Analysis of Cutting Conditions in the Process of Cross-cutting Wood by Circular Saws

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An analysis was conducted of the effects of cutting conditions in the cross-cutting of wood using circular saws. Gradual wear of the saw blade cutting wedges impacted the entire cutting process. Two different types of circular saw blades were used. One blade type featured sintered carbide tips and 54 saw blade teeth, whereas the other had high-speed steel with 56 teeth; both saw-blades were 600 mm in diameter with a rake angle of 20°. The two wood species were spruce (*Picea abies*) and beech (*Fagus sylvatica*). During sawing, the timber was fed at a velocity of v_f = 6 and 12 m·min^{-1}. The cutting speed (v_c) was set at 60 m·s^{-1}, 70 m·s^{-1} and 80 m·s^{-1}. The saw blades were coated with three types of PVD coatings. The least energy intensive saw blade was a sintered carbide-free saw blade with a coating (AlTiN) at a displacement speed of 12 m·min^{-1} and cutting speed of 60 m·s^{-1} with a power of 1310,63 W. Any change of a saw blade considerably affected torque for all the wood species, so a particular type of saw blade will always have an impact on torque. Other parameters distinctively and individually influenced the process of wood sawing.

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INTRODUCTION

The principal roles of the sawmill industry are the intensification of processing of wood as a raw material. Circular saws are widely used for wood cross-cutting. They are used to increase productivity and enhance the cut surface quality and reliability (Streklov 2015).
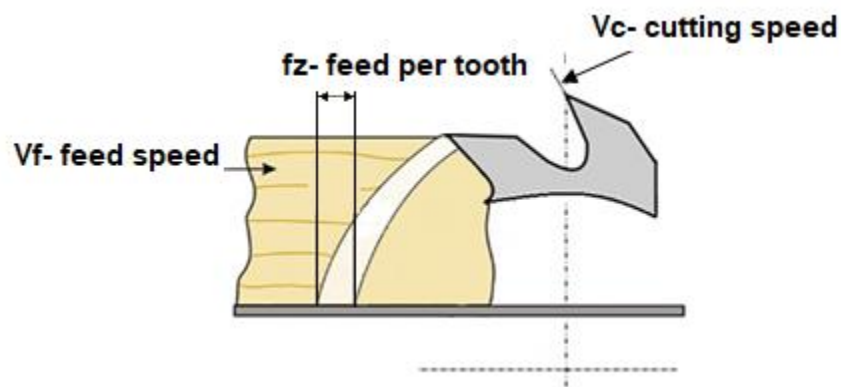

Fig. 1. Saw blade cutting kinematics (Author)

Cutting wood by circular saw blades is a complex process. To achieve ideal operating conditions, it is important to know the mutual interactions among a tool, a product and influence of technical and technological factors affecting the cutting power and final quality of the product. It is possible to obtain the required quality by setting these factors and parameters. Cutting quality is affected by tool wear (Kminiak and Siklienka 2016; Siklienka *et al*. 2017; Krilek *et al*. 2020). Saw blade cutting kinematics are shown in Fig. 1.

Cross-cutting saw blades are frequently used in sawmills to cut round timber, balks, and boards. Such machines are called circular saws or mitre saws. Svoreň (2002) divides cross-cutting operations into two types: preliminary cross-cutting with oversize dimensions and final cross-cutting to the required dimensions.

The crucial cutting tool in the process of cross-cutting is the rotating blade that cuts perpendicularly to wood fibres. The minor teeth cutting edges on the sides of a blade cut through the fibres and form the walls of a kerf. The bottom of the kerf is shaped by the main cutting edges (Lisičan 1982). These cutting edges are most commonly made with sintered-carbide plates, which are referred to as HW plates or tool steel (Banski 2000; Siklienka *et al.* 2012;). Saw blades with HW plates (HW means carbide plates) are more durable and wear-resistant than blades made of tool steel (high-speed steel HSS) (Suchanov 1984). The parameters of the process of wood cutting (energy consumption, dust, and noise), parameters of the worked product (dimensional accuracy and quality of the surface), and the parameters of the particles produced within the process (size and granulometric composition) (Table 1) are largely dependent on the durability of the blade teeth (Streklov 2015).

