Roughness of Surface Created by Transversal Sawing of Spruce, Beech, and Oak Wood

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The created surface irregularities, namely roughness profile R_a, after the sawing of spruce, beech, and oak wood on a sliding mitre saw with manual saw blade feeding were studied. The created surface roughness was monitored at a cut height, e, of 50 mm using three basic modes of solid wood transversal sawing (flatwise cross-cutting at φ_2=90°, flatwise edge-mitre cross-cutting, and flatwise mitre cross-cutting at φ_2=45°). The monitored surface was made using a sliding mitre saw with the gradual application of saw blades with 24, 40, or 60 teeth, and special saw blade with 24 teeth and a chip limiter (CL), respectively. The saw blades used had identical angle geometries. Three levels of feed force, F_p, of 15, 20, and 25 N corresponding to a range of feed forces used by different operators were used in the experiment. The roughness of sawn surfaces was significantly influenced by cutting model, wood species, type of saw blade, and feed force. The created surface roughness values were very close to the plane milling values.

Keywords: Transversal sawing; Feed force; Number of teeth; Surface roughness; Beech; Oak; Spruce

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INTRODUCTION

During transverse cutting, preliminary transverse sawing with a length allowance and final transverse sawing to the required dimension are distinguished. In transverse cutting to the required dimension, the created surface quality, primarily the created surface roughness, plays a significant role. In general, the roughness of the created surface should be at the level of plane milling, because from the technological point of view, after transverse cutting into the desired size followed by mostly just grinding operation.

Each process operation causes infringement of the work piece's initial properties and integrity and leaves typical irregularities on the machined surface. These are manifested by microscopic changes such as the machined surface roughness and macroscopic changes such as waviness, scratches, corrugations, hollows, and thorn fibers (Siklienka and Kminiak 2013). According to Malkoçoğlu (2007), the machining properties of woods are directly related to machining defects (fuzzy grain, torn grain, raised grain, *etc*.). The wood cutting parameters (energy consumption, dust level, and noise level), the emerging product parameters (dimensional accuracy and created surface quality), and the produced chip parameters (dimensions and particle size composition) depend on the teeth shape, teeth dimensions and number, cutting tool geometry, sharpness, and technological conditions of the process, such as feed speed, feed force, and cutting speed (Örs *et al*. 1991; Efe *et al*. 2007; Kvietková *et al*. 2015).

According to Budakçi *et al*. (2011), the surface quality depends mainly on the chip thickness as well as on the cutting speed and the rake angle, respectively. Because of the anisotropic structure of the wood, high quality machining of the wood depend on the use of proper machining procedures, the feed speed, the tool geometry, and the suitable technical treatment of these cutters in relation to sharpening and maintenance (Yildiz 2002).

A fundamental role, when sawing, is played by the blade perpendicular to the direction of the wood fibers. During transversal cutting, the lateral cutting edges of the saw blade teeth cut the fibers and form the walls of the cut kerf (Fig. 1b). The main cut edges during closed cutting form the gullet bottom. A typical feature of a surface created by sawing with saw blades are half-moon-shaped traces (Fig. 1a).

When comparing different wood species, deciduous trees generally yield a higher quality of surface than conifers. For example, Örs and Baykan (1999) found that surfaces with lower roughness and higher smoothness can be acquired on *Fagus orientalis* rather than on *Pinus sylvestris* wood. Sadoh and Nakato (1987) found that the surface smoothness results for diffuse-porous woods were smoother than for the ring-porous woods. Kilic *et al*. (2006) found that surface of sawn beech wood was rougher than that of aspen wood, although both wood species are diffuse porous. Moreover, Malkoçoğlu (2007) found that better surface quality can be obtained on summer wood than on spring wood. Other important factors include the physical and mechanical properties of wood, as these properties directly affect all woodworking processes (Barcík and Gašparík 2014; Gaff 2014; Gaff and Matlák 2014; Fekiač *et al*. 2015).

