The Dependence of Surface Quality on Tool Wear of Circular Saw Blades during Transversal Sawing of Beech Wood

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The article deals with the influence of the tool wear of several circular saw blades, each with different numbers of teeth (24, 40, and 60), on the quality of a machined wood surface. The surface quality was evaluated based on the surface roughness, which was represented by the surface arithmetical mean deviation R_a. To achieve the conditions of manual sawing, the saw blade was shifted into the cut with a constant feed force of 15 N. The results showed that the 40-tooth saw blade obtained the most suitable results; it exhibited the longest sawn distance and reached moderately good values of tool wear. The average values of surface roughness ranged from 3.9 to 14.5 µm, and the saw blade wear increased proportionally with sawn distance. The tool wear of the saw blade had no unambiguous effect; increase in tool wear did not lead to a deterioration of surface quality.

Keywords: Tool wear; Surface roughness; Transversal sawing; Surface quality; Feed force; Beech

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INTRODUCTION

The transversal sawing of wood is an operation that relates to almost every machined wood product. During transverse cutting, the quality of the sawn surface depends primarily on the surface roughness after cutting and not least also on the characteristics of the tool.

Every process causes a disruption in the material's initial properties and leaves certain irregularities on the machined surface. These irregularities are represented by microscopic (surface roughness, waviness) and macroscopic (scratches, corrugations, hollows, furrows, thorn fibers) changes on the machined surface (Siklienka and Kminiak 2013; Kminiak 2014). The quality of the machined wood surface depends primarily on the suitability of machining procedures used; machining parameters, such as feed speed, feed force, and cutting speed; as well as the suitable technical treatment of tools, such as regular sharpening and maintenance. Similarly Malkoçoğlu (2007) found that the machining conditions are directly related to defects created during the sawing (fuzzy grain, torn grain, raised grain). A number of authors, such as Örs *et al*. (1991), Efe *et al*. (2007), Budakçi *et al*. (2011), and Kvietková *et al*. (2015), have dealt with the influence of various technological parameters (cutting speed, feed speed, number of teeth) on the final surface quality of wood.

Tooth profile is directly responsible for the final quality because of its shape and geometry affects the individual wood elements during cutting. The tooth profile must conform to the desired utilization of a circular saw and to the quality of machined surface

(Kováč and Mikleš 2010). If the outer lateral edge of the set teeth is chamfered, then the bite profile is reduced while the surface quality becomes improved because of less damage to the wood fibers (cleaner cuts) (McKenzie 2000). Conversely, the chamfering of the inner lateral edge of the set teeth increases the bite profile. This can cause an increase in cutting forces and deterioration in the quality of machined surface (Naylor and Hackney 2013).

The properties of the wood are another factor affecting surface quality. The surface roughness is mostly influenced by wood structure, which includes direction and angle of fibers, spring and summer wood, and knots, but also physical properties such as moisture and density. The density affects almost all the mechanical properties of wood (Gaff 2014; Gaff and Matlák 2014), and thus also the machining processes.

An important factor affecting the machined surface quality is tool wear. Tool wear can be described as a gradual and small but sufficient change in wedge geometry during machining (cutting) by which the tool loses its sharpness and consequently its ability to cut effectively. Tool wear may exist as accidental wear or as normal (mechanical) wear. Accidental wear occurs when, during cutting, the tensile strength in the tooth reaches a higher value than the fracture strength of the material from which it is made. Mechanical wear can be characterized by the removal of metal particles from teeth by the friction between tool and the wood (Cosmin *et al*. 2009). Generally, tool wear is used to assess tool performance because of its direct influence on surface quality, cutting force, power consumption, *etc*. (Cristóvão 2013). In general, the higher the wear of tool, the worse surface quality of machined material. Increasing the blunting of tool leaves bigger and bigger tracks at the surface of the wood because it disrupts the wood fibers and raises them. Thus, tool wear increases the surface roughness, and thus the surface quality deterioration occurs.

The aim of this work was to determine the influence of number of saw blade teeth as well as sawn distance (sawn running meters) on the wear of saw blades and surface roughness of beech wood during transversal cutting at a constant cutting speed (v_c = 62 m/s).

