Cutting Power during Cross-Cutting of Selected Wood Species with a Circular Saw

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This study assessed the effect of selected factors, such as the feed force (F_f = 15, 20, and 25 N), wood species (beech (*Fagus sylvatica* L.), English oak (*Quercus robur* L.), and spruce (*Picea abies* L.)), and the number of saw blade teeth (z = 24, 40, and 60) on cutting power in the cross-cutting of lumber. The cutting was done using a circular saw with a rotating motion of the saw blade at a constant cutting speed (v_c) of 62 $m.s^{-1}$. The tangentially bucked lumber had a relative humidity (w_r) of 12% ± 1% and a thickness (e) of 50 mm. For the experiment, four circular saw blades with SK plates, a uniform diameter (D = 250 mm), and identical angular geometry (angle of clearance (α) = 15°, wedge angle (β) = 60°, and rake angle (γ) = 15°) were used. The saw blades had a different number of teeth (z = 24, 40, and 60), and one saw blade had 24 teeth and a chip limiter. The aim of this study was to expand the knowledge about the resulting cutting performance with different combinations of technological process parameters.

Keywords: Cutting performance; Bucking lumber; Thrust force; Type of saw blade; Beech lumber; Oak lumber; Spruce lumber

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INTRODUCTION

The circular saw is one of the most frequently used wood cutting machines and is designed for cross-cutting and rip-cutting wood. Sandak and Negri (2005) divide the operation of cross-cutting into two types, rough cross-cutting and final cross-cutting to size.

The rotating cutting tool plays a fundamental role in sawing, and the saw blade stays perpendicular to the grain of the wood. In cross-cutting, the edges of the saw blade teeth shear the wood fibers and form the walls of the seam. The main cutting edges in cross-cutting form the bottom of the notch groove (Siklienka and Kminiak 2013).

The parameters of the process of wood cutting (energy consumption, dust, noise, *etc.*), the resulting product (size accuracy, quality of the surface, *etc.*), and the produced wood chips (size, grain size distribution, *etc.*) depend on the physical and mechanical properties of the machined material; the shape, size, number of teeth, geometry, sharpness of the cutting tool; and the technical and technological conditions of the machining process (Kilic *et al*. 2006; Barcík and Gašparík 2014; Krilek *et al*. 2014; Gaff *et al*. 2015; Kvietková *et al*. 2015; Gaff *et al*. 2016).

The geometry and cutting conditions can reduce the cost of wood cutting by increasing the cutting capacity of the machine (saw), with the appropriate tool selection (Řasa and Gabriel 2000; Novák *et al.* 2011).

The energy intensity of the sawing process is monitored through the cutting power. According to the standard STN ISO 3002-4 (1995), cutting power is defined as the result of the scalar product of the vector of the cutting force (F_c) and the vector of the cutting speed (v_c) at the same time during a certain operation and under certain cutting conditions. The unit of power is the Watt, which is expressed in N.m.s^{-1}.

This study examined how the operator of the circular saw affects the energy intensity of the cross-cutting process of beech, oak, and spruce lumber, with the feed force, and how this force affects the operator holding the handle of the circular saw. This information is particularly necessary when sawing is performed outside an electric power distribution system, and it is necessary to plan the capacity of the portable source of electric power (generator power input). This study also investigated the most frequently used saw blades to find the most energy-efficient blade for the given type of circular saw.

EXPERIMENTAL

Materials

For the experiment, samples of beech (*Fagus sylvatica* L.), oak (*Quercus robur* L.), and spruce wood (*Picea abies* L.) were used. The lumber used to produce the samples was logged in 2012 in Zvolenská kotlina (Slovakia), and the average age of the trees was 45 years. The lumber was cross-cut, with a thickness (e) of 50 mm (± 1 mm) and a relative humidity (w_r) of 12% (± 1%). The lumber was dried in a hot air oven dryer. The lumber was used to produce test samples (Fig. 1), which had a height (h) of 50 mm (same as the thickness of the lumber), width (š) of 100 mm (parallel to the grain of the wood), and length (l) of 150 mm (perpendicular to the grain of the wood). Holes with a diameter (d) of 10 mm were drilled in precisely determined locations for mounting the samples to the plate of the measuring device. Tangentially cut test specimens from multiple stumps were used, making sure that the samples were cut from the same position on the trunk, with the same number of annual rings. The specimens were then sorted according to density, the average density values of test the specimens. The average density values measured at a 12% moisture content were:

Fagus sylvatica L.	680 kg.m^{-3}
Quercus robur L.	650 kg.m^{-3}
Picea abies L.	430 kg.m^{-3}

Fig. 1. Experimental samples of beech, oak, and spruce

Methods

Machinery characteristics

The experimental sawing of the lumber was conducted with a sliding miter saw with a rotating circular blade (GCM 10S Professional, Bosch, Munich, Germany). The technical parameters of the sliding miter saw are shown in Table 1.

Saw blade characteristics

Four saw blades with SK (sintered carbide) plates were selected (Fig. 2). The saw blades had identical diameters (D = 250 mm), identical instrument thickness (b = 3.2 mm), identical cutting edge geometry (angle of clearance (α) = 15°, wedge angle (β) = 60°, rake angle (γ) = 15°, bias bevel angle (ξ) = 15°, radial inclination angle (λ) = 7°), and alternate tooth geometry (WZ). Three of the saw blades were from Extol-Premium (Czech Republic), and they each had a different number of teeth (Fig. 3): 24, 40, and 60. The fourth blade was a Speedline-Wood from Bosch (Munich, Germany) with 24 teeth and a chip limiter (Fig. 2).

Table 1. Technical and Technological Parameters of Sliding Miter Saw (Bosch GCM 10S Professional)

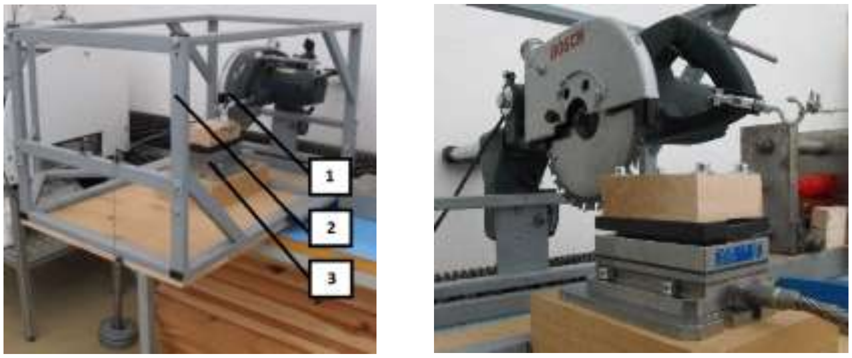
Cutting capacity (0°)	87 x 305 mm
Cutting capacity (45° miter)	87 x 216 mm
Cutting capacity (45° incline)	53 x 305 mm
Miter setting	52° L / 62° R
Incline setting	47° L / 0° R
Depth x length x height	78 x 68 x 54 cm
No-load speed	4.700 rpm
Saw blade diameter	254 mm
Saw blade bore diameter	30 mm
Weight	21.5 kg
Rated power input	1.800 W
Vibration emission value (ah)	1.9 m.s-²

Fig. 2. Saw blades used, from left to right: 24, 40, and 60 teeth; 24 teeth and a chip limiter

Characteristics of experiment

Because it was impossible to maintain the constant conditions of the experiment by manual feed, the constant feed force was simulated with an experimental stand (Fig. 3).

In the experimental stand, the movement of the hand was simulated by the movement of a pull rope, and the feed force was exerted by weights. As reported by Kminiak and Gaff (2015), the average feed force in cross-cut sawing by a circular miter saw with manual operation of the saw blade ranges between 13 and 28 N. For the experiment, a feed force (F_f) of 20 N was used. In the experiment, the test specimens were split exactly in half by the reciprocating movement of the saw blade.



a) b)

Fig. 3. Experimental stand. a) General view (1 - circular miter saw, 2 - experimental stand, 3 - Piezo–electric dynamometer with mounted sample); b) detail of the cutting zone