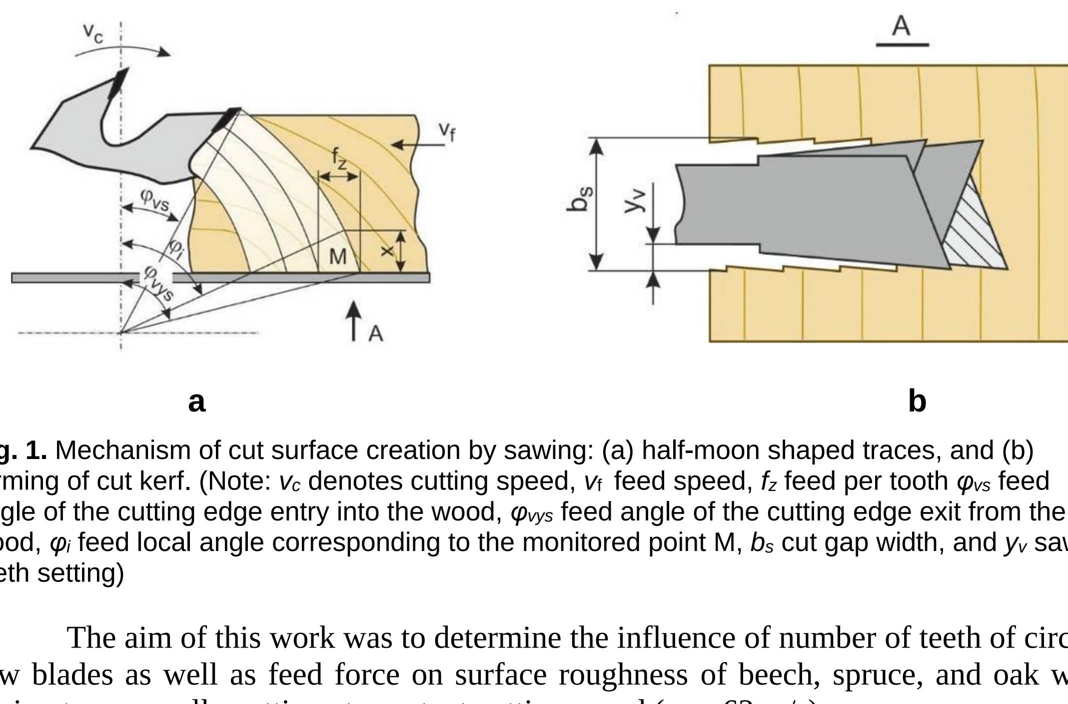

Fig. 1. Mechanism of cut surface creation by sawing: (a) half-moon shaped traces, and (b) forming of cut kerf. (Note: v_c denotes cutting speed, v_f feed speed, f_z feed per tooth φ_{vs} feed angle of the cutting edge entry into the wood, φ_{vys} feed angle of the cutting edge exit from the wood, φ_i feed local angle corresponding to the monitored point M, b_s cut gap width, and y_v saw teeth setting)

The aim of this work was to determine the influence of number of teeth of circular saw blades as well as feed force on surface roughness of beech, spruce, and oak wood during transversally cutting at constant cutting speed (v_c = 62 m/s).

EXPERIMENTAL

Materials

Three wood species with industrial relevance in Slovakia were selected for the experimental measurements: European spruce (*Picea abies* L.), European beech (*Fagus sylvatica* L.), and English oak (*Quercus robur* L.). The trees used for the experiment, which grew in the Zvolen location, were harvested in 2012 at an age of 45 years. Suitable zones were cut from the trunk at a height of 2 m from the stump. Flat-sawn wood samples had dimensions of 50 mm × 150 mm × 1000 mm.

Clear samples were conditioned in a conditioning room (relative humidity (ϕ) = 65 ± 3% and temperature (t) = 20 ± 2 ºC) for more than four months to achieve an equilibrium moisture content (EMC) of 12%.

Methods

Sliding mitre saw

The wood experimental cutting was carried out using a GCM 10S Professional sliding mitre saw (Robert Bosch GmbH, Germany) (Fig. 2). Table 1 summarizes the mitre saw parameters.

Fig. 2. Sliding mitre saw

Table 1. Mitre Saw Parameters

Parameters	
Rated power input	1,800 W
Cutting capacity, 45° bevel	53 mm × 305 mm
Cutting capacity, 45° mitre	87 mm × 216 mm
Cutting capacity, 0°	87 mm × 305 mm
Mitre setting	52° L / 62° R
Bevel setting	47° L
No-load speed	4,700 rpm
Saw blade diameter	254 mm
Sound pressure level	94 dB(A)

Saw blade

Four saw blades with sintered carbide plates were selected for the experiment (Fig. 3). The saw blades had identical diameters (D = 250 mm), identical tool thicknesses (b = 3.2 mm), identical cutting edge geometries (clearance angle α = 15°, cutting angle of edge β = 60°, rake angle γ = 15°, lateral edge relief angle ξ = 15°, and frontal edges radial inclination angle λ = 7°), and alternating teeth (WZ). Three of these saw blades were PREMIUM (EXTOL, Czech Republic) with various numbers of teeth: 24 teeth (Fig. 3b, Fig. 4b), 40 teeth (Fig. 3c), and 60 teeth (Fig. 3d); there was also a SPEEDLINE-WOOD (Robert Bosch GmbH, Germany) blade with 24 teeth and a chip limiter (Fig. 3a, Fig. 4a).

