Zdeněk Kopecký, Vít Novák, Luďka Hlásková, Jakub Rak[1]

Impact of Circular Saw Blade Design on Forces During Cross-Cutting of Wood

Utjecaj izvedbe lista kružne pile na sile pri poprečnom piljenju drva

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ABSTRACT • *This paper evaluates the impact of the number of saw blade teeth on kinematic and dynamic parameters during cross-cutting of soft and hard woods with mitre saw BOSCH GCM 12 GLD Professional. The forces measured using a three-dimensional XYZ dynamometer Kistler 9257B and subsequent calculation based on a mathematical model were applied in the Ernst-Merchant diagram and the forces acting in the cutting of spruce and oak planks were analysed and compared. The wood cutting was performed by four geometrically and structurally similar blades with a 300 mm diameter and with different count of WZ-shaped teeth (z = 26, 36, 48, 60). The optimum saw blade for the given cutting conditions was subsequently assessed by statistical analysis. Unlike many studies researching the cutting resistances in transversal and longitudinal wood cutting, this experiment and force analysis was performed in dependence on the constant feed force.*

KEYWORDS: *saw blade; mitre saw; Kistler dynamometer; cross-cutting; force analysis; Ernst-Merchant model; statistical analysis*

SAŽETAK • *U ovom se radu ispituje utjecaj broja zubi lista pile na kinematičke i dinamičke parametre tijekom poprečnog rezanja mekih i tvrdih vrsta drva poprečnom klatnom pilom BOSCH GCM 12 GLD Professional. Vrijednosti sila izmjerene spomoću trodimenzionalnog XYZ dinamometra Kistler 9257B te vrijednosti naknadnih izračuna primjenom matematičkog modela uvrštene su u Ernst-Merchantov dijagram te je napravljena analiza i usporedba sila pri piljenju smrekovih i hrastovih piljenica. Uzorci drva piljeni su s četiri geometrijski i strukturno slična lista pile promjera 300 mm s različitim brojem zubi tipa WZ (z = 26, 36, 48, 60). Statističkom analizom određen je optimalan list pile za zadane uvjete piljenja. Za razliku od mnogih istraživanja u kojima su proučavani otpori pri poprečnome i uzdužnom piljenju drva, ovo istraživanje i analiza sila provedeni su pri konstantnoj posmičnoj sili.*

KLJUČNE RIJEČI: *list pile; poprečna klatna pila; Kistlerov dinamometar; poprečno piljenje; analiza sila; Ernst-Merchantov model; statistička analiza*

[1] Authors are researchers at Mendel University in Brno, Faculty of Forestry and Wood Technology, Department of Wood Science and Technology, Brno, Check Republic.

1 INTRODUCTION
1. UVOD

Cutting of wood-based materials is one of the most widespread technologies in woodprocessing. A circular saw is used for cross-cutting or longitudinal cutting of materials, especially in the production of elements of timber structures or joinery products. Cross-cutting of wood in the production of final products is usually carried out as accurate cutting to the required dimensions using mitre or transverse saws (Sandak and Negri, 2005; Orlowski *et al*., 2020). In the past, most authors, Prokeš (1982), Pernica (1999), Wasilewski-Orlowski (2012) and others, examined the process of wood-cutting with a machine feed of a constant speed. The fixed speed during the machine feed of the workpiece determines the constant feed per tooth and the thickness of the layer cut.

It is also common knowledge that with an increasing tooth count, the feed per tooth decreases evenly as well as the thickness of the uncut chip removed with a tooth. On the other hand, the total cutting force and the force required to feed the workpiece grow proportionally with the number of teeth in contact. When cross-cutting wood using transverse or mitre saws, the saw blade feed is most often done manually. If such saws are used, it is necessary to select the geometry, the tooth count and achip thickness limiter so that the blade tooth is able to remove a chip and make a quality cut with minimal energy demands for the application of an average feed force. Similar issues have been addressed in, for example, Kminiak and Kubš (2016), Kminiak and Siklienka (2016), who sought to clarify this process from an energy point of view based on an assessment of the general cutting power.