Three basic cross-cutting models were used on the circular miter saw, front face cutting (M1) (Fig. 4a, b, c), slant front face cutting with the angle of grain cut (φ_2) at 90° (miter cutting) (M2) (Fig. 4b), and slant front face cutting with the φ_2 at 45° (M3) (Fig. 4c). The angle of grain cut (φ_2) is the angle of the resultant vector of the cutting speed and the direction of the wood grain. The experiment was carried out at a constant saw blade cutting speed (v_c) of 62 m.s^{-1}.

a) b) c)

Fig. 4. Three basic cross-cutting models were used

Measuring cutting power

The cutting power was measured indirectly by measuring the cutting force on the monitored level of dynamometer power components, *Fy* and *Fz*, exerted by the saw blade on the cut sample. The measuring apparatus for the measurement of the force included a piezo–electric dynamometer (9257B, Kistler, Ostfildern, Germany) (Fig. 5a), a multi-channel amplifier (5070A, Brand, City, Country) (Fig. 5b), a 16-bit A/D converter (5697A, Kistler Instrumente AG, Winterthur, Switzerland) (Fig. 5c), and a PC for evaluation, which included the software DynoWare (Kistler). The necessary cutting power (P_c) was determined according to Eq. 1,

$$P_c\ (\mathrm{W}) = F_c * v_c \qquad (1)$$

where F_c is the cutting force (N) and v_c is the cutting speed ($\mathrm{m.s^{-1}}$).

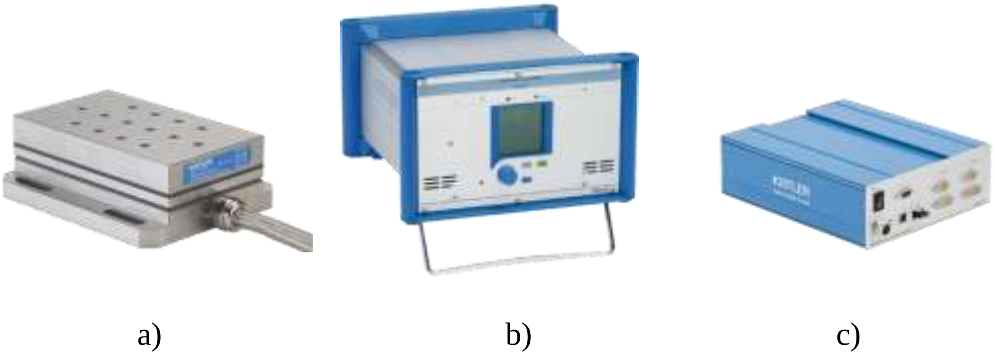


Fig. 5. Block diagram of the monitoring equipment. a) Piezo–electric dynamometer 9257B, b) multi-channel amplifier 5070A, and c) 16-bit A/D converter 5697A

The cutting performance was monitored and evaluated in terms of the effect of the wood species, cutting model, type of saw blade used, and feed force at a v_c of 62 $\mathrm{m.s^{-1}}$. The resulting cutting performance values were statistically evaluated by STATISTICA 12 software (Statsoft Inc., Tulsa, OK, USA).

RESULTS AND DISCUSSION

A multi-factor analysis of variance (Table 2) showed that the effect of all the monitored factors was statistically significant, and the effect of their interaction was significant as well. The Fisher’s F-test ranked the monitored factors according to statistical significance, from highest to lowest, in the following order: cutting model, feed force, wood species, and type of saw blade.

Table 2. Statistical Evaluation of the Effect of Factors and their Interaction on the Cutting Power

Monitored Factor	Sum of Squares	Degree of Freedom	Variance	Fisher's F-Test	P
Intercept	132967368.00	1	132967368.00	118881.11	0.001
1) Wood species	4818499.08	2	2409249.54	21540.25	0.001
2) Type of saw	1130240.55	3	376746.85	3368.36	0.001
3) Feed force (F_f)	11365981.90	2	5682990.93	50809.61	0.001
4) Cutting model	37325340.20	2	18662670.10	166856.32	0.001
1*2*3*4	16772207.80	24	698841.99	6248.10	0.001
Error	72477.99	648	111.85		

During the experiment, the cutting power values were measured in the range of 45.80 W to 1100.13 W. A one-factor and two-factor analysis of the effects of individual process factors was conducted on the measured data at a 95% confidence interval. During evaluation, the material factors (wood species and cutting model) and technical and technological process factors (type of saw blade and feed force) were analyzed separately.

