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SURFACE IRREGULARITIES OF OAK WOOD AFTER TRANSVERSAL CUTTING WITH A CIRCULAR SAW

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ABSTRACT

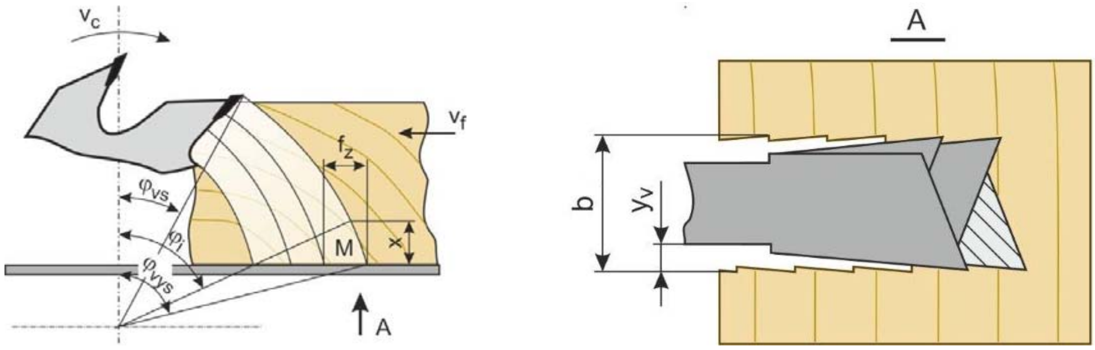
This paper deals with the effect of saw blade type (24, 40 and 60 teeth) and sawn distance on the primary profile (P_z) of tranvesre surface of European oak (*Quercus robur* L.) after transversal cutting. Transversal cutting was provided at constant cutting speed v_c = 62 m·s^{-1} and with manual feeding using circular saw blade. An additional parameter was to determine the maximum sawn distance for each type of saw blade up to the point where the saw blade overheated, as well as the beginning of the blackening of the wood surface. The highest values of the primary profile (P_z) were achieved with a saw blade with 24 teeth, lower values were measured on wood cut with a 40 tooth blade and the lowest values after cutting with a 60 tooth blade. As the saw distance increased, there was no rapid and steep increase in the primary profile values, but these values gradually increased slightly, probably due to the gradual blunting of the tool.

KEYWORDS: Circular saw, surface quality, primary profile (P_Z), saw blade, tranversal cutting.

INTRODUCTION

Global wood consumption is on the rise and wood is considered a strategic raw material. The wood mass of our forests is a reproducible raw material while respecting all propositions. At the moment, the maximum effort for a comprehensive and ecological solution to the problem of the use of wood raw material with an orientation towards finalization from the aspect of quality and economy of its processing is in place. As energy and raw material costs rise, it is increasingly important to reduce the cost of machining (Orlowski and Walichnowski 2013) as well as improve the quality of the surface after machining (Krenke et al. 2017a,b).

In the woodworking and furniture industries, wood cutting using a saw blade plays a very important role (Williams and Patel 2016), which is undoubtedly the most commonly used type of tool for cutting wood and wood-based materials (Mikleš et al. 2010, Walker 2006, Nasir et al. 2018). The process of cutting wood materials using a saw blade, whether solid or treated, laminated or agglomerated wood, is a very complex process (Nasir and Cool 2020), which is influenced by a large number of simultaneous factors as well as variables (Fig. 1) (Kvietková 2015).



(Note: v_c - cutting speed, v_f - feed speed, fz - 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 - cut gap width, and y_v - saw teeth setting) (Kminiak and Gaff 2015).

Fig. 1: Cutting parameters of the saw blade and the principle of surface formation in transversal cutting of wood: (left) arc shaped traces, and (right) forming of cut kerf.

