Wood Crosscutting Process Analysis for Circular Saws

Jozef Krilek, Ján Kováč,* and Marián Kučera

This article deals with the influence of some cutting parameters (geometry of cutting edge, wood species, and circular saw type) and cutting conditions on the wood crosscutting process carried out with circular saws. The establishment of torque values and feeding power for the crosswise wood cutting process has significant implications for designers of crosscutting lines. The conditions of the experiments are similar to the working conditions of real machines, and the results of individual experiments can be compared with the results obtained *via* similar experimental workstations. Knowledge of the wood crosscutting process, as well as the choice of suitable cutting conditions and tools could decrease wood production costs and save energy. Changing circular saw type was found to have the biggest influence on cutting power of all factors tested.

Keywords: Circular saw; Cutting power; Torque; Cutting edge geometry

*Contact information: Technical University in Zvolen, Faculty of Environmental and Manufacturing Technology, Department of Forest and Mobile Technology, T. G. Masaryka 24, 960 53 Zvolen, Slovakia; *Corresponding author: kovac@tuzvo.sk*

INTRODUCTION

Crosscutting of wood is often used during the exploitation of forest resources. It is used to cut down trees, shorten trunks, and produce assorted wood products. Research performed regarding the optimum wood machining conditions (Eyma *et al.* 2004; Méausoone 2001) has shown that there are generally three basic factors affecting the cutting process: factors attributed to the device, factors associated with wood species, and the moisture content of the wood.

Factors that are considered to have a significant effect on the torque are the depth of cut, the rake angle, and the edge radius. The torque increases with depth of cut, increases with edge radius, and decreases with rake angle. Furthermore, cutting the wood end grain yields the largest torque, while the lowest is observed when cutting along the fiber direction. Work-piece parameters have been used as predictors in statistical modeling to describe torque trends. Often used parameters are density, moisture content, and grain direction. The density does not dramatically change with respect to moisture content as a result of this change in volume. It is generally accepted that tool forces decrease with increasing work-piece moisture content, although an exception to this rule has been found for frozen wood samples. Increased moisture content for frozen wood leads to an increase in tool forces. Furthermore, work-pieces at decreasing sub-zero temperatures are subject to increasingly higher tool forces.

The reason torque increases with increasing cutting speed is that the feed per tooth decreases and the chip thickness consequently decreases. It is known that cutting resistance is greater for small chip thicknesses; as a result, the torque increases when the chip thickness decreases (Barcík *et al.* 2008).

A tool is considered worn when the wedge has reached a critical state accompanied by an intolerable degradation in quality of the work-piece surface, an undesirable increase in cutting power, burning, or dimensional inaccuracy of the work-piece (Šustek and Siklienka 2012). In this study, extensive and accurate measurements and evaluations of torque in various types of solid wood were carried out. The results obtained can help in dimensioning the machine and tool equipment of dimension saws and at the same time, in optimizing technological conditions of machining in order to prevent unnecessarily high energy consumption and damage to machines and tools (Kopecký and Rousek 2005).

THEORETICAL BACKGROUND

Crosscutting Wood with Circular Saws

Figure 1 shows the reciprocal relations between wood and the cutting wedge generated when wood is penetrated by the tooth of a circular saw (Kováč and Mikleš 2010). The cutting wedge presses on the resisting wood. The result is a load on the frontal, rounded, and back surfaces of the cutting wedge. The cutting resistance is created as the chip is separated by the wedge. The cutting resistance is a reaction to the cutting force; it has the same size but is in the opposite direction.