Effect of wood species

The effect of the wood species on the energy intensity of the process of cross-cutting is illustrated in Fig. 6. The range of the measured data for individual wood species is shown in Table 3.

There was no statistically significant difference between beech and oak wood. Despite the fact that beech wood is diffuse-porous and oak wood is ring-porous, they have approximately the same density and comparable values of the given properties in terms of the effect of physical and mechanical properties on the defense mechanisms of the wood. A comparison of spruce and beech, as well as spruce and oak, showed that the cross-cutting of spruce was the least energy intensive, which was expected because of the previously mentioned parameters. Similar conclusions were published by Cristovao *et al.* (2012).

Table 3. Basic Statistical Characteristics of the Effect of Wood Species on the Cutting Power

Wood Species	**Cutting Power, P_C (W)**				
	Mean	**Standard error**	**-95.00%**	**95.00%**	**N**
Beech	497.05	26.14	445.57	548.52	252
Oak	451.52	18.84	414.43	488.62	252
Spruce	309.58	31.72	247.10	372.06	252

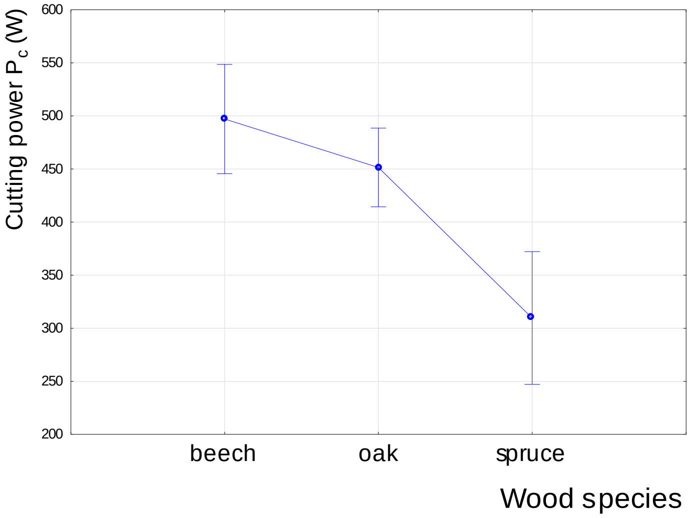


Fig. 6. The effect of the wood species on the cutting power

Effect of cutting model

The effect of the cutting model on the energy intensity of cross-cutting for individual wood species is shown in Fig. 7. The range of the measured data for each cutting model is shown in Table 4.

The energy intensity of the process of cross-cutting increased in the order of front face cutting (M1), slant front face cutting at a φ_2 of 90° (M2), and slant front face cutting at a φ_2 of 45° (M3). In the front face cutting model (M1), the wood elements were cut perpendicular to the direction of the motion of the saw blade, and the path of the saw blade was the shortest, equal to the width of the sample.

The increase in cutting power recorded in the slant front face cutting model at a φ_2 of 90° (M2) was attributed to two factors based on current knowledge. The first was that the direction of the saw blade with regard to the material resulted in a longer cutting path. This caused a higher energy loss due to a larger friction area of the saw blade being in contact with the cut material. In front face cutting, the saw blade path was equal to the width of the 15 cm sample, and in slant front face cutting, the saw blade cutting path was 21 cm. Another reason was that the direction of the wood fibers (elements), where the elements were cut at an angle other than 90°, resulted in a longer path that had to be overcome to cut the elements. There was an increase in the radial cross-section of these elements and the ideal circular cross-section of the wood elements became an enlarged elliptical cross-section. Sadoh and Nakato (1987) reached similar conclusions.