For practice, it is necessary to know the phenomena of mutual interaction of the tool with the workpiece, from the point of view of optimization and intensification of the machining process. The cutting process itself is conditioned by various factors (Gündüz et al. 2008) that strongly affect the output indicators of the process, such as unevenness of the machined surface, noise associated with the energy of the sawing process, as well as indicators related to the tool in terms of wear - cutting edge durability, service life, instability (Tesařová et al. 2010). Knowing the interrelationships between the mentioned indicators and the kinematics of the sawing process itself is an attempt to get closer to the most optimal outputs while keeping the costs of the process itself in terms of efficiency, effectiveness and economy of sawing while respecting the principles of safety and health at work (Wasielewski et al. 2012). It is very important that the whole process of cutting wood takes place with the least possible energy requirements and with the best possible quality of the final surface.

Each technological operation leaves characteristic inequalities on the surface, which can affect the function of these surfaces (Budakçı et al. 2011, 2013). A characteristic feature of the surface of wood sawn with circular saws are the arc traces on the transverse surface.

When the workpiece interacts with the saw blade, the chip thickness changes as a result of the cut indication, with which the pressures on the tooth face change and with them the deformations of the wood mass near the tooth edge. As stated by Lisičan (1996), the formation of grooves is directly proportional to the feed of the workpiece and the size of the tooth distribution of the saw blade. On the other hand, the grooves are inversely proportional to the height of the tooth, the number of revolutions and the number of teeth on the saw blade. Such a workpiece surface is not smooth, but scratches caused by the passage of the saw blade, especially its toothing, can be seen on it. During transversal cutting, the workpiece comes into contact with the saw blade in a plane perpendicular to the saw blade. This results in the cutting of the structural elements of the wood by the toothing of the saw blade. There are clear surface irregularities on the surface after cutting. Before measuring the surface roughness, it is necessary to determine l_n (evaluated length). The evaluated length includes six basic lengths and is considered as a normal length. The evaluated length l_n, at which the values of the surface quality parameters are evaluated, may comprise one or more basic lengths (Fig. 2).

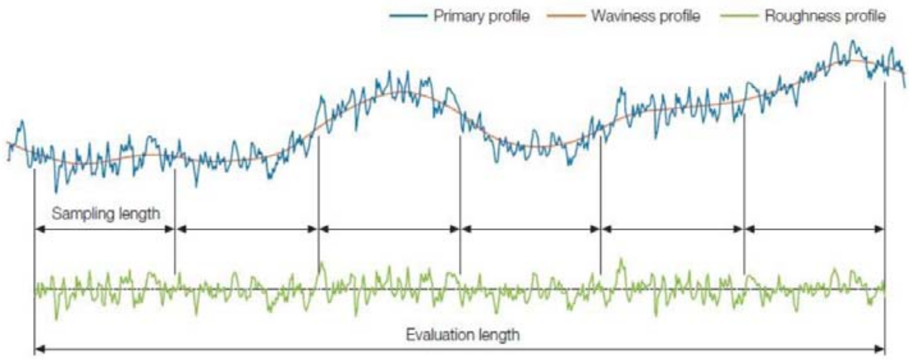


Fig. 2: Basic characteristics of wood surface quality (Khandoker 2020).

Surface unevenness (waviness + roughness) is evaluated in a system in which the spatial character of inequalities, created in the implementation process, is reduced to a plane. In this plane, a profile is obtained, which is evaluated with respect to the center line of the profile, called the primary profile (Pernikář et al. 2001).

Assuming absolute rigidity of saw tools and "vibration-free" movement of cutting tools, the cut surface will be grooved with traces of saw teeth, the depth (height or profile respectively) of which depends on the feed per tooth, mutual distance of teeth (spacing) and the degree of teeth setting. Whenever two surfaces come into contact with each other, the quality of the joined parts plays an important role in the use and wear of these parts (Gurau et al. 2005, 2012).

The height, shape, finishing and direction of surface irregularities on the workpiece depend on many factors such as technological parameters, e.g. feed rate, cutting speed, depth of cut, cutting tool geometry (cutting wedge angle, face angle and back angle), combination of workpiece and tool material as well as their mechanical properties, at last but not least from the quality and type of machine and tool used. It also depends on the attachment used and the vibration between the workpiece, the machine and the tool (Chuchala et al. 2012).

Surprisingly, despite research efforts, there are still several major problems and inconsistencies. This is especially visible in the field of woodworking, where the immediate characterization of the residual surface is needed for further development. The overall assessment of surface evenness has two main reasons, namely the assumption of the possibility of surface formation and monitoring of the production process.