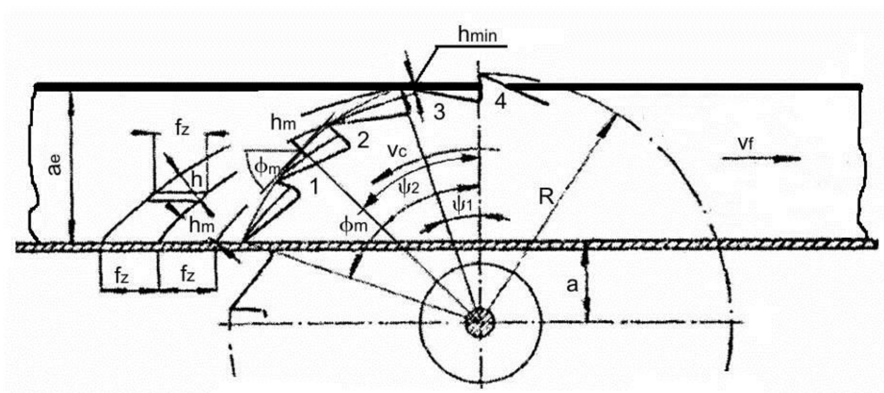

Fig. 1. Illustration of a circular saw cutting wood: *fz* – feed per one tooth [m.s^{-1}], a_e – cutting height [m], v_f – feeding speed [m.s^{-1}], v_c – cutting speed [m.s^{-1}], ψ_1 – incoming angle of a circular saw [°], ψ_2 – outgoing angle of a circular saw [°], φ_m – mean angle of cutting fibres [°], h_m – mean thickness of a chip [mm]

The resistances acting against the cutting wedge of a circular saw tooth can be summed as one resultant force F, the cutting resistance. F consists of the following:

- forces necessary for cutting a work piece using a cutting wedge *via* deformation of the piece surrounding the cutting edge,
- forces necessary for the deflection of chips and the overcoming of the chip's friction against the leading edge of the tooth, and
- forces necessary for suppression of friction on the back and leading surfaces in contact with the machined surface.

Defining the values of individual parts of the force F is quite difficult and depends on many factors. The component of the force F in the direction of cutting feed is called the cutting force and is used for practical calculations of energy expenditure during the cutting process.

The cutting force F on a tooth of a circular saw acts on chips of width b and thickness h *regarding to* the cutting resistance for disintegrated material K:

$$F = \frac{K.b.h.v_f}{60.v_c} \quad \text{[N]} \qquad (1)$$

The cutting power P_c is defined as the product of cutting force F and cutting speed:

$$P_c = \frac{F \cdot v_C}{1000} \quad \text{[W]} \qquad (2)$$

It is also possible to calculate the cutting power P_c *via* torque M_k, and the diameter of a circular saw D as:

$$P_c = \frac{2 \cdot M_k \cdot v_c}{D} \quad \text{[W]} \qquad (3)$$

Cutting Conditions during Woodcutting Performed by Circular Saws

Modern circular saw blades for crosscutting wood-based materials are equipped with various adjustable components (Vesely *et al.* 2012). The following are types of circular saws, classified by the shape of their cut: flat, relieved, concurrent, and saddle. They differ in tooth profile and the method of sharpening. The tooth profile and the method of sharpening depend on the required performance of the saw and the required quality of the machined surface. They must be varied according to the type of work piece (soft/hard wood and other types of work pieces) and the material of the cutting edge (tool steel/cemented carbide plates).

On each circular saw, there is marked a maximum revolution speed of 100 $m.s^{-1}$. This speed is not the maximum functional speed; instead, it represents the maximum operationally reliable speed guaranteed by a producer. To achieve the optimal performance of a circular saw, it is necessary to choose cutting conditions based on the material to be cut. The recommended cutting speeds for circular saws are 60 to 100 $m.s^{-1}$ for softwood and 50 to 85 $m.s^{-1}$ for hard and exotic wood.

The recommended cutting speed for a chosen material depends on the requirements of cutting surface quality, the technological state of the machine, and other factors. Deviating from the recommended cutting speed is economically impractical. Circular saws are used in the manipulation of trunks with diameters in the range between 400 and 500 mm. Their advantages include a high cutting ability, maintainability, and long lifetime.

In practice, it is important to carry out the whole cutting process with the lowest energy consumption possible. Many factors influence torque, including the choice of a suitable cutting tool material, its geometry, and the optimal cutting conditions (cutting speed v_c and feeding speed v_f). The cutting power is a very important factor affecting energy consumption. The cutting-wedge angle β determines the performance of a tool and a machine, machined surface quality, and dimensional exactness of a work piece.