This paper presents the measurement and analysis of the forces on the tool tooth so that the suitability of a saw blade in terms of the tooth count can be assessed.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Test samples
2.1. Ispitni uzorci

Samples of spruce (*Picea Abies*) and European oak (*Quercus robur*) were used for the experiment. Five samples of oak and spruce in the form of planks were taken from tangential timber without growth defects and with evenly distributed tree rings. The sample dimensions were as follows: 250 mm width, 1000 mm length, and 50 mm thickness.The density of oak was $\rho = 671\ kg/m^3$ and spruce $\rho = 448\ kg/m^3$ at the relative moisture content $w_r = 11\ \%\ (\pm 2\ \%)$.

2.2 Saw blades used
2.2. Upotrijebljeni listovi pila

Wood cross-cutting was carried out gradually by four blades FREUD (LU1C 0400, LU2A 1900, LU2A 2100 and LU2E 0200) with a diameter $D = 300$ mm; the blades were fitted with of tungsten carbide teeth, WZ-shaped, with the same width $s = 3.2$ mm and with the same tooth geometry - clearance angle $\alpha_f = 15°$, cutting edge angle $\beta_f = 60°$, rake angle$\gamma_f = 15°$ and set of cutting edges $\kappa_r = 10°$. The saw blades only differed in the tooth count $z = 26$, $z = 36$, $z = 48$, and $z = 60$ and were marked accordingly as PK26, PK36, PK48 and PK60. At least 25 cuts were made with each saw blade, in both hard and soft wood.

A measurement of the tooth blade rounding radius was carried out for each blade (Figure 1); it ranged at an interval $\rho = 7 \div 10\ \mu m$, which corresponded to a correct sharpening. Measurement of blade rounding was performed using the Keyence VHX 5000 microscope.

2.3 Testing and measuring devices
2.3. Uređaji za ispitivanje i mjerenje

The experiment was carried out on a test device (Figure 2) consisting of a BOSCH GCM 12 GLD Professional mitre saw ($P = 2$ kW, $n = 3800$ rpm, $v_c = 60$

Figure 1 Saw blade PK48 (LU 2A 2100) and tooth blade edge
Slika 1. List pile PK48 (LU 2A 2100) i radijus oštrice

Figure 2 View of Bosch mitre saw test device with Kistler dynamometer
Slika 2. Pogled na poprečnu klatnu pilu Bosch s Kistlerovim dinamometrom

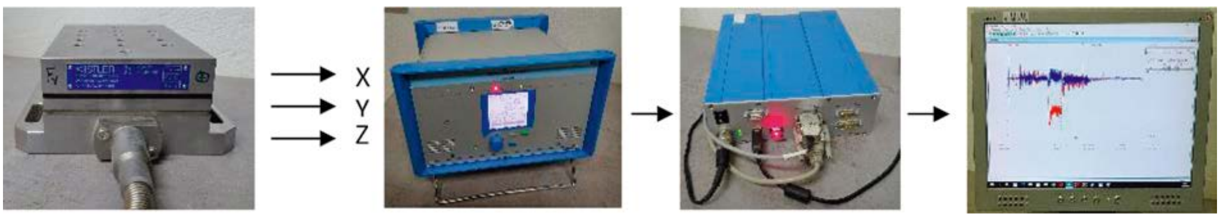
m/s), with adjustable angle 52° L / 60° R, with max. transverse cut 104 mm × 341 mm.

The saw was accompanied by a modified table, which allowed the installation of high-end dynamometer Kistler 9257 B with a measurement and evaluation system (Figure 3). The measuring chain consisted of a PC with DynoWare application, A-D converter with data bus 5679A, eight-channel amplifier 5070A, and four-sensor three-axis piezoelectric dynamometer (force sensor) Kistler 9257B. Further, the saw was equipped with a cable mechanism with a changeable weight (from 1 kg to 5 kg), which allowed the constant feed force to be set and the blade to be pushed towards the cut. An average constant feed force of 30 N was used throughout the experiment.