EXPERIMENTAL

Materials

Forty-five-year-old European beech (*Fagus sylvatica* L.) trees, which grew in the Zvolen basin, were used for the experiment. Suitable zones were cut from the trunk at a height of 1.5 m, measured from the stump. The flat-sawn samples (wood fibers angle φ_3 = 90° ÷ 80°) had dimensions of 25 × 150 × 1000 mm. Clear samples were conditioned in a conditioning room (relative humidity (ϕ) = 65 ± 5% and temperature (t) = 20 ± 2 °C) for more than four months to achieve their equilibrium moisture content (EMC) of 12%. The average oven-dry density of beech wood was 668 kg/m^3. Whole experiment contained 200 samples.

Methods

Sliding mitre saw

The cutting for the experiment was carried out using a GCM 10S Professional (Robert Bosch GmbH, Germany) sliding mitre saw. The mitre saw parameters are listed in Table 1.

Table 1. Mitre Saw Parameters

Parameters	Value
Power input	1,800 W
Cutting capacity, 45° incline	53 × 305 mm
Cutting capacity, 45° mitre	87 × 216 mm
Cutting capacity, 0°	87 × 305 mm
Mitre setting	52° L / 62° R
Incline setting	47° L
No-load speed	4,700 rpm
Saw blade diameter	254 mm
Flange diameter	75 mm
Mounting hole diameter	30 mm

Saw blade

Three "PREMIUM" saw blades (EXTOL, Czech Republic) with sintered carbide tips having 24, 40, and 60 teeth, respectively, were selected for the experiment (Fig. 1). The saw blades had identical diameters (D = 250 mm), identical tool thicknesses (b = 3.2 mm), identical angle geometries (clearance angle α = 15°, wedge angle β = 60°, rake angle γ = 15°), and alternating set teeth.

Fig. 1. Saw blades with a) 24 teeth, b) 40 teeth, and c) 60 teeth

Transversal sawing

Many similar experiments have used a constant feed speed, v_f. However, for the present experiment, the use of a feed force, F_p, is typical. Feed force was substituted for feed speed due to the manual feeding. Because the requirements for constant experimental conditions, such as a constant feed force, could not be met during manual feeding, the feed force was simulated in an experimental stand.

Fig. 2. Sequential saw blade movement through the sample with manual feeding

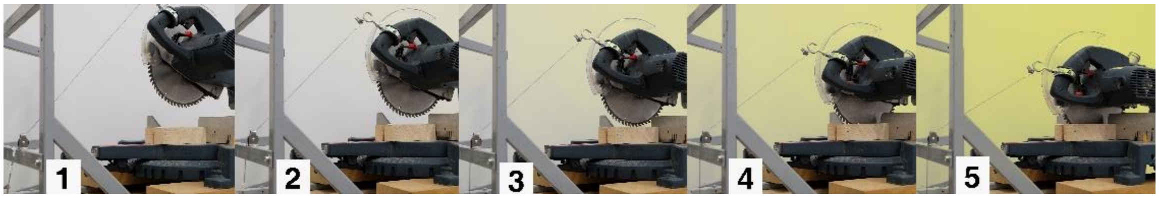

Fig. 3. Sequential saw blade movement through the sample with feeding by means of the experimental stand

Manual saw blade movement (Fig. 2) was simulated by the use of a hauling rope (Fig. 3), and the proper feed force was extracted using weights. During a preliminary stage, the average feed force was determined using a mechanical dynamometer FK 100 (Sauter AG; Switzerland) connected between the handle of the saw and a person. On the basis of these preliminary tests, the average feed force F_p = 15 N was selected. During the experiment, the 10-mm-thick pieces (slices) were cut from the conditioned longitudinally oriented samples using a sliding mitre saw. The experiment was carried out at a constant cutting speed v_c = 62 m/s. The movement of the saw blade was realized through an arc trajectory, which was the main difference between this study and the previous work Kminiak and Gaff (2015), where the feed was carried out using a rectilinear-reciprocating motion.

Measurements

Surface roughness

The surface roughness was measured using a laser profilometer, LPM-4 (KVANT s.r.o., Slovakia) (Fig. 4) in accordance with the standards ISO 4287 (1997) and ISO 4288 (1996). This profilometer used a triangulation principle. First, the image of the laser line was sensed by a digital camera at an angle. Then, the object profile, in cross-section, was evaluated from the taken image. Last, the obtained data were mathematically filtered, and the indices of the primary profile, corrugation profile, as well as roughness profile were determined.