Table 1. Criteria Influencing the Process of Cutting (Mikleš *et al.* 2010)

Criteria	Workpiece	Machine	Tool
External	Uncut chips cross section' and depth and quality of kerf	Feed rate, cutting forces, cutting speed, vibration, durability, and cutting power	Wear and cutting edge geometry
Internal	Wood species, wood strength, cutting direction towards fibres, moisture content, and wood density	Properties of material and type of material	Properties of material and type of material

According to several studies (Orlicz 1988; Orlowski *et al*. 2006; Orlowski 2007; Scholz *et al*. 2009; Naylor *et al*. 2012), the hardness of the material and the friction between the blade and workpiece are the most important parameters with respect to the particular saw blade tooth geometry. Recent work focusing on cutting mechanics (Atkins 2009; Kopecký and Hlásková 2014; Orlowski *et al*. 2014, 2020) found that the crack resistance of a workpiece (fracture toughness) is of equal importance to force and friction when determining the force and reducing the action of forces.

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 (Barcík and

Gašparík 2014; Krilek *et al.* 2014; Gaff *et al.* 2015; Kvietková *et al.* 2015; Gaff *et al.* 2016; Kminiak and Kubš 2016).

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. 2b). 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. 2a) (Kminiak and Gaff 2015).
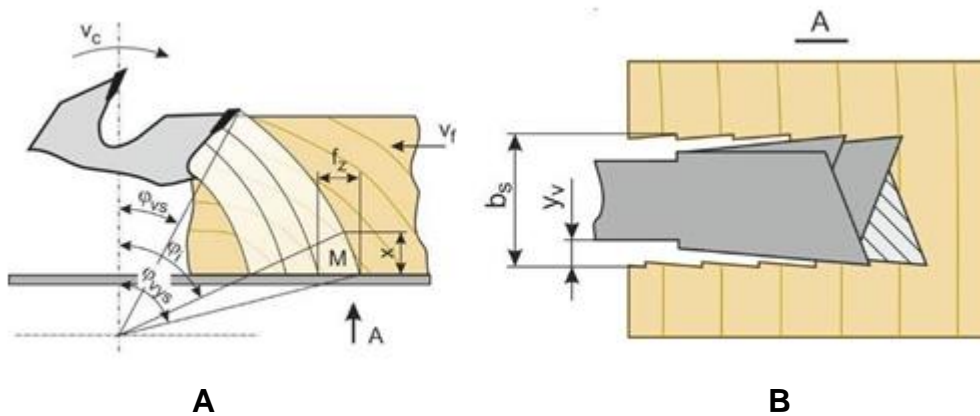
Fig. 2. Mechanism of cut surface creation by sawing: A half-moon shaped traces, and B forming of cut kerf. (Note: *vc* denotes cutting speed, *vf* feed speed, *fz* feed per tooth *φvs* feed angle of the cutting edge entry into the wood, *φvys* feed angle of the cutting edge exit from the wood, *φi* feed local angle corresponding to the monitored point M, *bs* cut gap width, and *yv* saw teeth setting). Copyright publishing illustrations we received from authors (Kminiak and Gaff 2015).

The widespread approach to determining the cutting power in a cutting process is by use of a model based on the specific cutting resistance k_c. Thus, the cutting power could be determined as (Orlowski *et al.* 2020),

$$P_C = F_C.v_C = k_C.A_{Dav}.v_C = k_c.S_t.h_{AV}.v_C \qquad (1)$$

where k_c is specific cutting resistance in (N.mm^{-2}), P_c is cutting power in (W), F_c is cutting force in (N), A_{Dav} is the average cross-sectional area of uncut chip in (mm^2), v_c is cutting speed in (m.s^{-1}), S_t is the overall set (kerf) in (mm), and h_{av} is the average uncut chip thickness in (*mm*).

The power (*P*) can also be calculated by deriving the relation to the torque calculation using the spindle speed,

$$P_C = \frac{M_K.n}{9550} \qquad (2)$$

where P_c is power (kW), M_k is torque (N·m), and *n* is speed (rpm).

The selection of adequate tools with a suitable cutting edge geometry and appropriate cutting conditions can reduce costs associated with sawing wood and thus increase the overall efficiency and cutting accuracy of the process. The energy intensity of the sawing process is commonly defined in terms of cutting output power (Siklienka *et al.* 2013). As specified by STN ISO 3002-4 (1995), the cutting output power defined as k_c indicates the difficulty of the cutting process and depends on various factors that determine cutting conditions, which include technical (influence of cutting parameters and tools) and

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technological parameters (cutting properties of the material). Because wood is an anisotropic material, and its properties vary at different sections of a tree trunk, the theoretical determination of k_c may be considerably complex and inaccurate (Skutko 2004; Siklienka and Mišura 2006).