European oak (*Quercus robur* L.) wood was chosen for this research. Oak wood was cut in the transverse direction using a circular saw with three different blades with 24, 40 and 60 teeth. The sawn distance was set at 750 m, but in addition, the maximum possible sawn distance was evaluated separately for each saw blade. The transverse surface after cutting was evaluated using an Olympus Lext OLS 4100 laser microscope and the primary profile (P_z) was determined.

MATERIAL AND METHODS

Material

European oak (*Quercus robur* L.) wood were used for the experiment. The flat-sawn samples had dimensions of 20 × 100 × 500 mm (Fig. 3). Clear samples were conditioned in a conditioning chamber (relative humidity (ϕ) = 65 ± 5% and temperature (t) = 20 ± 2°C) to achieve their equilibrium moisture content (EMC) of 12%. The average oven-dry density of oak wood was 795 $kg \cdot m^{-3}$. Whole experiment contained 216 samples.

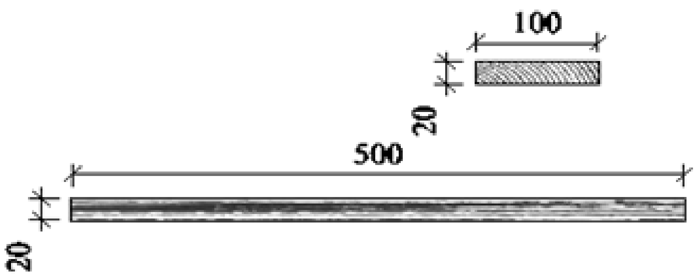


Fig. 3. Oak sample.

Methods

Circular saw

The GCM 10S Professional circular saw (Robert Bosch GmbH, Germany) was chosen for tranversal cutting of oak wood.

Saw blades

Three commonly used circular saw blades Premium (EXTOL, Czech Republic) with sintered carbide tips having 24, 40, and 60 teeth, respectively, were selected for the transverse cutting (Fig. 4). All saw blades had identical diameters (D = 250 mm), thicknesses (b = 3.2 mm), as well as angle geometries (clearance angle α = 15°, wedge angle β = 60°, rake angle γ = 15°). All saw blades had a alternating set teeth.

Fig. 4: Circular saw blades with a) 24 teeth, b) 40 teeth, and c) 60 teeth.

Transversal cutting

During the transversal cutting of the wood, which was provided with a Bosch circular saw, the feeding was carried out manually. As part of the cutting, the 10 mm thick pieces (slices) were cut from the longitudinally placed samples. The whole experiment was carried out at a constant cutting speed v_c = 62 m·s^{-1} and 4700 RPM. The movement of the saw blade was carried out through an arc trajectory using the same principle as in the previous work Kminiak et al. (2015).

Measurements

The primary profile (P_z) values of the transverse surface were determined using the Olympus Lext OLS 4100 Laser microscope (Fig. 5.) which was placed on the special Olymext anti-vibration table. This laser microscope operates on a contactless surface scanning principle.

Fig. 5: Laser microscope Olympus Lext OLS 4100 with additional equipment.

The surface quality was evaluated based on the arithmetic mean of the primary profile, P_z. Primary profile (P_z) measurements were carried out in three horizontal paths equidistant from one another along the sample width (2.5, 10, and 22.5 mm from the sample margin) (Fig. 6). The measuring path length was 60 mm. The primary profile was measured at a predetermined final sawn distance of 750 m.