Table 4. Basic Statistical Characteristics of the Effect of the Cutting Model on the Cutting Power for Different Wood Species

Cutting Model	**Wood Species**	**Cutting Power, P_C (W)**				
		Mean	**Standard error**	**-95.00%**	**95.00%**	**N**
M1	**Beech**	161.54	14.61	132.48	190.61	84
M2	**Beech**	496.10	40.89	414.78	577.42	84
M3	**Beech**	833.50	39.91	754.12	912.87	84
M1	**Oak**	237.04	12.19	212.79	261.29	84
M2	**Oak**	386.70	19.13	348.64	424.76	84
M3	**Oak**	730.83	34.05	663.11	798.55	84
M1	**Spruce**	109.44	7.18	95.17	123.72	84
M2	**Spruce**	255.93	6.98	242.04	269.83	84
M3	**Spruce**	563.37	87.96	388.42	738.31	84

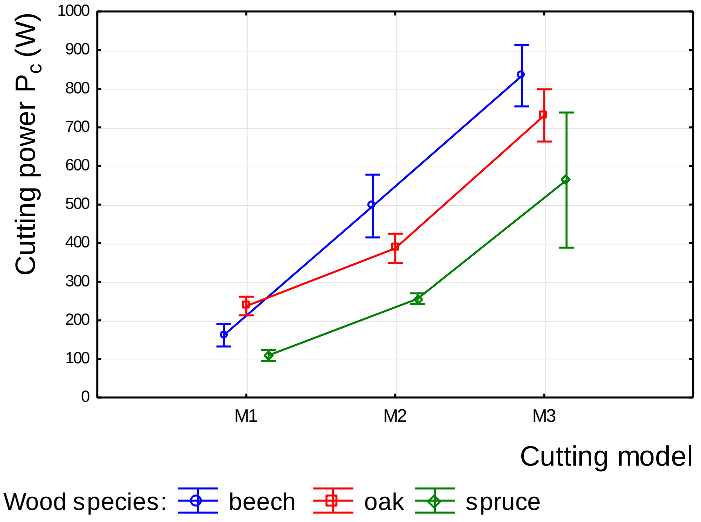


Fig. 7. Two-factor analysis of the effect of the cutting model on the cutting power for each monitored wood species. M1 is the front face cutting, M2 is the slant front face cutting at $\varphi_2 = 90°$ (*i.e.*, miter cutting), and M3 is the slant front face cutting at $\varphi_2 = 45°$ (*i.e.* cutting at a 45° angle).

The last monitored model, the slant front face cutting at a φ_2 of 45°, showed the largest increase in cutting power, which was partially due to the cutting of wood elements at an angle other than 90°. The increase in cutting power was mainly due to the 2 cm (29%) increase in the cutting height of the experimental sample compared to the other two cutting models, which caused an increase in the number of saw blade teeth in the cross-section. These findings confirmed the conclusions of Costes and Larricq (2002) and Mikleš *et al.* (2010), who found that an increase in the cutting height of materials results in an increase in cutting power and the force required to cut the wood.

Type of saw blade

The effect of the type of saw blade on the cutting power is illustrated in Fig. 8. The range of the measured data for the different types of saw blades is shown in Table 5. This data did not confirm the claims of Prokeš (1982) or Droba and Svoreň (2012), who showed that an increase in the number of saw blade teeth results in a decrease in the cutting force required to separate the layer of wood and a decrease in the cutting power (as a result of the decreased nominal thickness of the wood).

An increase in saw blade teeth from 24 to 40 did not result in a statistically significant change in cutting power for any of the wood species (Fig. 8). The situation repeated itself when the number of teeth increased from 40 to 60. In spruce wood, the cutting power for 60 teeth rose above the value measured for 24 teeth.

Table 5. Basic Statistical Characteristics of the Effect of the Type of Saw Blade on the Cutting Power

Type of Saw Blade	**Cutting Power, P_C (W)**				
	Mean	**Standard error**	**-95,00%**	**95,00%**	**N**
z = 24 +OHT	389.00	16.17	357.10	420.89	189
z = 24	409.43	26.30	357.55	461.31	189
z = 40	394.04	24.86	345.00	443.07	189
z = 60	485.07	46.61	393.14	577.01	189