Coating is used for improvement of saw blade properties in the wood-cutting process. Creation of thin isotropic coating on the functional surfaces of the cutting edge, for instance, can be a highly effective way for improvement of cutting material properties. Different properties for realization of processes evoke the need for a wider range of cutting materials with different chemical, physical, mechanical, and technological properties. (Hrubec 1990, 1988).

EXPERIMENT

The goal of the work was to use theoretical knowledge to prepare an experiment and to find the influence of saw blade coating on energetic consumption and parameters of wood cross-cutting. In practice this means to find values of torque on the crankshaft of the experimental device with respect to the course of frequency of revolutions in the specified conditions and finally to evaluate the results. The chemical composition of coating used in the process of coating by PVD method (*i.e.* Physical Vapour Deposition) was AlTiN, AlTiCrN, and AlTiCrSiN. These coatings were chosen on the basis of recommendations of producers, and they have been used for a very long time in practice. It was the same with cutting parameters (*i.e.* cutting speed, feed speed, type of saw blades, wood), which were chosen on the basis of previous experiments, measurements, and calculations.

Materials

The measurements of wood cross-cutting were taken on the testing machine (Fig. 3). All measurements of the cutting conditions were obtained from the Stend testing machine. The experimental device was designed, constructed, and further developed at the Department of Environmental and Forestry Machinery and in the workshops of the Technical University in Zvolen (Zvolen, Slovakia). The testing machine was composed of two main members, which included the feeding system and the cutting system.
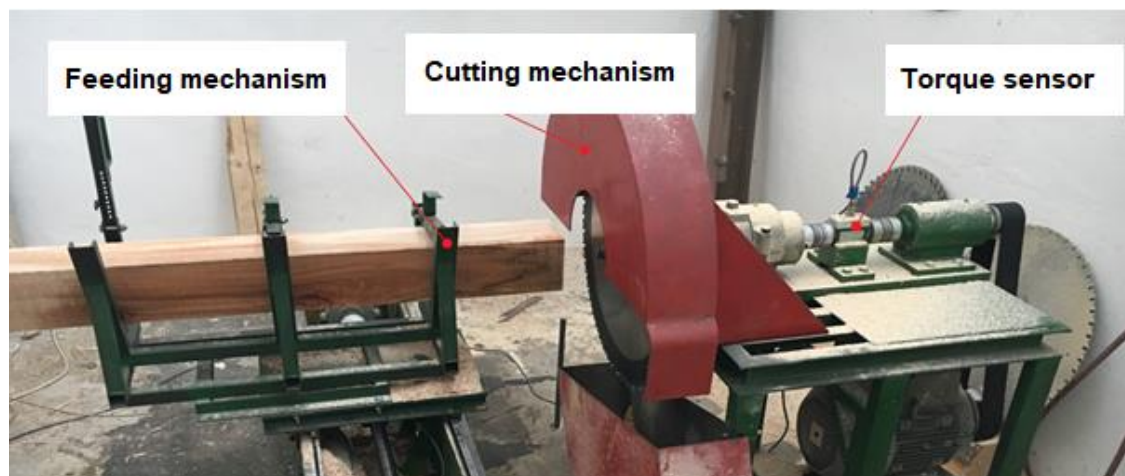

Fig. 3. Experimental device

The force and action of torque was transferred onto the saw blade *via* the cutting system (cutting mechanism). The sliding member ensured safe clamping and feeding of the workpiece. The test equipment (Fig. 3) consisted of a feeding mechanism, cutting mechanism, and a three-phase asynchronous motor with an output of 7.5 kW. The torque was transmitted through the belt of a safety coupling GIFLEX GFLL - 28 (Hottinger Baldwin Messtechnik GmbH T20WN, Darmstadt, Germany), an input coupling of the torque sensor (Hottinger Baldwin Messtechnik GmbH T20WN, Darmstadt, Germany), the output coupling of the torque sensor, and a saw-blade spindle head.

Test Samples

The measurements were performed on the samples of spruce wood (*Picea abies*) (Technical University in Zvolen, Forestry Industry Zvolen, Zvolen, Slovakia) and beech wood (*Fagus sylvatica*) (Technical University in Zvolen, Forestry Industry Zvolen, Zvolen, Slovakia) with the dimensions of 200 mm × 200 mm × 1000 mm. The dimensions were selected based on the technical parameters of the testing machine.