2.4 Methods
2.4. Metode

The cross-cutting of spruce and oak samples took place in a enclosed cutting mode (Lisičan *et al.*, 1996; Varkoček *et al.*, 2001). The main cutting edge of a WZ tooth with the set of cutting edges κ_r = 10° cut in the tangential-transversal model with angles φ_1 = 10° (angle between the tooth main cutting edge and the direction of wood fibres), φ_2 = 10° (angle between the direction of wood fibres and the cut plane), φ_3 = 90° (angle between the cutting force vector and the direction of wood fibres).

The measurement of forces by the Kistler dynamometer was carried out on two axes, *Y* and *Z*. Force



Piezoelectric dynamometer (force sensor, three-axis) Kistler 9257B → 8-channel amplifier 5070A → A-D data bus converter 5679A → PC with DynoWare A-D measuring application
Piezoelektrični dinamometar (senzor sile, tri osi) Kistler 9257B → 8-kanalno pojačalo 5070A → A-D pretvarač sabirnice podataka 5679A → PC s DynoWare A-D mjernom aplikacijom

Figure 3 Measuring chain of the Kistler dynamometer
Slika 3. Mjerni lanac Kistlerova dinamometra

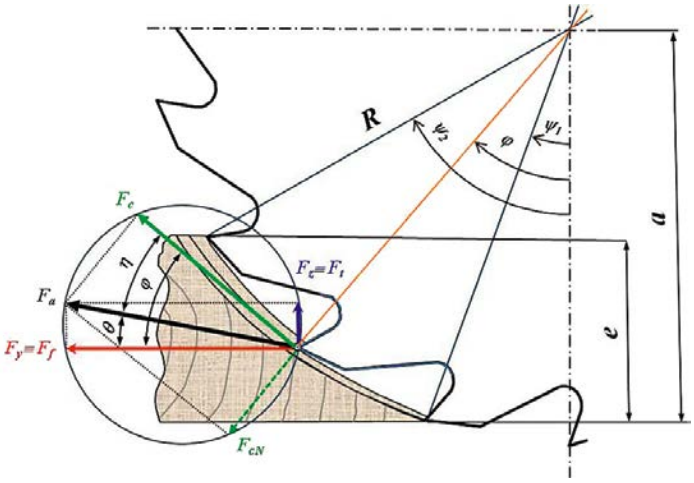


Figure 4 Circular sawing machine cutting force model
Slika 4. Model sile rezanja listom kružne pile

F_y, which is directly equal to the feed force F_f, was measured on Y axis. Force F_z, which equals the thrust force F_t, was measured in Z direction. This force can push the workpiece to the table or even away from it, in dependence on the current cutting conditions and resistances. The diagram of the saw blade and workpiece interaction captured by Ernst-Merchant circle is shown in Figure 4. Although this is not an orthogonal cutting for the main cutting edge ($\kappa_r = 10°$), it is possible to use an Ernst-Merchant circle for decomposition and force analysis.

The geometry of the saw blade and the Ernst-Merchant circle (Figure 4) yields a simple mathematical apparatus for calculating additional forces that classify the entire cutting process (Kopecký *et al*., 2019).

As the radius of the saw blade (R), the position of the table (workpiece) to the axis of the saw blade rotation (a) and the cutting height - thickness of the cut material (e) are known, it is possible to express the technological angles and tooth path in the workpiece:

Tooth angle when entering the workpiece

$$\psi_1 = \cos^{-1}\frac{a}{R} \tag{1}$$

Tooth angle when getting out of the workpiece

$$\psi_2 = \cos^{-1}\frac{a-e}{R} \tag{2}$$

Tooth position angle at the point of the mean uncut chip thickness

$$\varphi = \frac{\psi_1 + \psi_2}{2} \tag{3}$$

Angle of cut

$$\psi = \psi_2 - \psi_1 \tag{4}$$

Length of tooth path in workpiece

$$l = \frac{\pi \cdot D}{360}\psi \tag{5}$$

Active force

$$F_a = \sqrt{F_y^2 + F_z^2} \tag{6}$$

Cutting force

$$F_c = F_a \cdot \cos\eta \tag{7}$$

Angle between active force F_a vector and cutting force F_c vector

$$\eta = \varphi - \theta \tag{8}$$

Angle between active force F_a vector and feed force F_f

$$\theta = \tan^{-1}\frac{F_z}{F_y} \tag{9}$$

Number of teeth, z^I, which simultaneously remove a chip from the workpiece

$$z^1 = \frac{l}{t_p} \tag{10}$$

Where tooth pitch

$$t_p = \frac{\pi \cdot D}{z} \tag{11}$$

Cutting force per tooth of the saw blade

$$F_c^1 = \frac{F_c}{z^1} \tag{12}$$

Calculation of kinematic technological parameters:

Feed speed $v_f = f_z \cdot n \cdot z = L / t$ (13)

Feed per tooth

$$f_z = \frac{L}{\frac{n}{60} \cdot t \cdot z} \tag{14}$$

Mean thickness of the cutting layer

$$h_m = \sin\varphi \cdot f_z \tag{15}$$

Where L – cut length (mm), n – revolution (rpm), t – time of cutting (s) - (Table 1), z – number of teeth.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

At least 25 cuts were made with each saw blade, in both hard and soft wood. A selected measurement record of cutting spruce with the PK36 blade is presented in Figure 5.

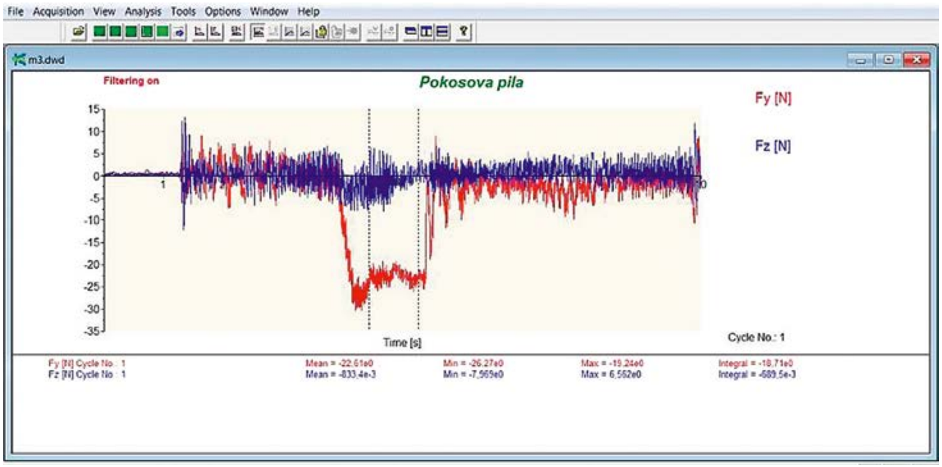


Figure 5 Record of measured forces F_y and F_z in DynoWare application - cutting spruce with saw blade PK36
Slika 5. Zapis izmjerenih sila F_y i F_z u aplikaciji DynoWare – piljenje smrekovine listom pile PK36

The DynoWare application of the Kistler measuring system allows direct analysis of the measured data in the displayed graph, i.e. it is possible to determine the mean values of the forces F_y (red progress) and F_z (blue progress) and the time of cutting t, from the measured selected progress of constant cutting.

The measured values can be stored in the memory and further processed in the form of tables or graphs, see Figure 6. For better clarity, the forces in the bar chart are expressed by the opposite sign than usually recorded by the Kistler dynamometer, in perspective of the direction of the force action on the saw handle.The measured forces F_y, F_z and the time of cutting t, can be further used to calculate other dynamic and kinematic parameters and construct Ernst-Merchant diagrams for individual blades and to assess the effect of the tooth count on the cutting process (in this paper, diagrams are only constructed for hardwood).