When the cutting-wedge angle, β (*i.e.*, the angle of the cutting part of a tool) increases, the cutting resistance of a material also increases. Cutting resistance is lowest when the cutting angle is as small as possible, but when the cutting angle is under a certain value, the hardness of a cutting edge is very low and it quickly wears out. To define a cutting-wedge angle, there must be defined values of the angles α and γ.

Friction between the cutting surface and the processed surface influences the cutting clearance angle, α. When this angle is small, the friction is high. This effect is caused by decreasing the cutting clearance angle between the cutting clearance and the processed surface directly behind the cutting edge. This surface gradually increases with higher wear of the cutting edge because a rounded, worn cutting edge does not cut material efficiently. It is mainly in the plane passing the lowest point of a cutting edge but it is also in the plane lying a little bit higher. The cutting clearance angle has direct influence on the dimension of cutting resistance and the work required to cut a piece. Typically, the cutting clearance angle is between 10 and 30°.

The cutting-edge side rake influences the chip creation process and the size of chips. The optimal value also depends on the type of processed material, direction of fibers, and dimension of feed on the piece's edge or the thickness of a chip.

EXPERIMENTAL

Materials and Methods

The experimental measuring device was developed for studying crosswise woodcutting parameters performed mainly by circular saws. It is shown in Fig. 2 (Kováč and Mikleš 2009). The measuring equipment consists of a cutting and a feeding part. The cutting part provides energy and transfers torque to a circular saw. The feeding part provides work to clamp the wood down and feed it into the cutting part.

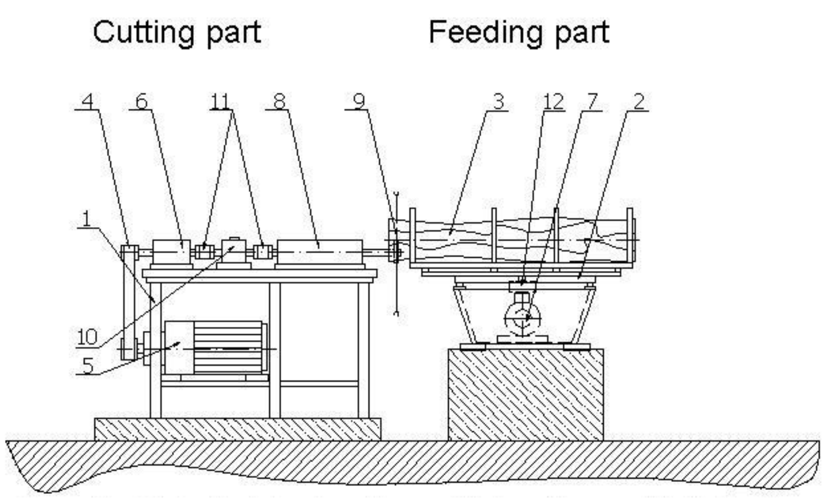

Fig. 2. Illustration of the experimental measuring device: 1 - a working table, 2 - a sliding line, 3 - a trunk of round timber, 4 - belts to drive the circular saw, 5 - an electric engine to drive the circular saw, 6 - a bearing cover, 7 - an electric engine to push the material to the cut, 8 - a spindle head of a circular saw, 9 - a circular saw, 10 - a T20WN recording device for torque and rotational speed, 11 - a GFLL-28 clutch, 12 - an S2 force recorder

As shown in Fig. 2, there is a three-phased asynchronous 7.5 kW electric engine. Its torque is transferred through the spindle head to a tool (circular saw). The wood sample is held on the plate within the holder by a lever system. The crosswise feeding force for of the work-piece is provided by a 5.5 kW electric engine with a safety clutch and a feed screw. Between the nut and the plate, there is an HBM S2 force sensor. Cables transfer measured force and torque signals to the SPIDER-8 measuring center, which is connected to a PC. The HBM T20WN torque sensor measures the rotational speed of the circular saw. Frequency converters with vector control regulate the rotational speed and the power of the electric engines.