Moisture readings were obtained *via* gravimetric analysis, which is a direct method to measure wood moisture by weight measurement. The principle of this method lies in evaluating a weight difference between wet and dry timber. Drying took place at 103 °C ± 2 °C in a MEMMERT UNB 200 drying oven (MEMMERT GmbH+Co.KG, Schwabach, Germany). The measurements of wood moisture are listed in Table 2.

Table 2. Moisture Content

Wood Species	Moisture Content (%)
Beech	61.22
Spruce	46.91

Saw Blades

The saw blades had the same cutting tooth geometry but different cutting tooth structures. The samples were cut by circular saws made with cemented carbide plates and of high-speed steel (their technical parameters are shown in Table 3).

Table 3. Basic Dimensions of Circular Saws

Basic dimensions	Diameter of a saw D (mm)	Width of a saw B (mm)	Cutting-clearance angle $\alpha(°)$	Cutting-edge side rake (°)	No. of teeth
Circular saw made of high-speed steel	600	5.4	20	-5, 0, 5, 10	56
Circular saw made with cemented carbide plates	600	5.4	15	-10, 0, 10, 20	54

One pair of saw blades (HSS, sintered carbide) was without coating, the second pair of saw blades was coated by PVD coat MAXIMIZER AlTiN (HSS_M, sintered carbide_M), the third pair of saw blades was coated by PVD coat CRONAL I. AlTiCrSiN (HSS_C_I, sintered carbide_C_I).

PVD coat MAXIMIZER (M) is on the basis of aluminium-titanium-nitrogen (AlTiN). It is suitable for medium cutting speed. The producer indicates $f_t = 0.6$ as a frictional coefficient. Coat AlTiN was spread for the temperature 500 °C. The frictional coefficient was 0.6. The thermal resistance is generated by the friction of the working surfaces of the wood cutting process was 800 °C.

PVD coat CRONAL I. (C_I) is on the basis aluminium-titanium-chromium-silicon-nitrogen (AlTiCrSiN). It is resistant to wearing. PVD coat CRONAL I. has of high content of chromium (Cr). It is especially designed for extreme cutting conditions in processing of hard materials. AlTiCrSiN coat was spread for temperature up to 500 °C. The frictional coefficient is 0.45. The thermal resistance in the cutting process when using another material reaches a temperature of up to 1,000 °C.

PVD coat KTRN I. (K_I) is on the basis of aluminium-titanium-chromium-nitrogen (AlTiCrN). It is resistant to high temperatures and wearing. PVD coat KTRN is suitable for application where chemical and thermal resistance are required. AlTiCrN coat is spread up to temperature of 500 °C. The frictional coefficient is 0.45.

Measuring Procedure

The experiment was performed by comparing two saw blades at different feeding speeds ($v_f = 6$ m·min^{-1} and 12 m·min^{-1}), rotational speeds (n = 1900 min^{-1}, 2230 min^{-1}, and 2550 min^{-1}), and cutting speeds ($v_c = 60$ m·s^{-1}, 70 m·s^{-1}, and 80 m·s^{-1}). The samples of beech wood and spruce wood were used. Each measurement was repeated several times to acquire adequate statistical significance. The samples were placed 50 mm below the axis of the spindle. The outcome of the experiment indicated the large influence of torque on the cutting process. The torque was measured by a HBM T20WN torque sensor (Hottinger Baldwin Messtechnik GmbH T20WN, Darmstadt, Germany), and a SPIDER8 electronic measurement system (Hottinger Baldwin Messtechnik GmbH T20WN, Darmstadt, Germany) was used for measurement of the mechanical quantities. The results were processed and evaluated using STATISTICA 12 software (DataFriends, s.r.o., vesion 12, Plzeň, Czech Republic).

RESULTS AND DISCUSSION

The aim of the measurements was to determine the extent to which changing factors such as cutting speed, saw blade type, wood species, and feeding speed, affect the amount of torque (cutting power) in the process of wood cutting.

On the basis of significance level (Table 3) and multifactorial analysis (ANOVA) of measured values it is a clearly visible influence of all factors and their interactions. From Table 3, in the case of spruce wood, the change in rotation speed had no effect on the torque and thus on the cutting power of the sintered carbide saw blade. Except in one case, the change in rotation speed did not affect the cutting performance of the high-speed saw blades. However, the results for beech samples were not so clear. The change in speed in most cases affected the cutting performance. Both spruce and beech wood samples affected the cutting performance by changing the feed rate observed with the high-speed saw blade and the saw blade with sintered carbide inserts. The type of saw blade used affected the cutting force of all woods, the feed rate and the rotation speed. Other parameters affect the type of wood, such as the feed rate, which is more observable at higher speeds.