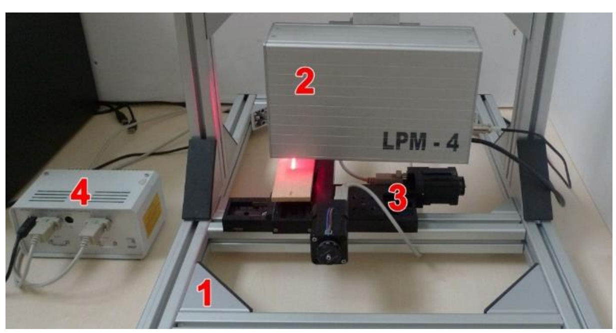

Fig. 4. Laser profilometer that measured the sample surface roughness: (1) bearing structure allowing the manual preset of the working distance and the fixing of both the profilometer head and sliding tables system; (2) profilometer head; (3) system of slides for axes X and Z; and (4) control unit of the work tables sliding system

A measurement was carried out in three paths equidistant from one another along the sample width (2.5, 10, and 22.5 mm from the sample margin). The path length was 60 mm (Fig. 5). The surface roughness was evaluated based on the arithmetic mean of the profile roughness, R_a.

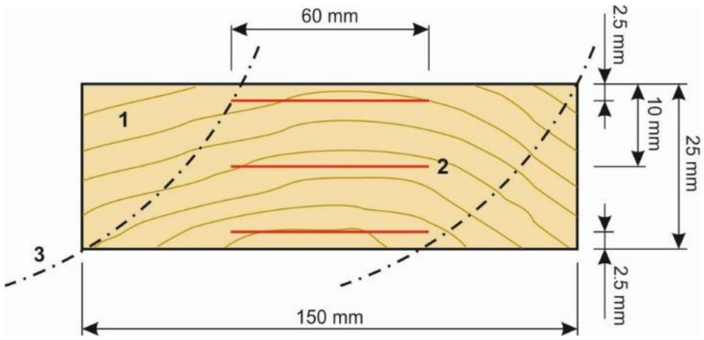

Fig. 5. The schematic representation of measuring paths on the sample: (1) sample; (2) measuring paths; and (3) track teeth of the saw blade

Tool wear

The tool wear was evaluated using the parameter SV, *i.e.*, the decrease in cutting edge/cutting edge loss (edge recession) (Fig. 6). After a certain sawn distance (0 m, 50 m, 100 m, *etc*.) tool wear, *i.e.*, loss in ability of the saw blade to cut well, evident when the saw blade started to burn the surface of the test samples and the pluck of wood fibers, began to set in; the tool wear as well as the surface roughness of samples were measured.