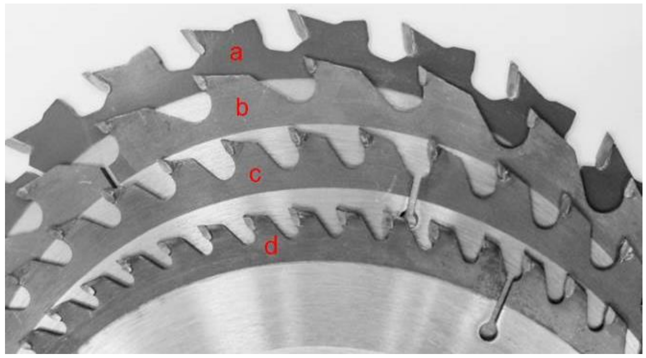

Fig. 3. Configuration of saw blades: (a) 24 teeth and a chip limiter; (b) 24 teeth; (c) 40 teeth; and (d) 60 teeth

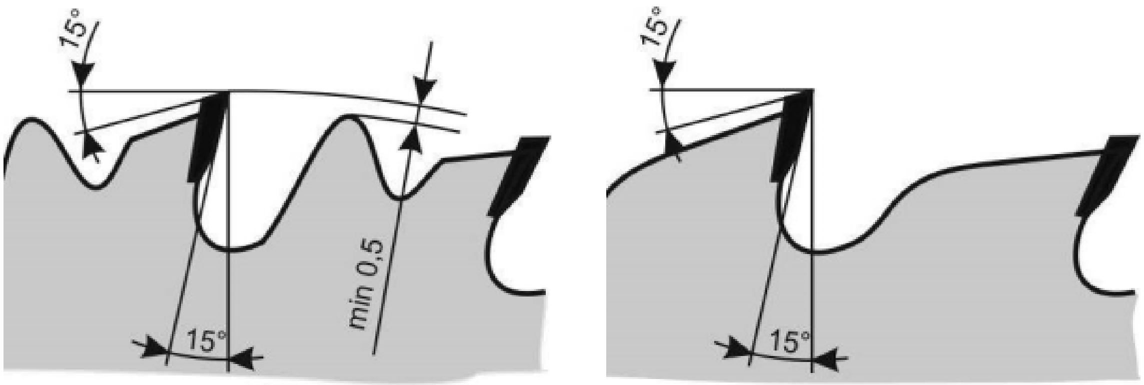

Fig. 4. Detail of 24-teeth saw blades: (a) saw blade with chip limiter; and (b) without chip limiter

Transversal sawing

Most similar experiments are based on constant feed speed v_f. For the present experiment, the use of a feed force, F_p, is typical. Feed force was substituted for feed speed because of manual feeding. This reflects the essence of the saw blade manual feed into the cut. Because constant experimental conditions, such as a constant feed force, cannot be met during real manual feeding, the feed force was simulated in an experimental stand (Fig. 5).

The hand movement (Fig. 6) is simulated by the movement of a hauling rope (Fig. 7), and the proper feed force is extracted by weights. The experimental feed force was determined on the basis of a preliminary experiment. Preliminary research determined the average feed force by a mechanical dynamometer (FK 100, Sauter AG; Switzerland) connected between handle of the saw and a person. The average value in the range of 13 to 28 N was calculated from the values, which were measured during the pulling of the saw by selected individuals (*i.e.*, groups of 10 women and 10 men between the ages of 19 and 24 years, with body weights between 50 and 95 kg and heights between 161 and 198 cm). On the basis of this preliminary experiment, three levels of feed force were selected for the present experiment: F_p = 15, 20, and 25 N.

Fig. 5. Experimental stand simulating feed force

Fig. 6. Sequential saw blade movement through the sample with manual feeding on the sliding mitre saw

Fig. 7. Sequential saw blade movement through the sample with feeding on the sliding mitre saw by means of the experimental stand

Fig. 8. Cutting orientation of samples: (a) flatwise cross-cutting at φ_2 = 90°; (b) flatwise edge-mitre cross-cutting; and (c) flatwise mitre cross-cutting at φ_2 = 45°

During the experiment, the 10-mm-thick test pieces were cut from the conditioned lumber by a saw blade. During the cutting, three basic models of transversal cutting on the sliding miter saw were applied: flatwise cross-cutting at φ_2 = 90° (M1) (Fig. 8a), flatwise edge-mitre cross-cutting at φ_2 = 45° (M2) (Fig. 8b), and flatwise mitre cross-cutting at φ_2 = 45° (M3) (Fig. 8c). The experiment was carried out at a constant cutting speed v_c = 62 m/s.

Measurements and Evaluation

The sample surface roughness was measured using a LPM-4 laser profilometer, (KVANT s. r. o., Slovakia) (Fig. 9). The profilometer is based on the triangulation principle of laser profilometry. The image of the laser line was sensed by a digital camera at an angle. Subsequently, the object profile in cross-section was evaluated from the captured image. The obtained data were mathematically filtered, and the individual indices of the primary profile, corrugation profile, and roughness profile were determined.

The roughness measurements were realized according to ISO 4287 (1997). A measurement was carried out in three tracks equidistant in the sample width (5, 25, and 45 mm from the sample margin), with a track length of 60 mm and the track oriented in the sample feed direction for the sawing process (Fig. 10).

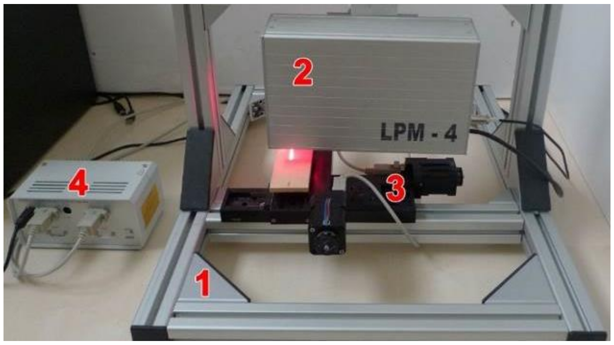

Fig. 9. Laser profilometer that measures sample surface roughness. (1) bearing structure allowing the manual preset of the working distance and the fixing of both profilometer head and sliding tables system; (2) profilometer head; (3) system of slides for axes X and Z; and (4) control unit of the work tables sliding system.