Table 3. Basic Table of Multifactor Analysis of Power for Saw Blade, Wood, Feed and Cutting Speed

Effect	Sum of squares	Degree of freedom	Sample of variance	F-test	p-value (sign. level)
Overall average	6.16410E+09	1	6.164104E+09	2559047	0.000000
Wood	1.61793E+04	1	1.617926E+04	7	0.009696
Saw blade	8.30450E+07	7	1.186356E+07	4925	0.000000
v_f	1.57358E+06	3	5.245258E+05	218	0.000000
v_c	1.26214E+08	2	6.310716E+07	26199	0.000000
Wood* Saw blade	2.43738E+06	7	3.481973E+05	145	0.000000
Wood*v_f	2.82974E+05	3	9.432451E+04	39	0.000000
Saw blade*v_f	7.71179E+06	21	3.672282E+05	152	0.000000
Wood*v_c	1.97527E+04	2	9.876362E+03	4	0.016860
Saw blade*v_c	9.13491E+05	14	6.524935E+04	27	0.000000
v_f*v_c	7.94450E+04	6	1.324083E+04	5	0.000013
Wood*Saw blade*v_f	2.74159E+06	21	1.305520E+05	54	0.000000
Wood* Saw blade*v_c	3.69769E+05	14	2.641210E+04	11	0.000000
Wood*v_f*v_c	1.49015E+05	6	2.483582E+04	10	0.000000
Saw blade*v_f*v_c	1.01259E+06	42	2.410928E+04	10	0.000000
Wood* Saw blade*v_f*v_c	8.46919E+05	42	2.016474E+04	8	0.000000
Error	2.31240E+06	960	2.408750E+03		

The cutting power increased with increasing cutting speed and it is also possible to see the difference between the saw blades on the graph of 95% confidence interval (Fig. 4). M-coated saw blades had lower energy consumption than other coatings and uncoated saw blades.

The results obtained are shown in Fig. 5 where the difference between the torque of the sawing of spruce wood and the sawing of beech wood was apparent.

In Figs. 6, 7, and 8 there are presented results of 95% confidence interval for mean power values depending on saw blades, wood and cutting feed speed. With increasing cutting speed there is also increased energetic consumption. The significant difference in performance is in case of coated and uncoated saw blades except the saw blade with coating MAXIMIZER (M) where the performance was the lowest.

This study was built on previous findings by Siklienka *et al.* (2013) and Krílek *et al.* (2014), which was why saw blades with a 20° cutting edge angle were selected, as previous research indicated that they were most effective.