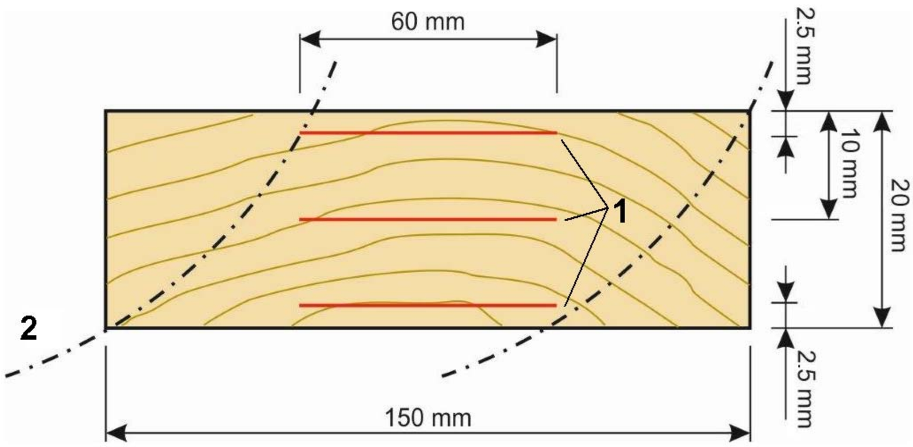


Fig. 6: The schematic representation of measuring locations on the transversal surface: (1) measuring paths; and (2) track teeth of the saw blade.

In addition, for each type of saw blade, the maximum sawn distance was determined, which is the longest possible sawn distance where the sawn blade has not yet overheated due to its friction with wood and dulling of teeth, which is also reflected in blackening of the wood transverse surface.

The acquired data were recorded and exported to MS Excel within the special Olympus software. The primary profile (P_z) values were then evaluated by using STATISTICA 13 software (TIBCO Inc., USA). Two-factor analysis of variance was carried out to a certain the effect of saw blade type and sawn distance on the primary profile (P_z) of transverse area based on the p-value with 95% confidence level. Correlation analysis was performed for a maximum sawn distance of individual saw blade.

Calculations and evaluation

Density was calculated according to ISO 13061-2 (2014) and Eq. 1:

$$\rho = \frac{m}{hbl} = \frac{m}{V}, \quad (1)$$

where: ρ - density of the sample ($kg \cdot m^{-3}$), m - mass (weight) of the sample (kg), h, b, l - the height, width, and length of the sample (m), V - the volume of the sample (m^3).

The moisture content was calculated according to ISO 13061-1 (2014) and Eq. 2:

$$w = \frac{m_w - m_0}{m_0} * 100, \quad (2)$$

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

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

RESULTS AND DISCUSSION

Based on the significance level "P" values given in Tab. 1, 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.

Tab. 1: Statistical evaluation of the impact of factors on the primary profile P_z.

Monitored factor	Sum of squares	Degree of freedom	Variance	Fisher's F - test	Significance level P
Intercept	22.66398	1	22.66398	13456.62	0.00
Number of teeth	0.62682	2	0.31341	186.08	0.00
Sawn distance	0.52245	30	0.01741	10.34	0.00
Number of teeth × Sawn distance	1.24936	60	0.02082	12.36	0.00
Error	0.31327	186	0.00168		

The dependence of the height of the primary profile (P_z) on the used saw blade is considerable (Fig. 7). The highest values of the primary profile were recorded using a saw blade with 24 teeth (24T) and, conversely, the lowest values with a saw blade with 60 teeth (60T). Although all saw blades had the same parameters, the unevenness of the machined surface depended on the number of teeth of each saw blade. Although all three saw blades cut at the same RPM, the smallest chip was removed at the 24T saw blade, which affected the unevenness of the machined surface. On the contrary, the saw blade 60T had the smallest value of feed per tooth, which was reflected even after the transversal cutting of oak wood in the form of a lower value of unevenness. This course could also be influenced by the structure of the wood.