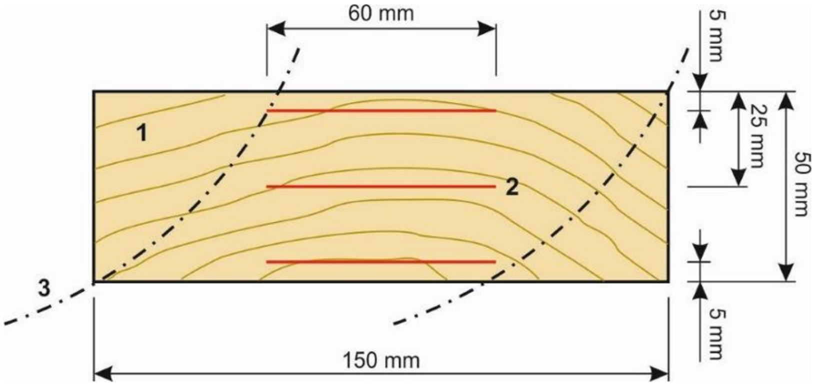

Fig. 10. The measuring paths on the test sample. (1) sample; (2) measuring paths; and (3) track teeth of the saw blade.

For each combination (type of saw blade × feed force × cutting model), 20 cuts per wood species were made so that each final average value was calculated from 60 measured values. The surface roughness was evaluated by the arithmetic mean of the profile roughness, R_a.

The influence of various factors on the surface roughness was statistically evaluated using ANOVA (Fisher's F-test) analysis, in STATISTICA 12 software (Statsoft Inc.; USA).

The moisture content of samples was determined and verified before and after testing. These calculations were carried out according to ISO 3130 (1975) and Eq. 1,

$$w = \frac{m_w - m_0}{m_0} * 100 \quad (1)$$

where w is the moisture content of the samples (%); m_w is the mass (weight) of the test sample at moisture content 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 3130 (1975), using the following procedure: wood samples were placed in the drying oven at a temperature of 103 ± 2 °C until a constant mass was reached. Constant mass is considered to be reached if the loss between two successive measurements carried out at an interval of 6 h is equal to or less than 0.5% of the mass of the test sample. After cooling the test samples to approximately room temperature in a desiccator, the samples were weighed rapidly enough to avoid an increase in moisture content of more than 0.1%. The accuracy of weighing was at least 0.5% of the mass of the test sample.

RESULTS AND DISCUSSION

From the multi-factor variance analysis in Table 2, all examined factors as well as their interactions are statistically significant. Based on the F-test, it can be concluded that the created surface roughness was most of all influenced by the cutting model, followed by the wood species, saw blade type, and least by the feed force. The obtained data statistical evaluation shows that the influence of the cutting model has three times the weight of the remaining examined factors.

Table 2. Influence of Individual Factors on Roughness

Monitored factor	Sum of Squares	Degree of Freedom	Variance	Fisher's F - Test	Significance Level P
Intercept	52,906	1	52,906	65,566	0.0001
Wood species	842	2	421	521	0.0001
Type of saw blade	1,133	3	377	468	0.0001
Feed force	636	2	318	394	0.0001
Cutting model (M)	2,244	2	1,122	1,390	0.0001
Wood species × Type of saw blade × Feed force × Cutting model	1,496	24	62	77	0.0001
Error	522	648	0.8		

As shown in Fig. 11, the surface with the highest quality was made in the case of the M1 model (flatwise cross-cutting at φ_2 = 90°), with a surface average roughness of 6.4 µm. For the M2 model, the roughness increased by 27% to an average value of 8.1 µm. This phenomenon can be explained by the different cutting angles of the cell elements. While the cell elements in the M1 model are cut at 90°, this angle is 45° in the M2 model. This causes greater stripping of the wood structure.

The created surface with the worst quality was obtained with the M3 model (flatwise mitre cross-cutting at φ_2 = 45°). Here, the surface roughness increases by 65%, to 10.6 µm. Based on conventional assumptions, the surface roughness should increase in the order of M1, M3, and M2. This did not happen, because when comparing M1 and M3, the expected increase is similar to the previous model due to change of the cell elements cutting angle from 90° to 45°. While comparing M3 and M2, the expected increase caused by the cut relative height increase was from 50 to 75 mm. At a constant cutting speed this situation causes enlargement of feed per tooth, as is demonstrated by Figure 1, and thus the increase of roughness at created surface.