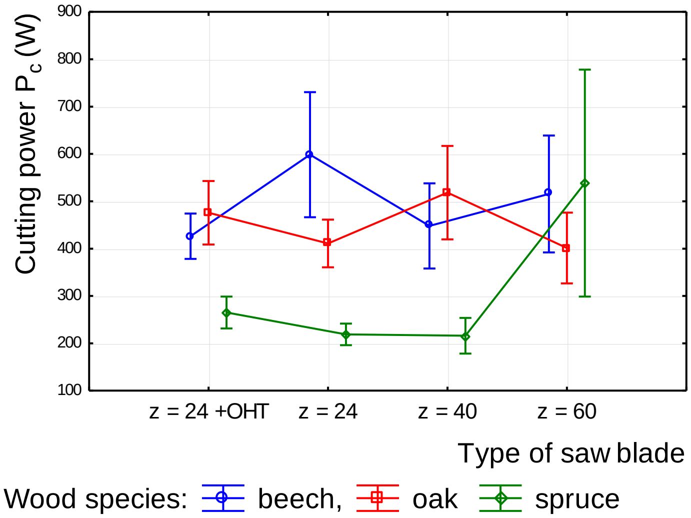


Fig. 8. Two-factor analysis of the effect of the type of saw blade on the cutting power for each monitored wood species

The principle of the given effect was in the basic features of this particular experiment. Unlike other authors who based their experiments on a constant feed speed (v_f), this study used a constant feed force (F_f), which, in the opinion of these authors, captured the principle of the manual feed of the saw blade more accurately.

At a constant feed force, the current feed per tooth and the nominal thickness of the chip depended on the current cutting resistance of the cut material and the resultant cutting force (vector sum of the cutting force and feed force). The effect of the decomposition of the resulting cutting force on a number of cutting wedges was also reflected here. More teeth on the saw blade equaled more teeth in the cut.

It was concluded from these results that for the given combination of material effects and input process variables, it was equally appropriate to use a saw blade with either 24 or 40 teeth.

In terms of assessing the criteria for the use of a saw blade with a chip limiter, it was discovered that a saw blade with 24 teeth and a chip limiter achieved the same cutting power as a saw blade without a chip limiter and with both 24 and 40 teeth. The synergistic effect of eliminating the potential risk of overloading the saw blade with a thrust force that is too high spoke in favor of a chip limiter.

The effect of the feed force

The effect of the feed force on the cutting power is shown in the graph in Fig. 9. The range of the measured data for individual feed forces is shown in Table 6.

The feed force values were selected from practical knowledge, where the feed force was often too high due to the subjective approach of the saw operator, as well as the high pneumatic locking system settings, which resulted in the displacement of the saw blade support on automated cutting lines.

Both cases led to an increased cutting power. This was caused by worse cutting economics, along with poor quality surfaces that required additional grinding. This experiment focused on the lowest and highest feed force values at which the sample can be completely cut without the blade getting jammed in the cut, at set cross-cutting conditions.

Table 6. Basic Statistical Characteristics of the Effect of the Feed Force on the Cutting Power for Different Types of Saw Blades

Feed Force, F_f (N)	**Type of Saw Blade**	**Cutting Power, P_C (W)**				
		Mean	**Standard error**	**-95.00%**	**95.00%**	**N**
15	**z = 24 + OHT**	290.60	24.25	242.14	339.07	63
20	**z = 24 + OHT**	352.87	25.52	301.85	403.89	63
25	**z = 24 + OHT**	523.51	25.88	471.79	575.24	63
15	**z = 24**	300.83	45.44	210.00	391.67	63
20	**z = 24**	389.77	34.36	321.08	458.46	63
25	**z = 24**	537.68	50.84	436.06	639.30	63
15	**z = 40**	254.36	13.36	227.65	281.07	63
20	**z = 40**	347.42	40.41	266.64	428.20	63
25	**z = 40**	580.34	53.85	472.68	687.99	63
15	**z = 60**	186.90	12.38	162.14	211.65	63
20	**z = 60**	688.62	123.82	441.10	936.14	63
25	**z = 60**	579.70	45.02	489.71	669.69	63