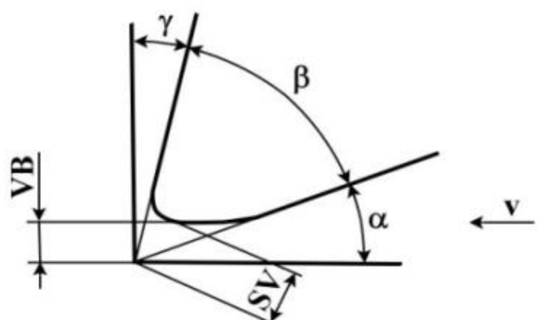

Fig. 6. Measurement of tool wear

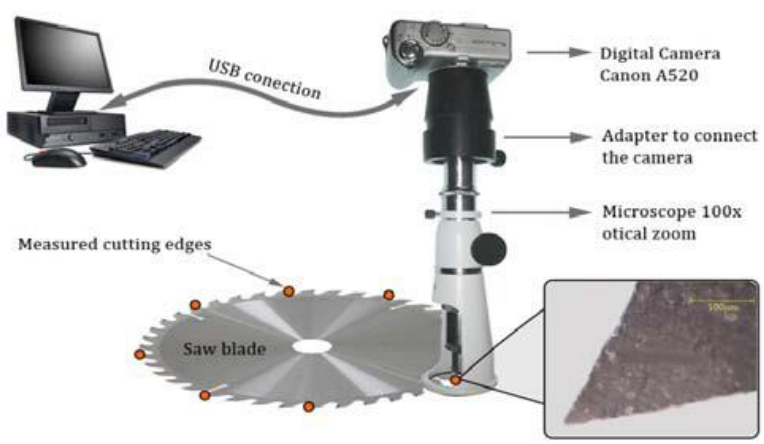

Fig. 7. Measurement of saw blade wear

The measurement of tool wear was carried out using a digital microscope HC 100-L (HITEC, Germany) and digital camera PowerShot A520 (CANON, Japan) plus software Zoombrowser EX 5.0 (Fig. 7). The number of teeth (4 teeth for a 24-tooth saw blade, 7 teeth for a 40-tooth saw blade, and 10 teeth for a 60-tooth circular saw blade, respectively) was selected and marked on each circular saw blade. After the saw was applied for a certain length cut, the marked teeth were measured again in order to detect blunting. The evaluation of blunting was carried out by comparing the sharp cutting edge with the worn cutting edge, and then the SV was measured.

Evaluation and Calculation

The surface roughness and wear values were evaluated by means of ANOVA analysis, specifically utilizing Fisher's F-test, in STATISTICA 12 software (Statsoft Inc., USA).

The density was defined as an auxiliary indicator. Density was calculated according to Eq. 1 from ISO 13061-2 (2014),

$$\rho_w = \frac{m_w}{a_w * b_w * l_w} = \frac{m_w}{V_w} \tag{1}$$

where ρ_w is the density of the test sample at a certain moisture content w (kg/m^3), m_w is the mass (weight) of the test sample at certain moisture w (kg), a_w, b_w, and l_w are dimensions of the test sample at certain moisture w (m), and V_w is the volume of the test sample at a certain moisture w (m^3).

The moisture content of the samples was determined and verified before and after thermal treatment. These calculations were carried out according to ISO 13061-1 (2014) and Eq. 2,

$$w = \frac{m_w - m_0}{m_0} * 100 \tag{2}$$

where w is the moisture content of the samples (%), m_w is the mass (weight) of the test sample at a certain moisture w (kg), and m_0 is the mass (weight) of the oven-dry test sample (kg).

Drying to oven-dry state was also carried out according to ISO 13061-1 (2014).

RESULTS AND DISCUSSION

Tool Wear

The ANOVA results are shown in Table 2. All examined factors as well as their interactions were found to be statistically significant.

The saw blade durability (lifetime), as defined by Šustek and Siklienka (2012), is the time period or sawn distance during throughout which the saw blade is able to function, *i.e.*, to cut with proper quality. For the present experiment, this point at which the saw blade lost its ability to properly cut was defined as the point at which the saw blade started to burn and yanks the wood fibers on the wood surface. This point was different for the different saw blades. Generally, if the number of teeth increases, so the durability of saw blade will increase as well during transversal cutting. This fact was confirmed only up to 750 m but could not be applied in terms of maximum durability.

For the 24-tooth sawn blade, this phenomenon occurred at the sawn distance of 750 m. The 60-tooth saw blade demonstrated an increase in sawn distance of 6.67% over that of the 24-tooth blade, *i.e.*, 800 meters.

Table 2. Influence of Individual Factors on Tool Wear

Monitored factor	Sum of Squares	Degree of Freedom	Variance	Fisher's F - Test	Significance Level P
Intercept	561,694	1	561,694	14,372.7	0.0001
Number of teeth	51,596.3	2	25,798.2	660.1	0.0001
Sawn distance	99,997.7	15	6,666.5	170.6	0.0001
Number of teeth × Sawn distance	7,153.0	30	238.5	6.1	0.0001
Error	3,751.7	96	39.1		

The longest sawn distance, 1,200 m, was found for 40-tooth saw blade, which constituted an increase of 60% beyond that of the 24-tooth blade and of 50% beyond that of the 60-tooth saw blade. This saw blade reached a moderate cutting resistance of wood because has a proper number of teeth therefore good force distribution in wood occurred. Sawn distance is directly affected by bite per tooth, which depends on number of teeth, feed speed and cutting tool rotation. Based on the comparison of the results measured for the individual blades with different numbers of teeth, it was clear that the highest degree of tool wear was found for the 24-tooth circular saw blade (Fig. 8).