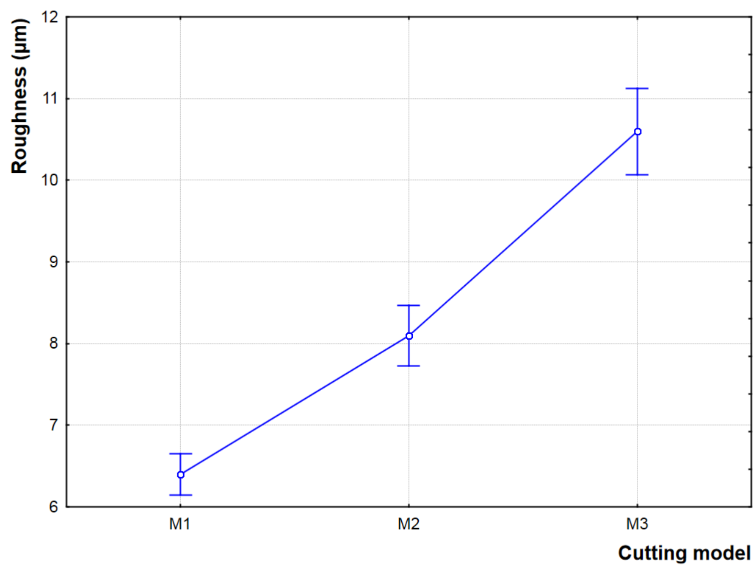

Fig. 11. Impact of cutting model on surface roughness. Data presented as the average ± standard deviation

To explain this phenomenon, it is necessary to emphasize that at constant feed speed, the actual feed per tooth depends on the actual cutting resistance, cutting force, feed force as well as the number of teeth. Thus, the cut height increase acted exactly the opposite way for the M2 model, and the feed force was distributed on various cutting wedges, thereby causing the feed per tooth to decrease. Another reason for a more substantial increase in the surface roughness for the M3 cutting model is the elongation of earlywood and latewood sections, since the different densities of earlywood and latewood causes different cutting resistance in their respective sections and thereby affects the feed per tooth; this is demonstrated by the width of the intervals, as shown in Fig. 11, since the cut length increases from 150 to 210 mm.

As shown in Fig. 12, the surface roughness increases in the following order: beech – oak – spruce. In numerical terms, the surface roughness is 6.9 µm for beech, 8.7 µm for oak (26% greater than beech), and 9.5 µm for spruce (37% greater than beech). The main difference between beech and oak is interesting, because these are wood species with approximately the same density and cutting force per unit area. However, this difference has a quite simple explanation. As previously mentioned, the created surface quality depends directly on feed per tooth and, simultaneously, the actual feed per tooth depends on actual cutting resistance of the cut material, cutting force, and number of teeth. Beech, as the densest wood species, and, as far as the macroscopic structure is concerned, the wood species with the most regular configuration of microscopic elements, such as libriform fibers, exhibits the best surface roughness.

Despite the similar density value of oak, the surface quality (roughness) was impaired significantly because of the more irregular distribution of microscopic elements and greater difference between earlywood and latewood. As expected, spruce exhibits the worst roughness because it has the lowest density and most irregular distribution of microscopic elements.

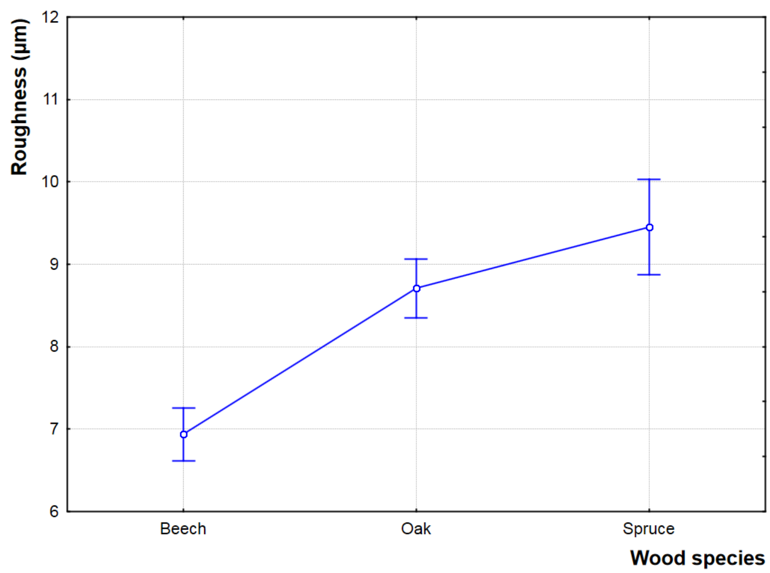

Fig. 12. Impact of wood species on surface roughness. Data presented as the average ± standard deviation

Similar to constant feed speed, a surface roughness decrease occurred with feed force and with increasing number of saw blade teeth (Fig. 13). This is because of the increase of teeth number in the cut and therefore the distribution of cutting force into more cutting wedges. This causes chip thickness reduction and a decrease in the surface roughness. It is possible to conclude that the created surface roughness depends almost proportionally on the teeth number, being ruled by the following equations,

$$R_a = -0.0885 * z + 11.881 R^2 = 0.884 \tag{2}$$

$$R_a = 0.0031 * z^2 - 0.3534 * z + 16.807 R^2 = 1 \tag{3}$$

where R_a is the arithmetic mean of profile roughness (µm) and z is the number of teeth on the saw blade.