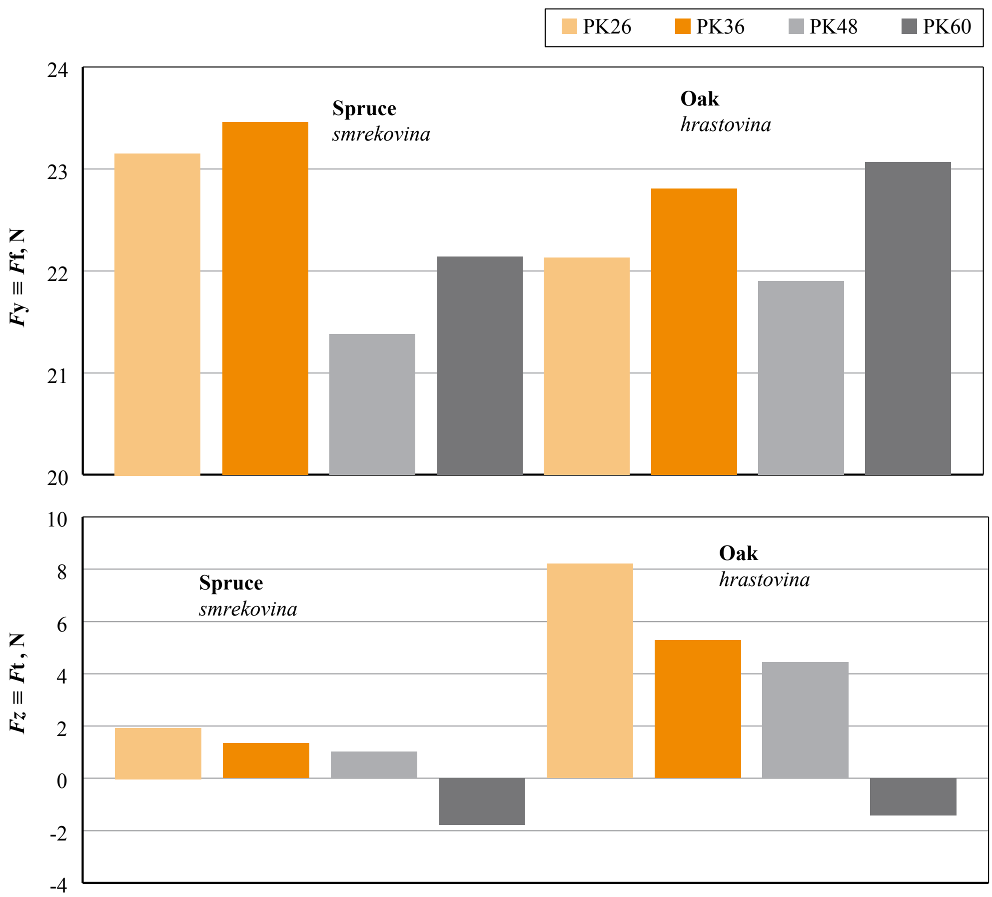


Figure 6 Mean values of forces for individual saw blades and woods
Slika 6. Srednje vrijednosti sila za pojedine listove pila i za ispitivane vrste drva

Table 1 Input and calculated values to generate Ernst-Merchant diagram for oak cutting
Tablica 1. Ulazne i izračunane vrijednosti za generiranje Ernst-Merchantovim dijagramom pri piljenju hrastovine