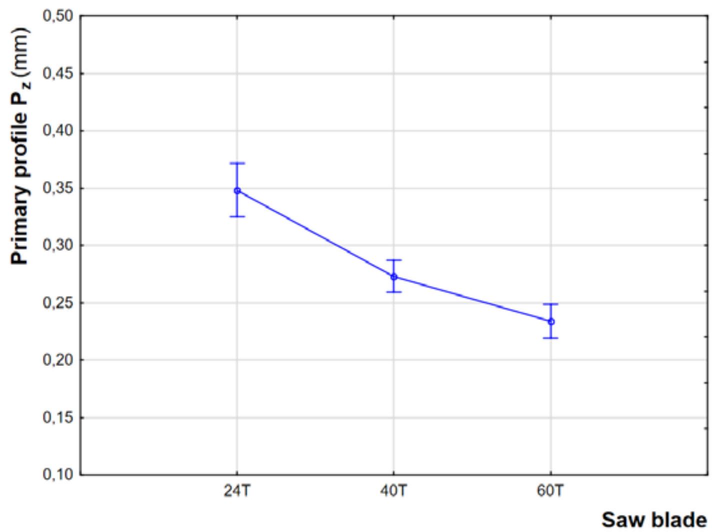


Fig. 7: 95% confidence interval showing the influence of the saw blade type on the primary profile P_z.

An expression of the dependence of primary profile on the sawn distance is presented in Fig. 8, where the ascension can be seen.

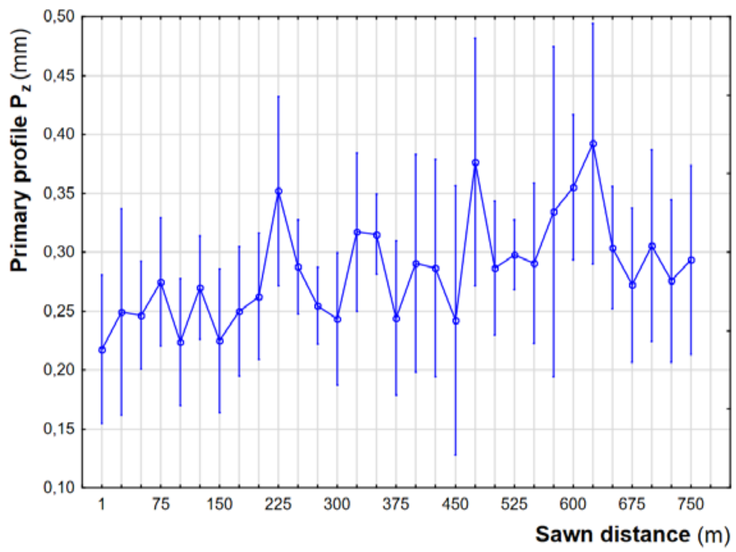


Fig. 8: 95% confidence interval showing the influence of the sawn distance on the primary profile P_z.

Towards the end, the curve of the values of the primary profile has a decreasing tendency, which may be caused by the beginning overheating of the saw blade and the consequent resulting partialy burning of the wood surface.

As can be seen in Fig. 9, the largest differences in the measured values of the primary profile were observed with the saw blade 24T, followed by the saw blade 40T, and the lowest values were shown in the saw blade 60T. Also, the largest variance of the measured values of the primary profile was highest at the 24T saw blade and the lowest values were found at the 60T saw blade. The sawn distance did not have a significant effect on the values of the primary profile when using the saw blades 40T and 60T, but when using the saw blade 24T, the values of the primary profile also increased with the increase of the sawn distance.

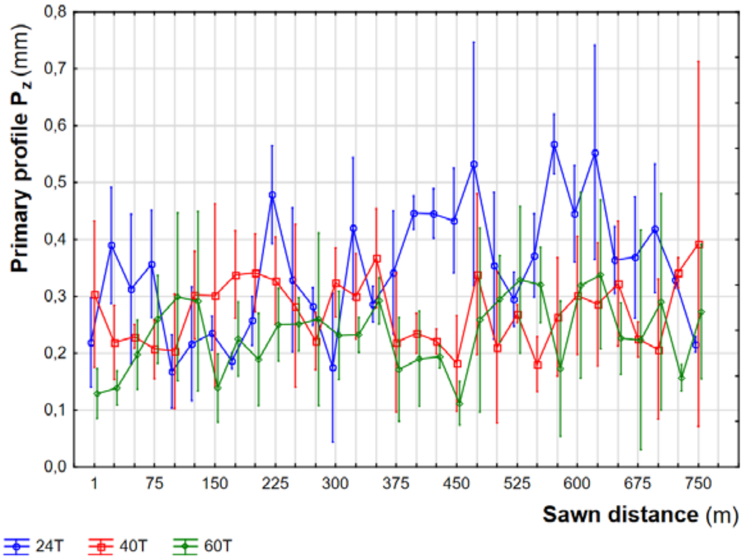


Fig. 9: 95% confidence interval showing the mutual influence of the saw blade type and sawn distance on the primary profile P_z.