In cutting with HSS steel saw blades, the progress of Cutting Power was defined by a rapid increase until reaching the maximum value, which was followed by mild decline and then a rapid decrease. The rapid decline was caused by the end of the wood cutting operation. The same results were obtained by Kováč and Mikleš (2009).
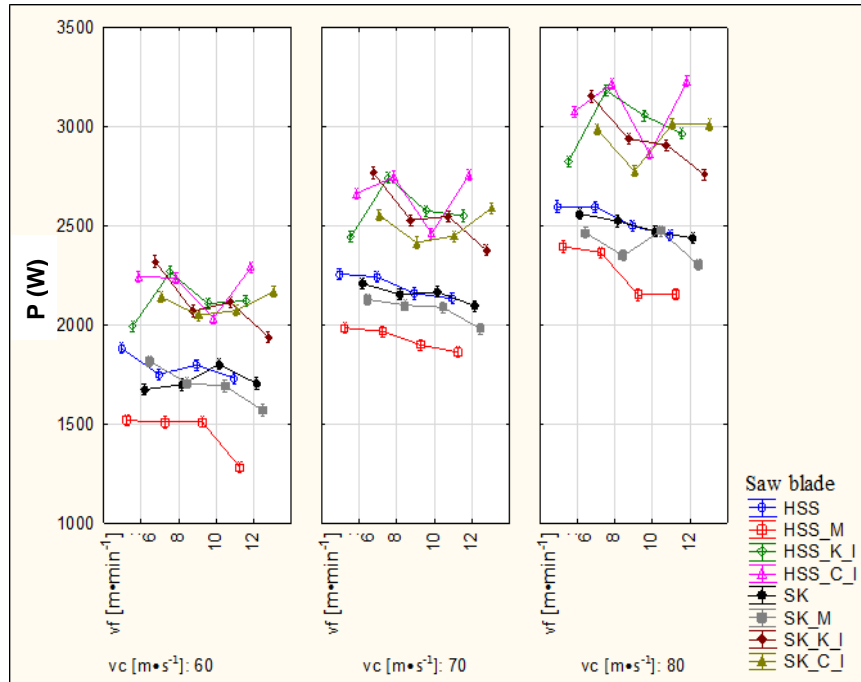
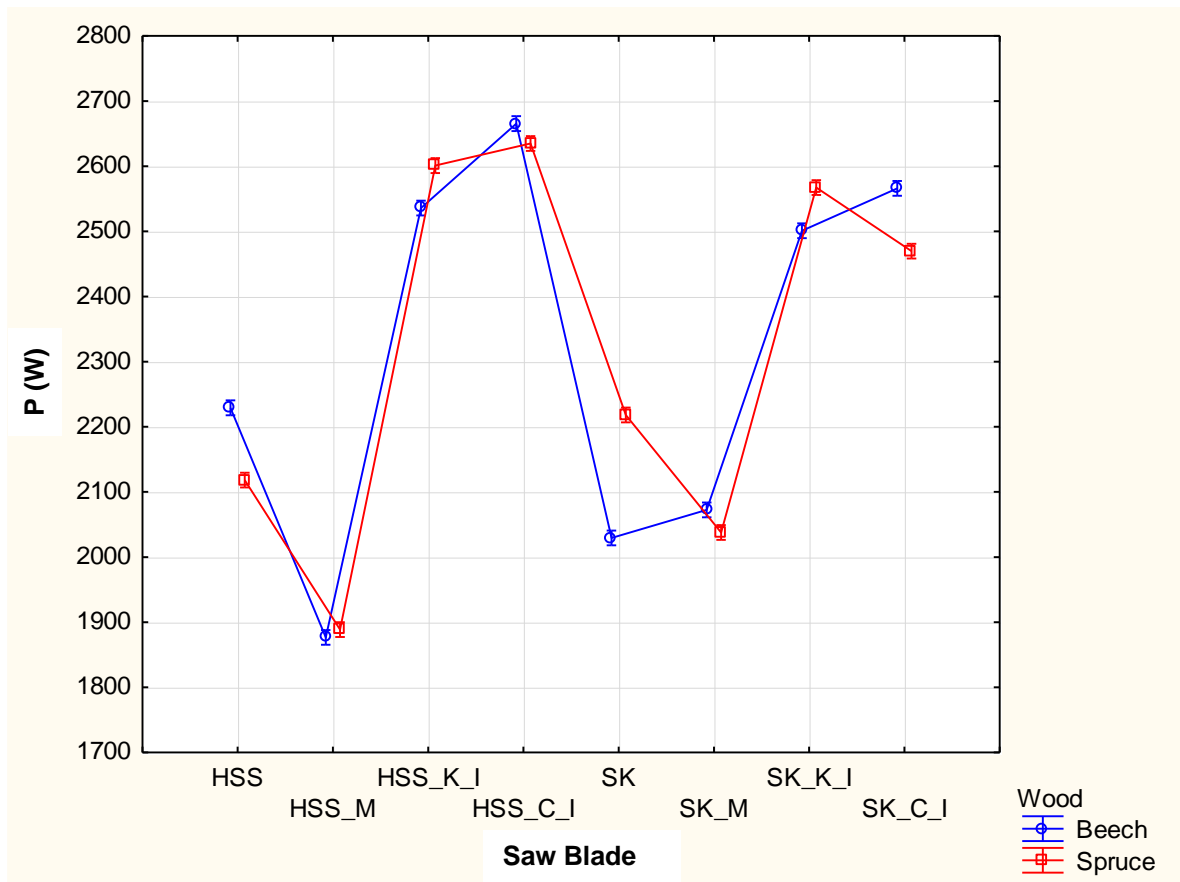**Fig. 4.** 95% confidence interval for mean power values depending on saw blades, cutting and feed speed