			PK26	PK36	PK48	PK60
a	148 mm		PK26	PK36	PK48	PK60
e	50 mm	F_y, N	22.1	22.8	23.1	21.9
R	150 mm	F_z, N	8.2	5.9	4.4	-1.4
L	80 mm	*t*, s	1.3	2.1	2.5	6.7
Tooth angle - entry into the workpiece ψ_1, ° *Kut zuba – pri ulasku zubi u zahvat* ψ_1, °			9.367			
Tooth angle - exit to the workpiece ψ_2, ° *Kut zuba – pri izlasku zubi iz zahvata* ψ_1, °			49.207			
Tooth position in the middle chip thickness φ, ° *Položaj zuba pri srednjoj debljini strugotine* φ, °			29.287			
Resulting (active) force F_a, N / *Rezultantna (aktivna) sila* F_a, N			23.6	23.4	23.5	22.0
Angle between active force vector and feed force vector θ, ° *Kut između vektora aktivne sile i vektora posmične sile* θ, °			20.329	13.023	10.859	-3.733
Angle between cutting and active force η, ° *Kut između sile rezanja i aktivne sile* η, °			8.957	16.264	18.428	33.020
Cutting force F_c, N / *Sila rezanja* F_c, N			23.4	22.4	22.3	18.4
Length of tooth path in workpiece (length of layer taken) *l,* mm *Duljina putanje zuba u obratku (duljina luka zahvata) l,* mm			104.297			
Number of teeth z^l per length of layer taken *Broj zubi u zahvatu,* z^l *po duljini luka zahvata*			2.877	3.984	5.312	6.640
Cutting force per tooth , N / *Sila rezanja po zubu,* , N			8.1	5.6	4.2	2.8
Feed speed v_f, m/min^1 / *Posmična brzina* v_f, m/min			3.609	2.254	1.912	0.717
Feed per tooth f_z, mm / *Pomak po zubu* f_z, mm			0.037	0.023	0.019	0.007
Mean thickness of the cutting layer h_m, mm *Srednja debljina odvojene strugotine* h_m, mm			0.019	0.012	0.010	0.004

When manually feeding the workpiece at a mean constant feed force, the feed per tooth f_z and mean thickness of the cutting layer h_m depend not only on the current cutting resistance of the cut material, but also the number of cutting edges that simultaneously remove a chip from the workpiece. When cutting oak, as opposed to spruce, the cutting time gets significantly longer, the feed per tooth and chip thickness decrease, the tooth gradually loses the ability to form a chip. The calculated values presented in Table 1 lead to a partial conclusion that, with a slightly decreasing total cutting force F_c, the cutting force per tooth decreases proportionally with an increasing number of saw teeth (Figure 7). This phenomenon is also known from previous research by authors (Stewart, 1979; Porankiewicz *et al.*, 2007) who dealt with machine feeds with fixed feed per tooth. When using a constant feed rate (simulation of machine feed), the feed force applied constantly "pushes" the saw teeth into the cut at the same speed, so the blade tooth is forced to form a chip and, when