For constant feed speed, the use of a chip limiter would not make sense because the chip nominal thickness is affected by the feed speed value and teeth number. At constant feed force, the use of a chip limiter results in the stabilization of the chip nominal thickness and also created surface roughness.

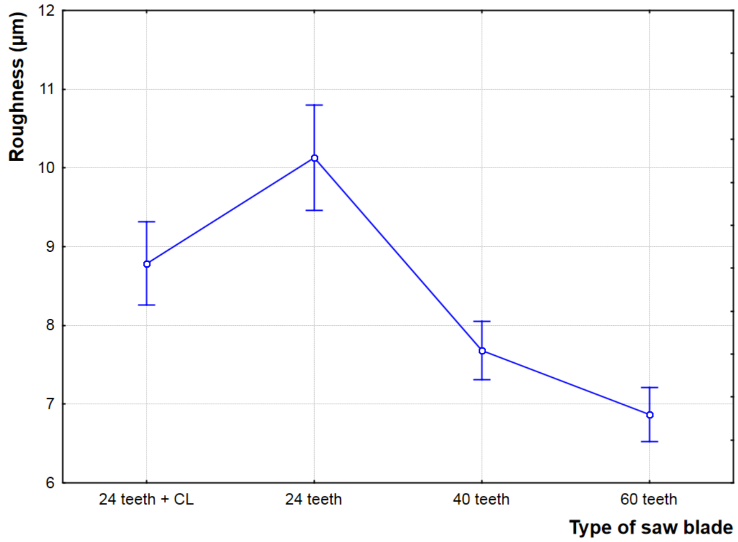

Fig. 13. Impact of saw blade type on surface roughness. Data presented as the average ± standard deviation

The feed force impact on the created surface roughness is shown in Fig. 14. Generally, a feed force increase also increases the created surface roughness. If one regards the feed force as a separate factor, its impact on the surface roughness can be described by the following equations,

$$R_a = 0.2122 * F_P + 4.1213 R^2 = 0.892 \quad (4)$$

$$R_a = 0.0256 * F_P{}^2 - 0{,}813 * F_P + 19{,}946 R^2 = 1 \quad (5)$$

where R_a is the arithmetic mean of profile roughness parameter (µm) and F_p is the feed force (N). However, for an objective assessment of the feed force impact, this shall be considered in an interaction with the already evaluated factors because these limit the impact on the proper sawing process. Therefore, the authentic multi-factor analyses are more objective (Figs. 15, 16, and 17).

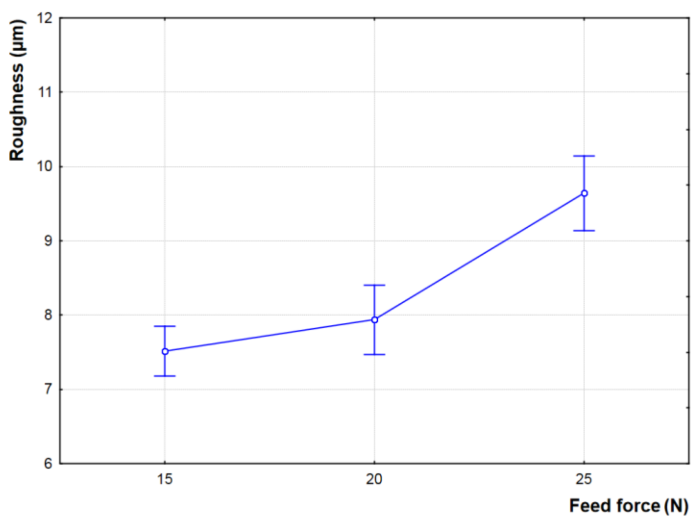

Fig. 14. Impact of feed force on surface roughness. Data presented as the average ± standard deviation

These figures confirm the already formulated functions, *i.e.*, that the created surface roughness is directly dependent on the actual cutting resistance (which is affected by the cutting model and wood species within the experiment), cutting force (affected by saw blade type), and feed force (affected by saw blade type and the proper feed force value as set up).

A typical feature of this process is precisely the attempt to simulate the saw blade manual feed into the cut and ensuring constant feed force, in contrast to studies dealing with transversal sawing which take into account constant feed speed. It is this fact that makes it impossible to compare the results with each other. If the feed per tooth is the comparison criterion, similar tendencies with experiments with constant feed speed can be observed.