The correlation pattern for the 24T saw blade (Fig. 10) shows the variance of the smallest and largest values of the primary profile. When using this saw blade, the variance of values is the largest of all saw blades.

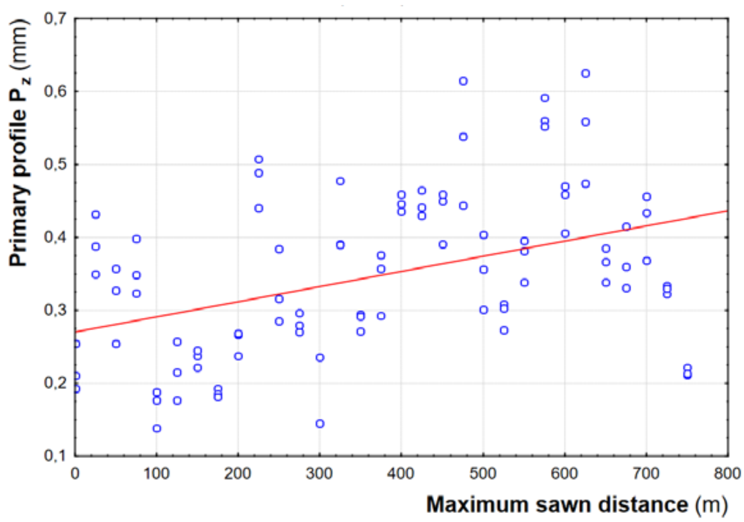


Fig. 10: Correlation of primary profile P_z and maximum sawn distance for saw blade 24T.

Correlation equation of maximum primary profile (P_z) and maximum sawn distance for saw blade 24T: $P_z = 0.2705 + 0.0003*x$.

Figs. 10 – 12 describe the course of correlation of the height of the unevenness profile from the cut distances by individual types of saw blades. Use a 60T saw blade caused the lowest variance of the minimum and maximum values of the primary profile of all three saw blades. This fact was influenced by the largest number of teeth of the saw blade, and thus also the smallest feed per tooth.

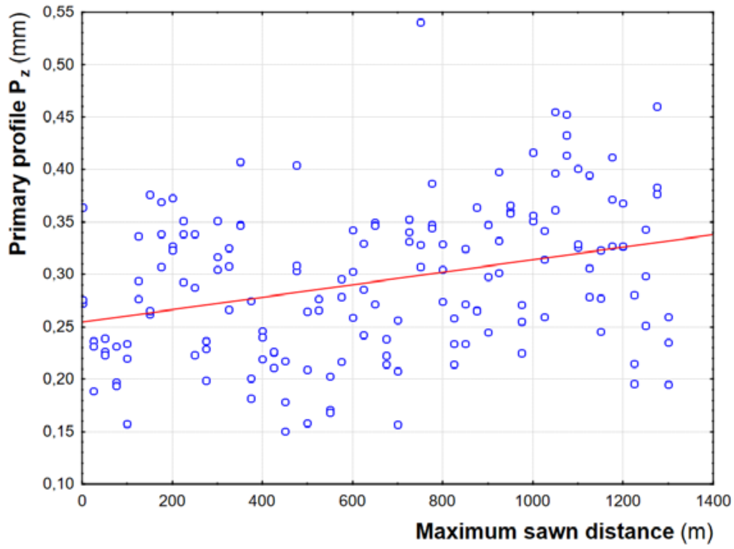


Fig. 11: Correlation of primary profile P_z and maximum sawn distance for saw blade 40T.

Correlation equation of maximum primary profile (P_z) and maximum sawn distance for saw blade 40T: $P_z = 0.2564 + 5.9685E\text{-}5*x$.