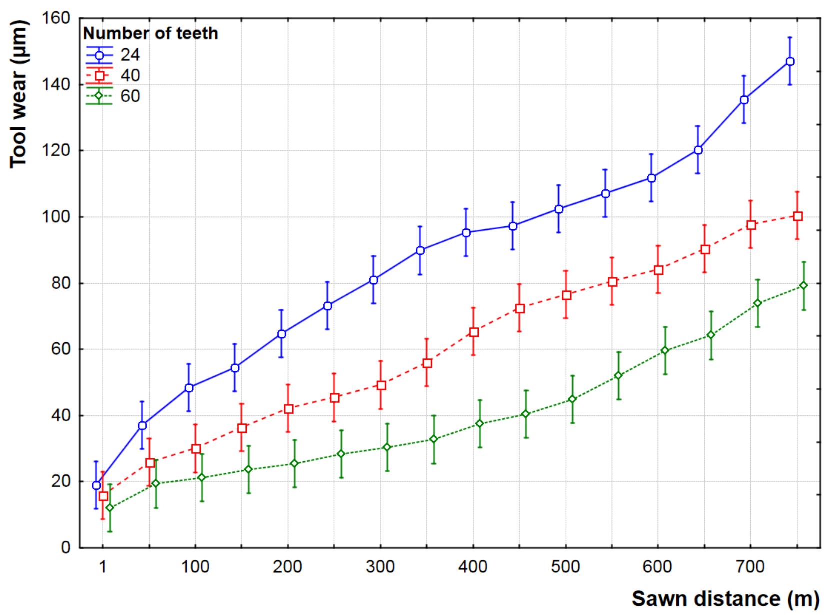

Fig. 8. Measured average tool wear as a function of the sawn distance and number of teeth

For the 24-tooth saw blade, the tool wear was 147.3 µm. The tool wear of the 40-tooth saw blade was 32% lower in comparison with the 24-tooth saw blade, and approximately 39% lower than the 60-tooth saw blade (Table 4). This fact can be explained simply by the dependence of the cut chip thickness on the feed force: it is because the feed force is distributed over the individual teeth during cutting.

The wear value, as already mentioned, was found to depend on the saw blade tooth number, which is explained by the fact that increasing the number of teeth of the saw blade renders the individual teeth responsible for removing less of the material volume of the sawn object. It was, moreover, possible to conclude that the tool wear of a saw blade depended almost proportionally on the sawn distance, which was ruled by the following equations,

- For 24-tooth saw blade

$$TW = 0.1472L + 31.312 \qquad R^2 = 0.9746 \tag{3}$$

- For 40-tooth saw blade

$$TW = 0.099L + 22.655 \qquad R^2 = 0.9905 \tag{4}$$

- For 60-tooth saw blade

$$TW = 0.088L + 7.925 \qquad R^2 = 0.9456 \tag{5}$$

where TW is the tool wear of the saw blade (μm) and L is the sawn distance (m).

The following linear equation expresses the impact of the number of teeth on the tool wear,

$$TW = -\ 23.124z + 108.7 \qquad R^2 = 0.9949 \tag{6}$$

where TW is the tool wear of saw blade (μm) and z is the number of teeth on the saw blade.

Surface roughness

Based on the significance level "P" values given in Table 3, the effects of the number of teeth and sawn distance could be deemed statistically significant. For the purposes of the statistical evaluation of the results, the sawn distance interval was reduced to 750 m.

Table 3. Influence of Individual Factors on Average Roughness

Monitored factor	Sum of Squares	Degree of Freedom	Variance	Fisher's F - Test	Significance Level P
Intercept	11,739.1	1	11,739.1	3934.6	0.0001
Number of teeth	416.9	2	208.5	69.9	0.0001
Sawn distance	300.7	15	20.1	6.7	0.0001
Number of teeth × Sawn distance	245.8	30	8.2	2.7	0.0001
Error	286.4	96	2.9		

The quality of the surface increased with the number of teeth on the saw blade. For the 24-tooth saw blade, the average roughness was 10.48 µm, while for the 40-tooth saw blade it was only 9.96 µm, a difference of 5.2%. The 60-tooth saw blade, which had an average roughness of 6.64 µm, reached a 36.6% lower values compared to the 24-tooth saw blade. This raised the question of why there was not a direct correlation between improvement in quality (represented by surface roughness) and an increase in the number of teeth, even though the decrease in roughness was almost linearly proportional to the sawn distance. The machined surface contains furrows made by the individual teeth known as cutting wedges. The greater the distance between these furrows, the deeper they are and the higher the surface roughness will be. The distance between furrows depends on the chip thickness. Chip thickness depends on a combination of the resulting cutting speed that is transferred to the workpiece by the teeth of the saw blade within the cut and the local resistance of the cut material. Thus, the greater the number of teeth, the lesser will be the resulting cutting force per tooth, and the lesser will be the chip nominal thickness (Dzurenda *et al*. 2008; Krílek *et al*. 2014).