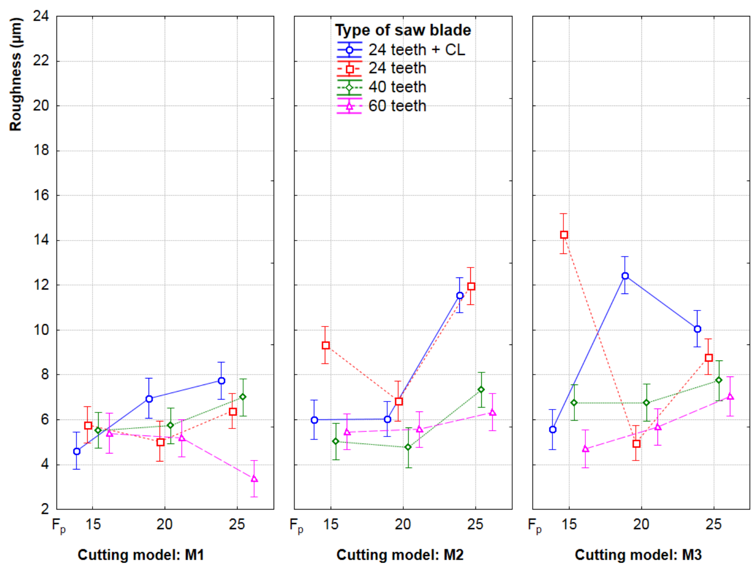

Fig. 15. Impact of saw blade type, cutting model, and feed force on surface roughness of beech. Data presented as the average ± standard deviation

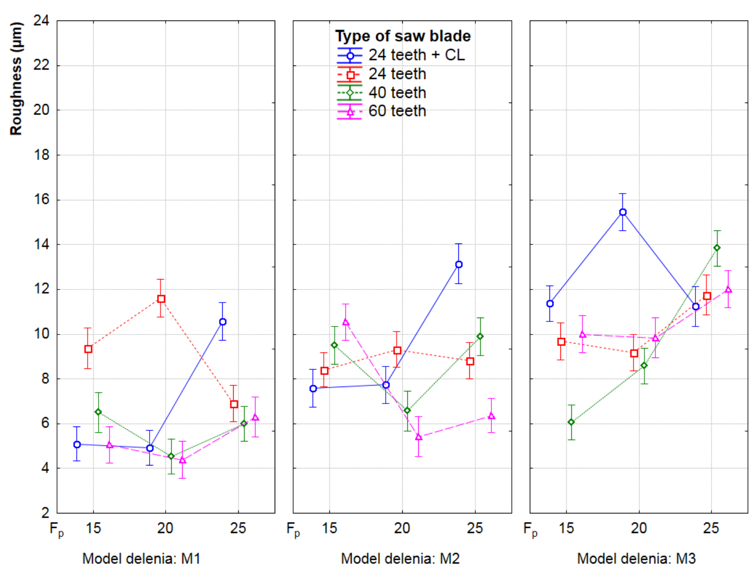

Fig. 16. Impact of saw blade type, cutting model, and feed force on surface roughness of oak. Data presented as the average ± standard deviation

Table 3 shows the roughness average values for the created surface, including the 95% confidence intervals for all examined factors and wood species.

Table 3. Average Values of Roughness for Individual Combinations of Factors

Type of saw blade	Feed force (N)	Cutting model	Roughness R_a (μm)								
			Beech			Oak			Spruce		
			Mean	-95%*	+95%*	Mean	-95%	+95%	Mean	-95%	+95%
24 teeth + CL	15	M1	4.6	3.8	5.5	5.1	4.3	5.9	5.8	5.0	6.6
24 teeth + CL	15	M2	6.0	5.1	6.9	7.6	6.7	8.4	4.6	3.7	5.4
24 teeth + CL	15	M3	5.6	4.7	6.5	11.4	10.6	12.2	14.9	14.0	15.8
24 teeth + CL	20	M1	6.9	6.1	7.8	4.9	4.1	5.7	5.0	4.1	5.9
24 teeth + CL	20	M2	6.0	5.3	6.8	7.7	6.9	8.5	7.9	7.0	8.8
24 teeth + CL	20	M3	12.5	11.6	13.3	15.5	14.6	16.3	9.1	8.3	9.9
24 teeth + CL	25	M1	7.7	6.9	8.6	10.6	9.7	11.4	7.0	6.2	7.8
24 teeth + CL	25	M2	11.6	10.8	12.4	13.1	12.3	14.0	7.3	6.5	8.1
24 teeth + CL	25	M3	10.1	9.3	10.9	11.2	10.4	12.1	17.6	16.8	18.4
24 teeth	15	M1	5.8	5.0	6.6	9.4	8.5	10.3	8.8	8.0	9.6
24 teeth	15	M2	9.3	8.5	10.2	8.4	7.6	9.2	8.2	7.4	9.0
24 teeth	15	M3	14.3	13.4	15.2	9.7	8.8	10.5	7.2	6.4	8.0
24 teeth	20	M1	5.0	4.1	5.9	11.6	10.8	12.4	9.5	8.7	10.3
24 teeth	20	M2	6.8	5.9	7.7	9.3	8.5	10.1	8.7	7.8	9,6
24 teeth	20	M3	5.0	4.2	5.7	9.2	8.4	10.0	22.8	21.9	23.6
24 teeth	25	M1	6.4	5.6	7.2	6.9	6.1	7.7	7.7	6.9	8.6
24 teeth	25	M2	12.0	11.1	12.8	8.8	8.0	9.6	20.3	19.5	21.0
24 teeth	25	M3	8.8	8.0	9.6	11.8	10.9	12.6	21.9	21.0	22.8
40 teeth	15	M1	5.5	4.7	6.3	6.5	5.6	7.4	5.7	4.8	6.6
40 teeth	15	M2	5.0	4.2	5.8	9.5	8.7	10.3	7.0	6.2	7.8
40 teeth	15	M3	6.8	6.0	7.6	6.1	5.3	6.8	8.9	8.0	9,7
40 teeth	20	M1	5.7	4.9	6.5	4.5	3.8	5.3	5.5	4.7	6.3
40 teeth	20	M2	4.8	3.9	5.6	6.6	5.7	7.5	8.1	7.3	8.9
40 teeth	20	M3	6.8	5.9	7.6	8.6	7.8	9.4	12.7	11.9	13.5
40 teeth	25	M1	7.0	6.2	7.8	6.0	5.2	6.8	9.5	8.6	10.3
40 teeth	25	M2	7.3	6.6	8.1	9.9	9.0	10.7	8.9	8.1	9.8
40 teeth	25	M3	7.8	6.9	8.6	13.8	13.0	14.6	13.0	12.1	13.9
60 teeth	15	M1	5.4	4.5	6.3	5.1	4.3	5.9	5.3	4.5	6.2
60 teeth	15	M2	5.5	4.7	6.2	10.5	9.7	11.4	6.9	6.0	7.8
60 teeth	15	M3	4.7	3.9	5.5	10.0	9.2	10.8	9.8	9.0	10.5
60 teeth	20	M1	5.2	4.3	6.0	4.4	3.5	5.2	4.9	4.1	5,7
60 teeth	20	M2	5.6	4.8	6.4	5.4	4.5	6.3	7.0	6.2	7.8
60 teeth	20	M3	5.7	4.8	6.5	9.8	8,9	10.7	11.2	10.4	12.0
60 teeth	25	M1	3.4	2,6	4.2	6.3	5,4	7.2	5.7	4.9	6.5
60 teeth	25	M2	6.3	5.5	7.2	6.4	5.6	7.1	7.3	6.5	8.1
60 teeth	25	M3	7.0	6.1	7.9	12.0	11.2	12.8	8.7	7.9	9.6