In the experimental tests, wood trunk freshly cut (green) samples with dimensions of 150 x 150 mm and lengths of 1.5 m were used. The wood samples were prepared directly before the measurement. The samples with the mentioned dimensions were cut from the trunk at the diameter of 250 mm. The wood trunk samples were beech and spruce. Their moisture was approximately 45% (spruce) and 50 to 60% (beech). The use of these conditions is also supported by experimental work of Klement *et al.* (2010).

The samples were cut by circular saws with cemented carbide plates and with high-speed steel blades. The used circular saws were designed in SolidWorks 3D CAD solutions by authors of the paper and produced by STELIT, Ltd. The technical parameters of the circular saws are shown in Table 1).

Table 1. Basic Parameters of Circular Saws

Basic dimensions	Diameter of saw D (mm)	Thickness of saw B (mm)	Cutting-clearance angle α(°)	Cutting-edge side rake γ (°)	No. of teeth
Circular saw made of high speed steel (HSS)	600	3.5	20	-5, 0, 20	56
Circular saw made of cemented carbide plates (CCP)	600	3.5	15	-5, 0, 20	54

The material properties of circular saw blades according to grades are shown in Table 2.

Table 2. Material Properties of Circular Saw Blades

Circular saw blade type	Material definition	
Circular saw made of high speed steel (HSS)	Grade	HS 18-0-1 EN ISO 4957 : 2000 - High-speed tool steel
Circular saw made of cemented carbide plates (CCP)	Grade	ISO Code – K20

All observed circular saw blades had convex construction of the clearance surface of the circular saw blade teeth, concave construction of the rake surface of the circular saw blade teeth, and concave construction of the side surface of the circular saw blade teeth. More precise information about of the circular saw blade teeth for both types of observed materials is shown in Figs. 3 and 4.