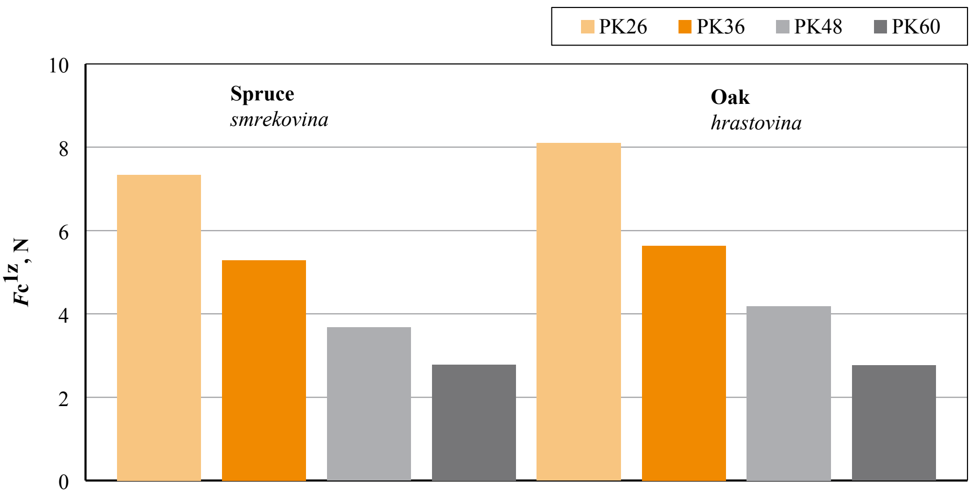


Figure 7 Cutting force per tooth
Slika 7. Sila rezanja po zubu

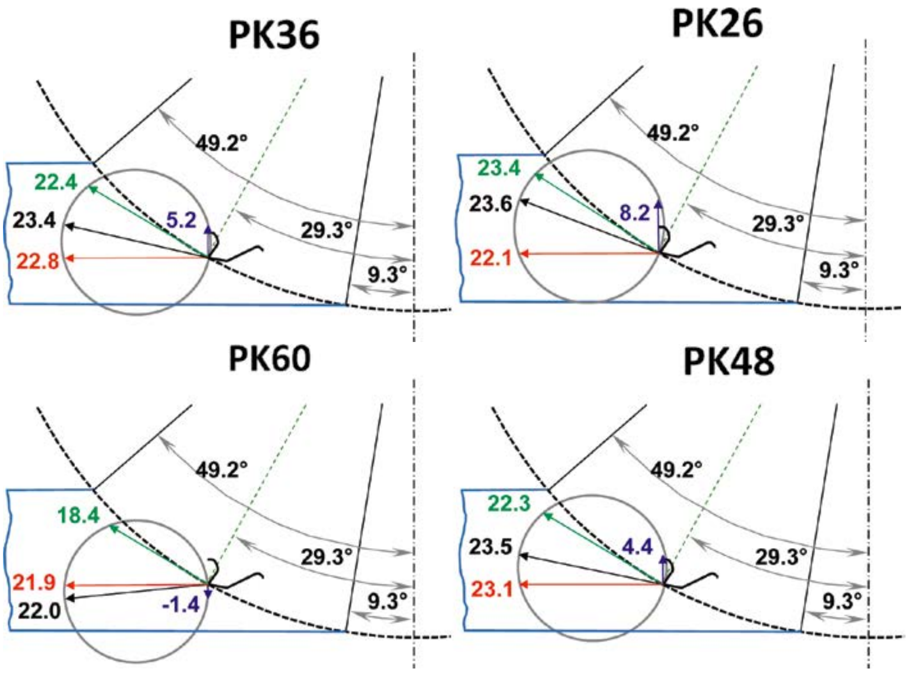


Figure 8 Graphical comparison of forces in Ernst-Merchant diagrams - oak cutting
Slika 8. Grafička usporedba sila u Ernst-Merchantovu dijagramu – piljenje hrastovine

the cutting resistance of the cut material increases, the cutting power increases too. This conclusion is in line with previous studies by Prokeš (1982) and Pernica (1999). Other studies by Kminiak and Kubš (2016) and Kminiak and Siklienka (2016), which dealt with issues similar to this research, were based on an evaluation of the cutting power depending not only on the saw tooth count, but also on the cutting direction. In the case of tangential-transversal cutting model, the authors concluded that the total cutting power slightly decreases with an increasing tooth count, which is in harmony with our results.

However, when evaluating cutting power only, without a detailed analysis of the forces and kinematic parameters of the saw blade tooth, it is difficult to determine the effect of the number of teeth on the total cutting process, since the total cutting force and power change only slightly when blades with different tooth counts are used.

Ernst-Merchant diagrams (Figure 8) show that all forces slightly decrease with an increasing tooth count in a saw blade. In our experiment, a constant feed force of 30 N was used, which is the common mean value of manual mitre saw arm shift in the case of a saw of the size used in the experiment. However, in the cutting process, part of this force is consumed by the chip formation and part to overcome friction in the cable mechanism and the saw feed mechanism; therefore, the measured values of the feed forces, F_f, are slightly lower, by 6 to 8 N.

Also, the overview of forces in Ernst-Merchant diagrams for individual blades (Figure 8) indicates a fundamental change in the direction of thrust force F_t in the case of PK60 blade. The thrust force changed the direction of action and began to push the workpiece against the table. The resultant active force F_a of the cutting process also acts towards the material. Based on these values, we can form a hypothesis that the teeth of PK60 blade form a chip with difficulty and they compress the layer of material taken under the clearance face. This is also related to the relatively small feed per tooth f_z = 0.007 mm and the mean thickness of the cutting layer h_m = 0.004 mm (Table 1), the size of which is below the current radius of tooth blade edge (Figure 1). It could be that there really is a small negative angle in the portion of the saw tooth at the tip where the rake angle becomes negative. Statistical analysis of variance ANOVA, Rak (2020), was used for an unbiased assessment of the effect of the different number of saw blade teeth on the cutting parameters in the cross-cutting of spruce and oak planks using constant feed force.