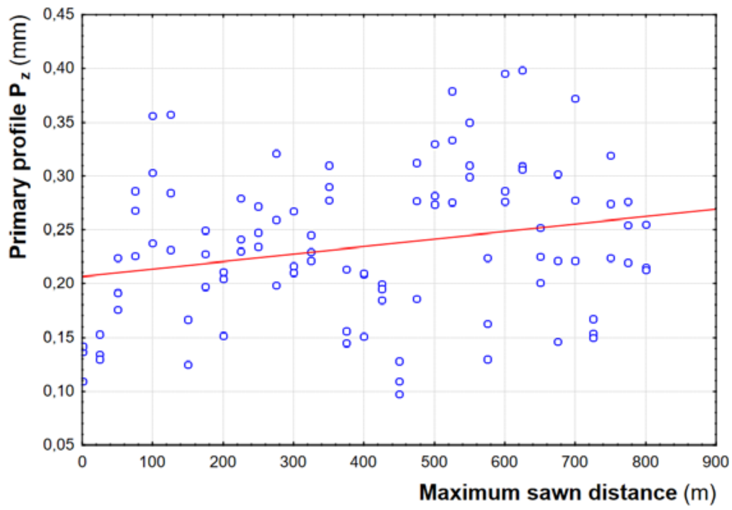


Fig. 12: Correlation of primary profile P_z and maximum sawn distance for saw blade 60T.

Correlation equation of maximum primary profile (P_z) and maximum sawn distance for saw blade 60T: $P_z = 0.2071 + 7.043E - 5*x$.

Tab. 2: Average Primary profile P_z for individual saw blades.

Saw blade	Sawn distance (m)	Average primary profile P_z (mm)			Sawn distance (m)	Average primary profile P_z (mm)			Average per group
		Mean	-95.0%	+95.0%		Mean	-95.0%	+95.0%	
	1	0.219	0.140	0.298	400	0.447	0.417	0.476	
	25	0.390	0.288	0.492	425	0.445	0.402	0.489	
	50	0.313	0.182	0.444	450	0.433	0.341	0.525	
	75	0.357	0.262	0.451	475	0.533	0.319	0.746	
	100	0.168	0.104	0.232	500	0.354	0.225	0.482	
	125	0.217	0.117	0.316	525	0.295	0.247	0.342	
	150	0.235	0.205	0.265	550	0.372	0.298	0.445	
24	175	0.186	0.172	0.200	575	0.568	0.515	0.621	0.348
teeth	200	0.257	0.214	0.300	600	0.445	0.360	0.530	(0.112)
	225	0.479	0.392	0.565	625	0.553	0.365	0.741	
	250	0.328	0.202	0.455	650	0.363	0.305	0.422	
	275	0.282	0.249	0.316	675	0.369	0.262	0.475	
	300	0.175	0.044	0.306	700	0.419	0.306	0.533	
	325	0.419	0.295	0.544	725	0.329	0.315	0.342	
	350	0.286	0.255	0.317	750	0.215	0.202	0.228	
	375	0.342	0.234	0.450					
	1	0.304	0.175	0.433	400	0.235	0.200	0.270	
	25	0.219	0.153	0.284	425	0.221	0.199	0.243	
	50	0.229	0.208	0.250	450	0.182	0.098	0.266	
	75	0.207	0.155	0.259	475	0.339	0.198	0.480	
	100	0.204	0.103	0.304	500	0.211	0.078	0.343	0.273
	125	0.302	0.225	0.379	525	0.269	0.253	0.285	(0.068)
	150	0.301	0.139	0.463	550	0.181	0.132	0.229	
40	175	0.338	0.261	0.415	575	0.264	0.160	0.367	
teeth	200	0.341	0.272	0.410	600	0.301	0.197	0.406	
	225	0.327	0.250	0.404	625	0.286	0.177	0.394	
	250	0.283	0.140	0.426	650	0.322	0.212	0.432	
	275	0.221	0.171	0.271	675	0.225	0.194	0.256	
	300	0.324	0.264	0.385	700	0.207	0.084	0.330	
	325	0.300	0.225	0.375	725	0.342	0.315	0.368	
	350	0.367	0.280	0.454	750	0.392	0.072	0.713	
	375	0.219	0.097	0.341					
	1	0.129	0.086	0.173	400	0.190	0.106	0.274	
	25	0.139	0.109	0.169	425	0.193	0.174	0.213	
	50	0.197	0.137	0.258	450	0.111	0.073	0.150	
	75	0.260	0.183	0.337	475	0.259	0.097	0.420	
	100	0.299	0.151	0.447	500	0.295	0.220	0.371	
	125	0.291	0.134	0.448	525	0.329	0.200	0.458	
	150	0.139	0.079	0.199	550	0.320	0.254	0.386	
60	175	0.225	0.160	0.290	575	0.172	0.054	0.291	0.234
teeth	200	0.189	0.108	0.270	600	0.319	0.156	0.483	(0.071)
	225	0.250	0.186	0.314	625	0.338	0.207	0.468	
	250	0.251	0.204	0.298	650	0.226	0.163	0.289	
	275	0.260	0.107	0.412	675	0.223	0.030	0.416	
	300	0.231	0.154	0.309	700	0.290	0.101	0.480	
	325	0.232	0.202	0.262	725	0.157	0.134	0.179	
	350	0.292	0.252	0.333	750	0.273	0.155	0.391	
	375	0.171	0.080	0.262					