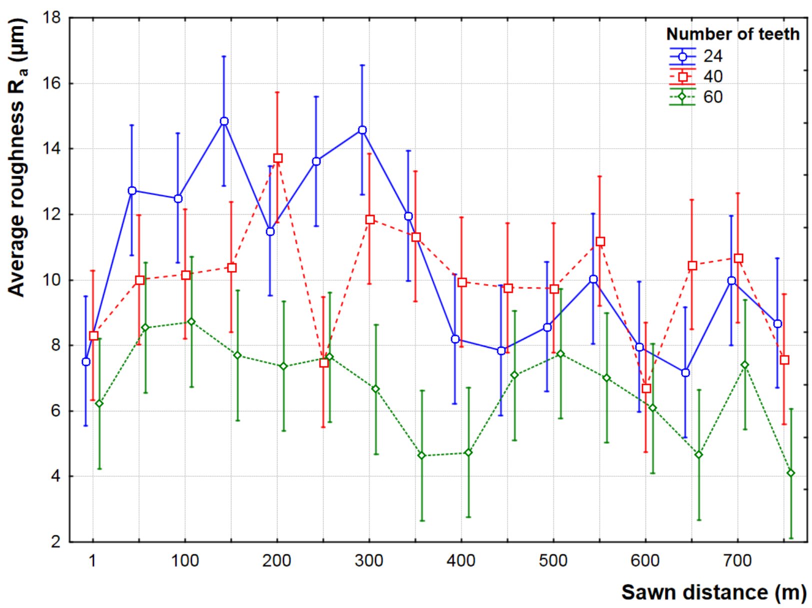

Fig. 9. Measured average roughness course as a function of the sawn distance and number of teeth

The sawn distance was also subjected to more detailed statistical analysis. As shown in Fig. 9, there was no possibility of finding an unambiguous trend in the created surface roughness. The average values for surface roughness ranged from 7.2 to 14.9 µm for the 24-tooth saw blade, from 6.7 to 13.5 µm for the 40-tooth saw blade, and from 4.1 to 8.7 µm for the 60-tooth saw blade. These results did not confirm the general assumption that a decrease in surface quality is associated with tool wear increasing. It is necessary to emphasize that wood is an anisotropic material whose properties are changing not only as a function of the anatomic orientation, but also locally within orientation. Because the quality is dependent on the local resistance yielded by the cut material, and the physical and mechanical properties of wood are changing from place to place, this could cause variations in surface roughness values.