*Note: ±95% confidence interval of variance

Droba and Svoreň (2012) and Mikleš *et al.* (2010) argue that with the correct choice of process parameters, transverse sawing can achieve quality of the resulting surface at the level of $R_a \leq 10$ mm, which corresponds to plane milling. Siklienka and Janda (2013), Novák *et al*. (2011), and Sandak and Negri (2005) found that when creating smoother surfaces, this smoothness is affected by the anatomical structure of the material. The present conclusions fully correspond with Krílek *et al*. (2014) and Droba and Svoreň (2012), who found that the design of the saw blade directly affects the power relations in the cutting process, which is subsequently reflected in the quality of the generated surface.

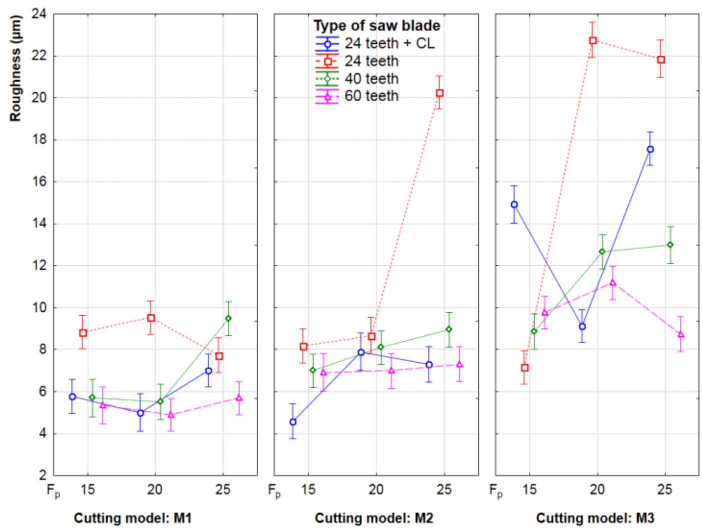

Fig. 17. Impact of saw blade type, cutting model, and feed force on surface roughness of spruce. Data presented as the average ± standard deviation

CONCLUSIONS

1. Surface roughness similar to that of plane milling can also be achieved by a transversal sawing. The roughness values ranged from 4 to 23 µm, depending on the actual cutting model, wood species, saw blade type, and feed force.
2. The used cutting model influences the created surface roughness increase in the following order: flatwise cross-cutting at φ_2 = 90° (M1), flatwise edge-mitre cross-cutting at φ_2 = 45° (M2), and flatwise mitre cross-cutting at φ_2 = 45°.
3. The feed force acts by means of cutting wedges (teeth) on the work piece. An almost proportional decrease of the surface roughness was found with increasing teeth number.
4. Both sawn wood homogeneity and density influence the created surface roughness. The denser and more homogeneous the wood, the smaller the created surface roughness.

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