The probability value P is lower than 0.05. Therefore, there is a statistical significance between the data, and Scheffe's multiple comparison was used. Scheffe's multiple comparison (Tab. 3) shows the statistical difference in the PK60 saw blade. It differs significantly from the other blades. Cutting with blades PK24 and PK48 differs from each other and they both differ from the PK60. Based on the test results, but also the size and direction of the forces applied, the acceptable feed per tooth f_z = 0,023 mm and the mean uncut chip thickness h_m = 0,012 mm, it can be concluded that the PK36 saw blade with 36 teeth (Freud LU2A 1900) is the most suitable for the cross-cutting process of the timber studied.

Table 2 Results of statistical analysis of variance for cross-cutting of spruce
Tablica 2. Rezultati statističke analize varijance za izmjerene sile pri poprečnom piljenju smrekovine

FACTOR

Groups *Listovi pila*	**Count** *Broj rezova*	**Sum** *Zbroj*	**Average** *Srednja vrijednost*	**Variance** *Varijanca*
PK26	3836	7286.15	1.90	92.81
PK36	4253	5668.07	1.33	96.86
PK48	5122	5183.59	1.01	142.79
PK60	7467	-13313.68	-1.78	80.96

ANOVA

Source of variation *Izvor varijacija*	***SS***	***df***	***MS***	***F***	***P-value***	***F crit***
Between groups *između listova pile*	49252.1781	3	16417.39	161.36	2.14E-10^{3}	2.61
Within groups *unutar lista pile*	2103391	20674	101.74			
Total *Ukupno*	2152643.18	20677				

Table 3 Scheffe’s multiple comparison
Tablica 3. Scheffeova višestruka usporedba

			PK24	PK36	PK48	PK60
	Count *Broj rezova*		3836	4253	5122	7467
		Average *Srednja vrijednost*	1.90	1.33	1.01	-1.78
PK24	3836	1.90	0.00	2.52	**4.12**	**18.38**
PK36	4253	1.33	2.52	0.00	1.53	**16.08**
PK48	5122	1.01	**4.12**	1.53	0.00	**15.27**
PK60	7467	-1.78	**18.38**	**16.08**	**15.27**	0.00

4 CONCLUSIONS
4. ZAKLJUČAK

Choosing the tooth count of the saw blade used is a fairly important step when using a saw. It affects not only the energy aspect, but also the tooth wear and the quality of the cut, Mikleš *et al*. (2010).

The results of this paper confirm the fact that, in the case of manual feed by constant force, the energy performance of the cutting process is directly dependent on the interaction of the material properties and the tool construction – especially the number of actively cutting teeth, Schajer and Wang (2002). In this process, the said interaction adjusts the feed per tooth and the nominal uncut chip thickness, making the process analysis much more complicated.

With an increasing tooth count, the constant feed force is divided among a larger number of cutting edges that concurrently participate in the cutting. If the force per a cutting edge is too small, the material may not be cut at all. In general, the more teeth are cutting, the lower force is applied to a tooth blade in the cutting process and the tooth is less forced to form a chip. There is a risk that the cutting process will stop, the workpiece will get burnt and the tool will get heavily worn.

Another finding was that, with an increasing tooth count and a decreasing mean uncut chip thickness, the vector of the resultant (active) force of the cutting process, F_a, “turns” into the material cut. This causes greater elastic plastic deformation of the material under the tooth edge, there is more friction, especially under the tooth clearance face, and the chip formation is reduced or stopped.

If the quality of the cut is not critical, it is preferable to use blades with a medium tooth count for mitre saws when cutting wood transversely, from the perspective of energy demands.

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Corresponding address:

Doc. Ing. ZDENĚK KOPECKÝ, CSc.
Mendel University in Brno, Faculty of Forestry and Wood Technology, Department of Wood Science and Technology, Zemědělská 3, 61300 Brno, CZECH REPUBLIC, e-mail: kopecky@mendelu.cz