Table 4. Average Surface Roughness and Tool Wear for Individual Saw Blades

Number of teeth	Sawn distance	Average roughness R_a (μm)				Tool wear (μm)			
		Mean	-95.0%	+95.0%	Average	Mean	-95.0%	+95.0%	Average
24	1	7.5	5.5	9.5	10.48 (1.47)	19.1	11.9	26.2	86.5 (5.89)
24	50	12.7	10.8	14.7		37.0	29.9	44.0	
24	100	12.5	10.5	14.5		48.3	41.3	55.3	
24	150	14.9	12.9	16.8		54.2	47.2	61.2	
24	200	11.5	9.5	13.5		64.3	57.5	71.0	
24	250	13.6	11.6	15.6		73.1	66.1	80.0	
24	300	14.6	12.6	16.6		81.0	73.8	88.2	
24	350	12.0	10.2	13.9		90.0	82.7	97.2	
24	400	8.2	6.2	10.2		95.3	88.1	102.4	
24	450	7.9	5.9	9.8		97.2	90.2	104.2	
24	500	8.6	6.6	10.6		102.4	95.3	109.5	
24	550	10.0	8.1	12.0		107.1	99.9	114.2	
24	600	8.0	6.0	9.9		111.4	104.6	118.1	
24	650	7.2	5.2	9.2		120.5	113.2	127.8	
24	700	10.0	8.0	12.0		135.2	128.2	142.2	
24	750	8.7	6.7	10.7		147.3	139.9	154.7	
40	1	8.3	6.3	10.3	9.96 (1.04)	16.1	8.7	23.4	60.5 (5.79)
40	50	10.0	8.0	12.0		26.0	18.7	33.3	
40	100	10.2	8.2	12.2		30.1	22.8	37.3	
40	150	10.4	8.4	12.4		36.2	29.2	43.2	
40	200	13.7	11.8	15.7		42.2	35.0	49,4	
40	250	7.5	5.5	9.5		45.6	38.3	52.9	
40	300	11.9	9.9	13.8		49.5	42.1	56.9	
40	350	11.3	9.3	13.3		56.1	48.8	63.4	
40	400	9.9	8.0	11.9		65.6	58.3	72.8	
40	450	9.8	7.8	11.7		72.4	65.3	79.4	
40	500	9.8	7.8	11.7		76.4	69.4	83.4	
40	550	11.2	9.2	13.2		80.3	73.4	87.1	
40	600	6.7	4.7	8.7		84.2	76.9	91.4	
40	650	10.5	8.5	12.4		90.5	83.6	97.4	
40	700	10.7	8.7	12.7		97.7	90.6	104.7	
40	750	7.6	5.6	9.6		100.2	93.3	107.0	
60	1	6.2	4.2	8.2	6.64 (0.81)	12.3	4.9	19.7	40.3 (5.69)
60	50	8.5	6.6	10.5		19.5	12.2	26.8	
60	100	8.7	6.7	10.7		21.1	14.1	28.1	
60	150	7.7	5.7	9.7		23.3	16.5	30.1	
60	200	7.4	5.4	9.3		25.5	18.3	32.6	
60	250	7.6	5.7	9.6		28.4	21.1	35.6	
60	300	6.7	4.7	8.6		30.3	23.1	37.4	
60	350	4.6	2.7	6.6		32.4	25.6	39.2	
60	400	4.7	2.8	6.7		37.2	30.3	44.0	
60	450	7.1	5.1	9.1		40.4	33.2	47.6	
60	500	7.7	5.8	9.7		45.2	37.7	52.6	
60	550	7.0	5.0	9.1		52.3	44.8	59.8	
60	600	6.1	4.1	8.1		59.5	52.4	66.6	
60	650	4.7	2.7	6.6		64.4	57.0	71.7	
60	700	7.4	5.4	9.4		74.1	66.7	81.4	
60	750	4.1	2.1	6.1		79.3	72.0	86.6	

*****Note: ±95% confidence interval of variance; values in parentheses represent ±SD

Each cut has its own high variability of surface roughness, independent of the previous and subsequent cuts, caused probably by wood structure and the impact of tool wear can be distorted or completely subdued. If the wood were to have the same composition in each transverse cut, then the surface roughness of wood would rise with distance sawn because of the increase in tool wear. Magoss (2008) found that the surface roughness of beech after milling with a blunt tool was 22 µm, while after milling with a sharp tool, the surface roughness was only 9.9 µm. Thus, a sharp tool was able to provide a surface quality that was 55% better.

This study was in agreement with the results of Dzurenda *et al*. (2008), who concluded that the suitable choice of technological parameters during the transverse sawing can ensure quality of the resulting surface at the level $R_a \leq 10$ µm and thus the quality of the surface after the plane milling. Sandak and Negri (2005) also found that during sawing, the surface quality was affected by the anatomical structure of the machined material.

CONCLUSIONS

1. The general assumption that the cutting edge durability would increase with the number of saw blade teeth was confirmed but only up to 750 m sawn distance. The overall durability of the 24-tooth saw blade was 750 m, while for the 60-tooth saw blade it was 800 m, and for the 40-tooth saw blade it was 1,200 m.
2. The quality of the sawn surface improved with the increase in number of teeth per saw blade. The average roughness for 24-tooth saw blade was 10.48 µm, for the 40-tooth saw blade 9.96 µm, and for the 60-tooth saw blade only 6.64 µm.
3. The general presumption that the surface quality decreased with increasing values of tool wear was not confirmed. The values of the tool wear were 147.3, 100.2, and 79.3 µm for the 24-tooth, 40-tooth, and 60-tooth saw blade, respectively.

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