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

As the sawn distance increased, the wear of the cutting edge also increased, which also caused higher values of the primary profile. Tool wear is not only an important parameter for assessing tool life, but also directly affects the surface quality of machining. This fact was also confirmed in their research by Wei et al. (2018).

Tab. 2 shows the average values of the primary profile measured for each type of blade. When comparing the results, it can be concluded that the observed trends of the influence of individual parameters in the transverse cutting of oak wood are confirmed. Homogeneity and density of sawn wood influences the created surface quality (Kúdela and Lagaňa 2010). As reported by Caceres et al. (2018) the reason for the different courses of surface irregularities could be the heterogeneity of the wood material (wood density, deflection of wood fibers), as well as the kinematics of the sawing process (the angle at which the wood fibers are cut, cutting model, imperfect parallelism of fibers with the cutting path) or the occurrence of random effects sawing (crooked cut due to movement caused by deformation of the saw blade shape or vibrations). These factors also affect measurement deviations (Sandak and Martino 2006). This statement fully corresponds with Krilek et al. (2014), Droba and Svoreň (2012) as well as Nasir and Cool (2019), who found that the design of the saw blade directly affects the force relationships in the cutting process, which is subsequently reflected in the quality of the created surface.

At small feeds per tooth, when the chip thickness approaches the existing cutting radius of the edge, there is a hyperbolic increase in the specific cutting resistance (k_c), also known as the so-called size effect (Curti et al. 2017, Atkins 2009), which in turn affects the primary profile such as can also be seen from our results. The specific cutting resistance decreases with increasing chip thickness. This phenomenon is known mainly from the field of metalworking, but it has also been recorded in wood cutting, especially in the case of saw blade cutting (Siklienka et al. 2013). Koleda et al. (2019) state that higher feed rates can be used when cutting with a saw blade, and the durability of the cutting edge can be extended with increasing overhang, but other factors, such as e.g. the diameter of the saw blade (impact on the price, but also on the width of the cutting gap), increasing the cutting power and reducing the quality of the cut must be considered. Ensuring these conditions, of course, leads to further operations, which are undesirable and there is an effort to prevent them both in terms of time and money.

CONCLUSIONS

(1) The value of the primary profile depends on the value of the feed per tooth. These measurements confirmed the theory that the greater the feed per tooth (feed rate), the higher the values of the largest height of the primary profile. The feed rate (feed per tooth) has a significant effect not only on the cutting power, but also on the final quality of the machined surface. *(2)* The shear force acts on the workpiece by means of cutting wedges (teeth). With increasing number of teeth, an almost proportional decrease in the primary profile, i.e. essentially also the surface roughness, was found. *(3)* A similar surface quality as in the case of face milling can also be achieved by transversal sawing. This fact depends on the actual cutting model, the type of wood, the type of saw blade and the feed force.

Depending on the indicated chip length, the quality of the machined surface deteriorates, which is also caused by wear of the cutting tool.

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