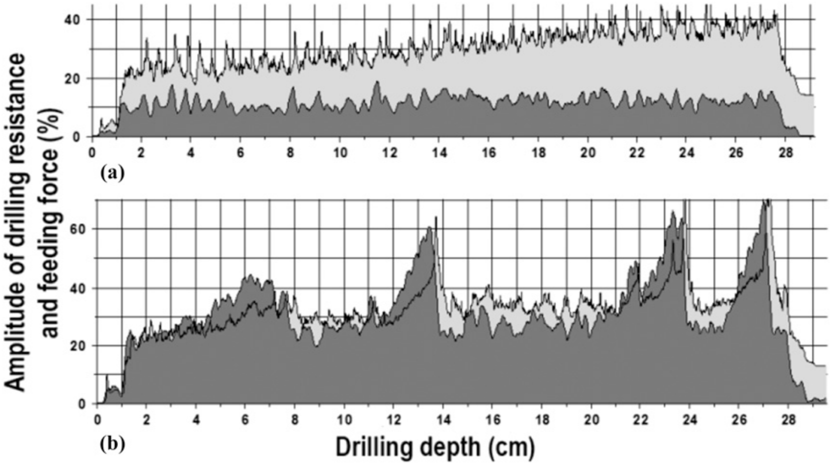

Figure 9. Drilling resistance (light color) and feeding force (dark color) profiles recorded in PD-Tools PRO software. Measurements were made at two vicinal locations (20 mm apart) on the green yellow birch (*Betula alleghaniensis*) log, one with the new drill bit (a) and the other with the used one (b) with maximum cutting path length of 5011 m.

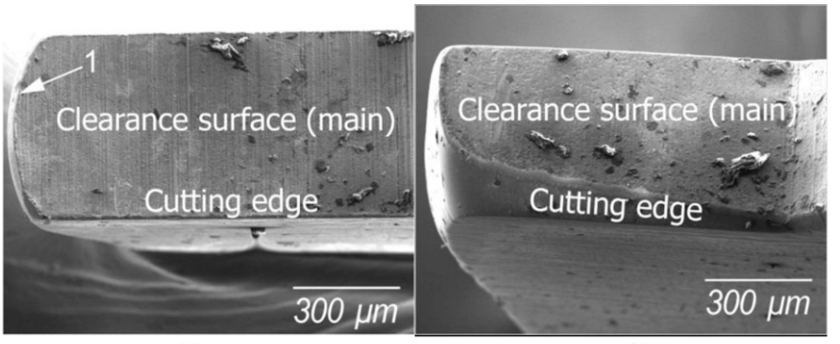

Figure 10. SEM micrographic images with 100× magnification showing the microgeometry of the drill bit. (a) New spade-type needle drill bit, 1 is the intersection line of main and side clearance surfaces; (b) used drill bit after reaching the maximum cutting path length of 5011 m.

of CPL, drilling resistance could increase more significantly.

Wood Species Consideration

In this study, wear behavior of the drill bit and its blunting effect were characterized through drilling resistance measurements on a green yellow birch log. From the standpoint of practical application, it is highly desirable that wear behavior and service life of drill bits be predictable for different wood species. Okai et al (2006) studied the tool wear behavior in three distinctly different wood species, afina (*Strombosia glaucescens*), sugi (*Cryptomeria japonica*), and oil palm (*Elais guineensis)*. At maximum CPL of 1100 m, the cutting edge recession on the clearance face for afina was more than two times higher than that for sugi, equivalent to the differences in specific gravity and strength property between the two species. In the case of oil palm, although it has lower specific gravity and mechanical properties, it was found to have the greatest tool wear because of its higher silica content. Close results for silica content in oil palm wood was investigated by Darmawan et al (2006). Konishi (1972) investigated the relationships between tangential and normal components of the cutting forces and wear of the cutting edge for eight different wood species (Japanese white birch, Japanese beech, Japanese elm, Japanese lime, Japanese larch, apitong, kapur, and hopea). He found that tangential and normal cutting forces increased with the wear parameter in a similar pattern. However, the force-wear patterns were found to vary with wood species.

Ivanovskii (1974) studied cutting resistance for 15 wood species (Siberian fir, Siberian cedar, aspen, lime, spruce, pine, elm, maple, birch, yew, ash, larch, oak, beech, and hornbeam) but found no particular links to the physical and mechanical properties of wood. He identified the cutting work per unit (J/sm^3) for three main cutting directions. Radial drilling mainly consists of cutting along and across the grain, with values of 21 J/sm^3 for birch, 13.5 J/sm^3 for aspen, 15.5 J/sm^3 for pine, 31 J/sm^3 for beech, and 46.5 J/sm^3 for oak.

Based on the results of previous research (Koch 1964; Ivanovskii 1974), it is hypothesized that there is an interaction between wear and blunting parameters of a cutting tool and its cutting work per unit (cutting forces) of different wood species in a drilling process. We speculate that wear and blunting parameters will increase proportionally with cutting work per unit. Further drilling experiments on various wood species are necessary to prove or disapprove this hypothesis.

MC Consideration

In this study, all resistance drilling measurements were conducted on a green log in a relatively short period, assuming without significant moisture changes. However, MC of wood is an important factor to consider in characterizing the wear behavior of a wood-cutting tool and the wood-cutting process. Some conflicting findings have been reported in previous work with respect to moisture effect on wear and the wood-cutting process (Suzuki 1960; Klamecki 1978; Eckstein and Sass 1994; Mattheck et al 1997; Lin et al 2003; Johnstone et al 2011; Anagnostopoulou and Pournou 2013). In the case of cutting into green wood, the effect of MC on the cutting process can be very complicated. Above the FSP, free water in cell lumen may act as lubricant for cutting surfaces; thus, high MC could reduce the cutting forces and power consumption (Lucic et al 2004; Moradpour et al 2013). Conversely, for a closed cutting process such as resistance drilling measurement, high MC could also increase the friction forces between the cutting tool, pulled-out chips, and cutting surfaces (Lyubchenko 2004). In addition, high MC can increase corrosive wear (Ramasamy and Ratnasingam 2010). Influence of MC on wear and power consumption during resistance drilling measurements should be investigated in future studies. One approach is to improve the design of the cutting head of a drill bit by creating positive side clearance angles for friction reduction.

CONCLUSIONS

In this study, we investigated the wear and blunting of the drill bit and its effects on drilling resistance measurement on a green yellow birch log. Based on the experimental results obtained and the observations of microgeometry changes through 375 drillings, we conclude the following:

1. The initial geometry parameters of the cutting edges in a drill bit greatly impacted tool wear and blunting, thus affecting the precision of resistance drilling measurement. Improvements can be made in drill bit design and manufacturing processes to create positive side clearance angles, which may increase the accuracy of wood density prediction.
2. Intensive blunting and wear of the cutting edges occurred on clearance faces and increased proportionally with the total cutting path length, which is a function of drilling depth, rotational speed, and feed rate of the drilling process. Wear along the cutting edges was not uniform because of variations of the cutting speed, cutting path length, working angles, and temperature along the edges.
3. Feeding force was found to be sensitive to the blunting of the cutting tool, and it increased continuously as the total cutting path length increased. Consequently, feeding force may be used to predict the service life of a drill bit.
4. Rounding of the cutting edges and the average drilling resistance were found to be relatively constant under the experimental conditions of this study, indicating that resistance drilling measurements were still accurate when the total cutting path length reached 5011 m (375 drillings). However, drilling resistance could increase significantly with further increase of drilling measurements.

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