Fig. 5. 95% confidence interval for mean power values depending on saw blades and wood
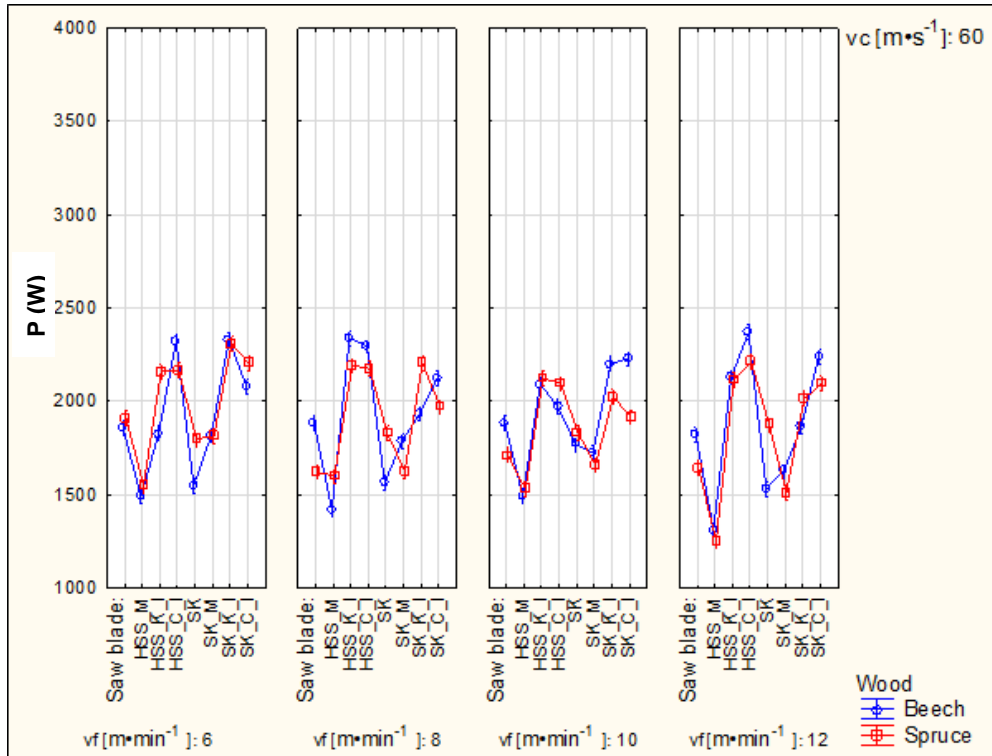
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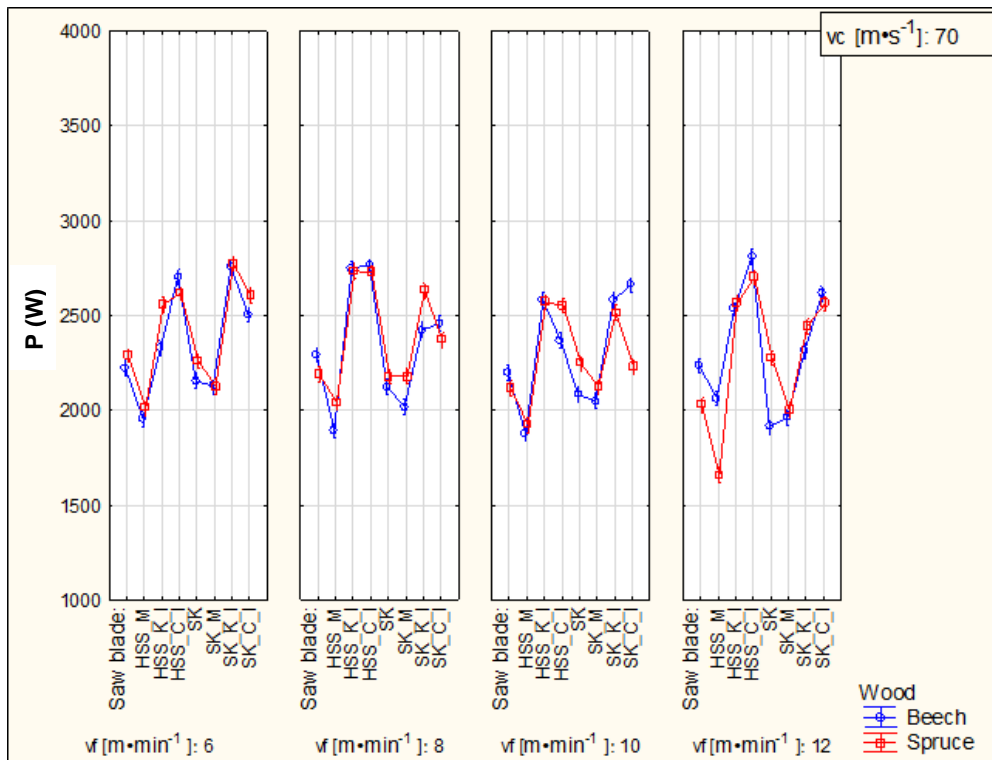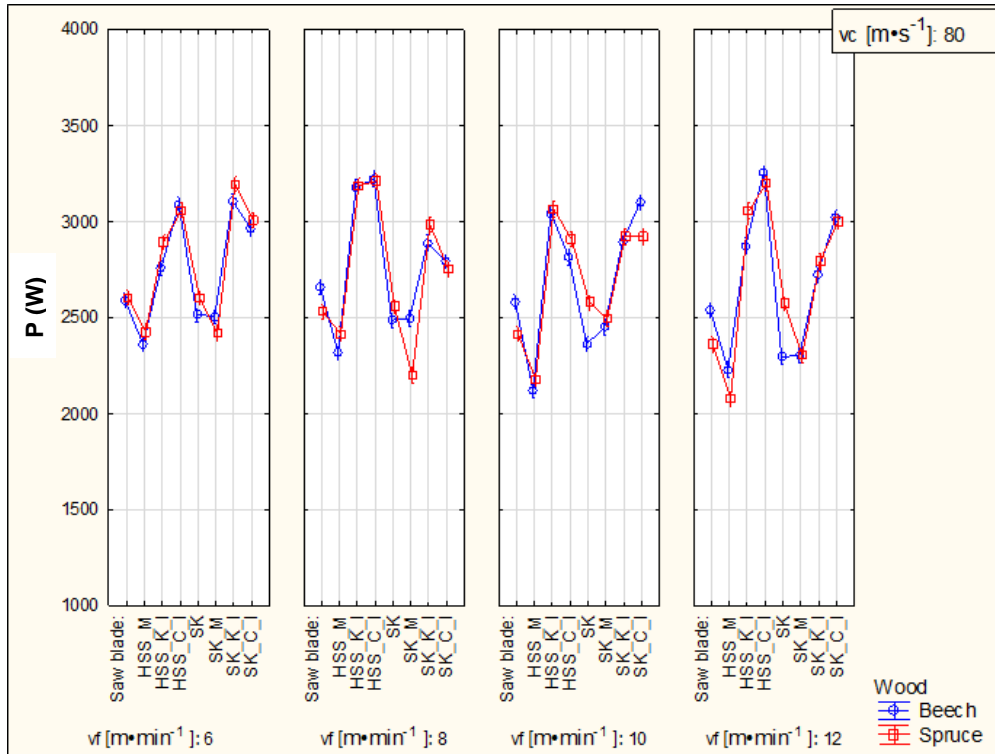**Fig. 6.** 95% confidence interval for mean power values depending on saw blades, wood, cutting feed speed (v_c= 60 m.s^{-1})