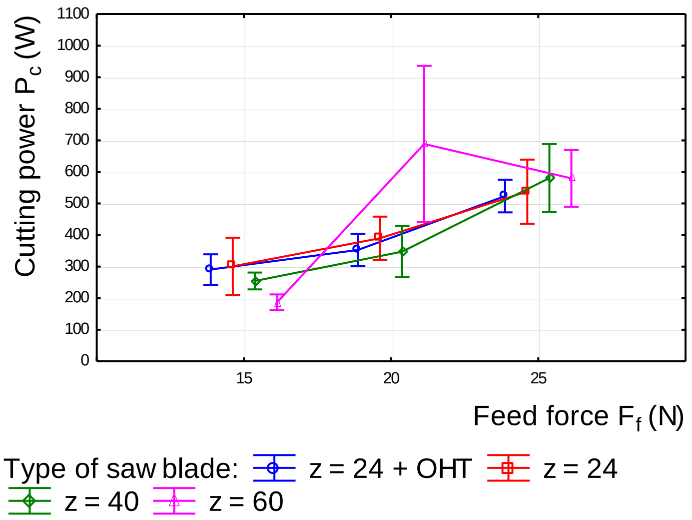


Fig. 9. Two-factor analysis of the effect of the feed force on the cutting power for each monitored saw blade

By increasing the feed force, the time necessary to cut the sample was reduced, which implied that the feed speed increased. This was shown by a graph of the relationship between the type of saw blade and the feed force (F_f), and the cutting time (Fig. 10).

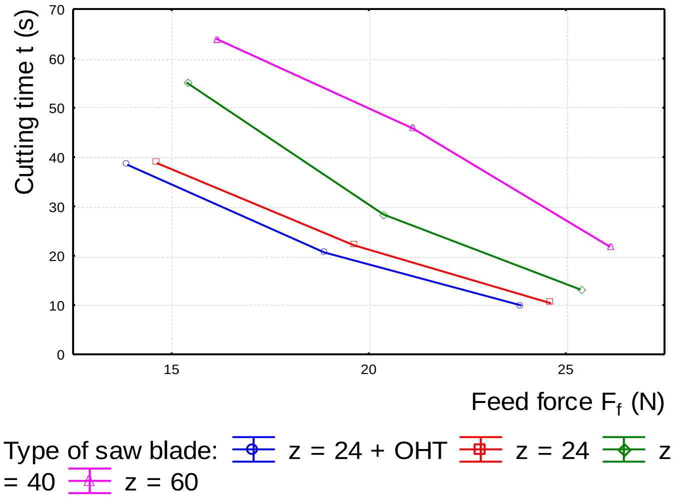


Fig. 10. Two-factor analysis of the effect of the feed force on the cutting time for each monitored saw blade

The cutting power increased along with an increase in the feed force. This increase in cutting power was attributed to the previously mentioned fact that an increase in the feed force resulted in an increase in the feed speed. This increased the thickness of the cut layer and the feed per tooth, which resulted in the need for a greater cutting power to separate the chips.

CONCLUSIONS

1. The cross-cutting process at a constant feed force had its own specifics, and not all patterns derived from the experiments based on a constant feed speed applied to it.
2. This study pointed out the fact that at a constant feed speed the energy intensity of the process directly depended on the interaction of the material (density, direction of the grain, *etc.*) and the tool (number of active cutting teeth, chip limiter, *etc.*), which was further complicated by the fact that the given interaction also determined the nominal chip thickness. These factors considerably complicated the analysis of the process.
3. The energy intensity of the cross-cutting process increased in the order of spruce, beech, and oak. The energy intensity of cutting oak and beech was almost identical.
4. The experiment showed that the energy intensity of the process of cross-cutting depended on the cutting model and increased in the order of front face cutting (M1), slant front face cutting at a φ_2 of 90° (M2), and slant front face cutting at a φ_2 of 45° (M3).
5. These results did not confirm the hypothesis that a higher number of saw blade teeth results in a decrease in the cutting power necessary to separate the layer of wood, thereby decreasing the cutting power.
6. For the cross-cutting process of selected wood species, saw blades with both 24 and 40 teeth were equally suitable.
7. The experiment confirmed a direct correlation between the cutting power and feed force. The cutting power increased with the feed force, and also resulted in a shorter cutting time.

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