Fig. 7. 95% confidence interval for mean power values depending on saw blades, wood, cutting feed speed (v_c= 70 m.s^{-1})

Fig. 8. 95% confidence interval for mean power values depending on saw blades, wood, cutting feed speed (v_c= 80 m.s^{-1})

Based on the change of the input factors that interacted in the cutting process (feed speed (v_f), minimum overhang, and type of circular saw blade), feed rate (v_f) appeared to be the most important determinant of energy performance in the cutting process and thus cutting input power. From the measured values, it can be noted that the PVD coating MAXIMIZER (AlTiN) had a positive effect on the energy intensity of the wood cutting process and reduced the magnitude of the cutting power when sawing beech and spruce trees. PVD coatings KTRN I. (AlTiCrN) and CRONAL I. (AlTiCrSiN) did not show a positive effect on the cross-cutting process of wood and increase the energy intensity of the process. The authors think this is due to the surface treatment process, which was different from the MAXIMIZER surface treatment, and its treatment could improve the resulting performance values.

CONCLUSIONS

1. The possibility of verifying the calculation of the torque and construction of the teeth of the saw blades had a fundamental impact on the energy intensity of the production of different types of wood.

2. The least energy-intensive saw blade was a saw blade without sintered carbide with a surface treatment (AlTiN), for sawing beech wood.

3. The least energy intensive saw blade is a sintered carbide-free saw blade with a coating (AlTiN)

4. The conditions under which the experiments were performed mimicked real-world conditions. Therefore, it was possible to compare the results of this study with those of other research institutions.

ACKNOWLEDGMENTS

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