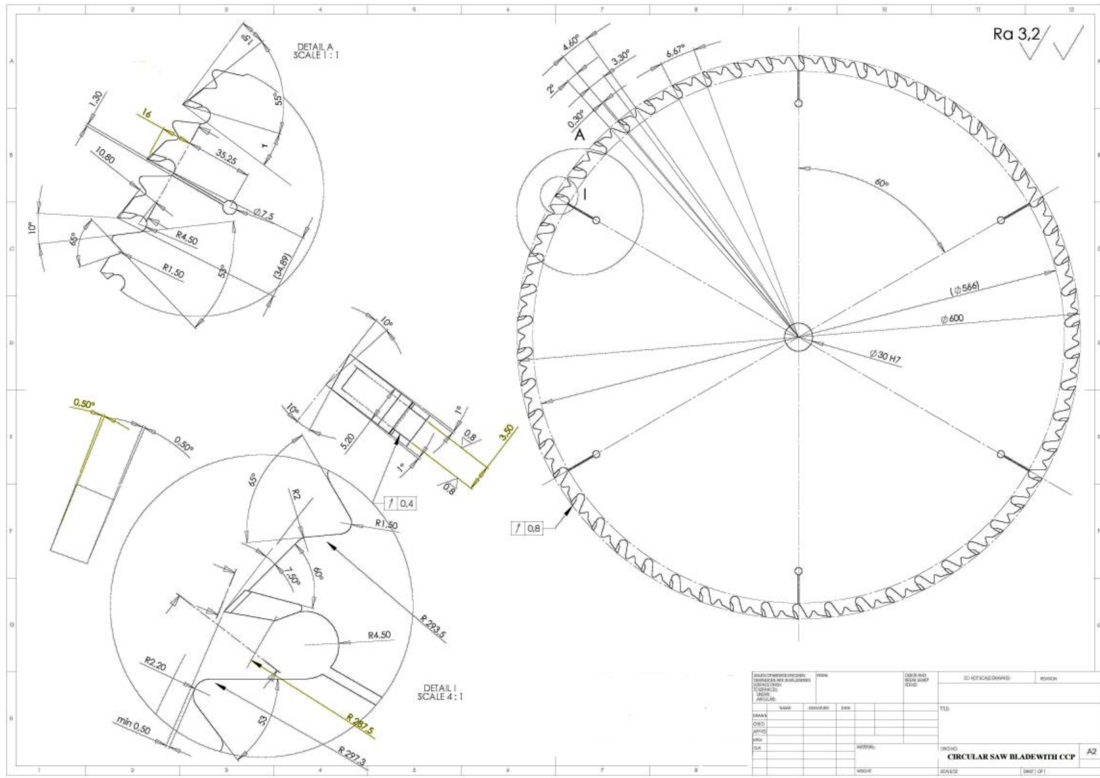

Fig. 3. Teeth parameters for a circular saw blade made of cemented carbide plates (CCP)

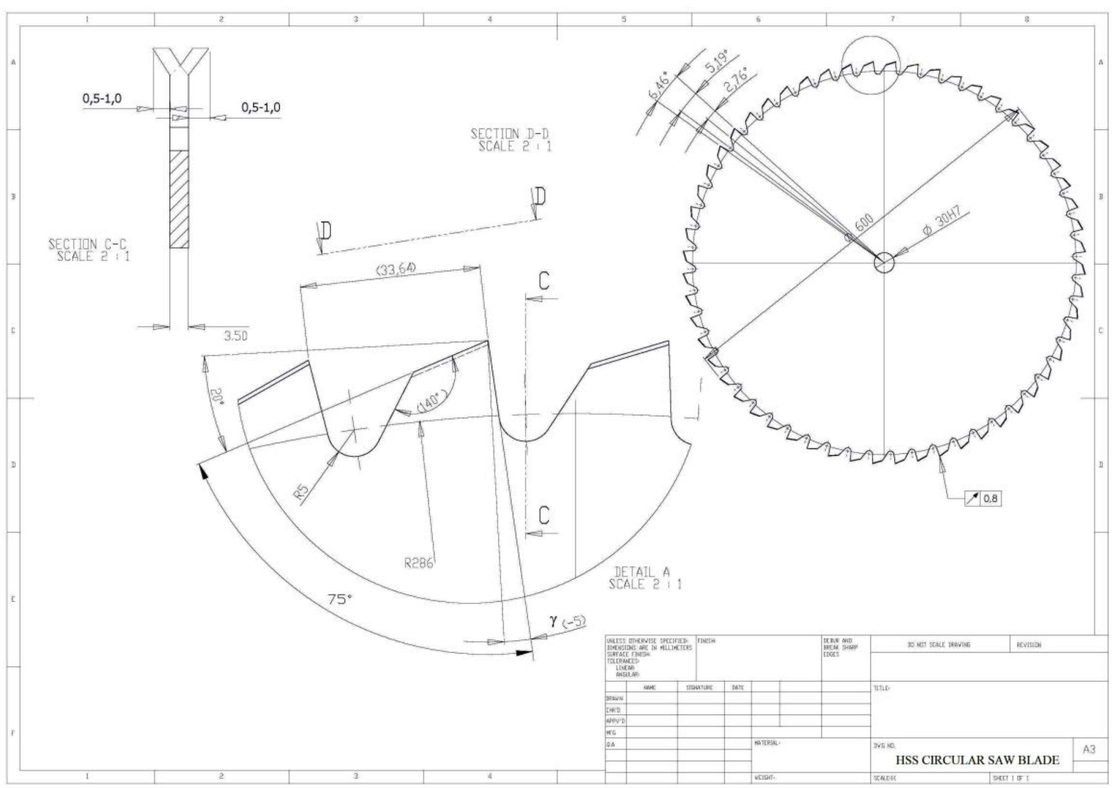

Fig. 4. Teeth parameters for a circular saw blade made of high speed steel (HSS)

The measurements for beech and spruce were performed at 1900, 2230, and 2550 min^{-1}, with cutting speeds (v_c) of 60, 70, and 80 m.s^{-1} and feeding speeds (v_f) of 6, 8, 10, and 12 m.min^{-1}.

Every cutting test was performed 30 times for every observed item, *i.e.* each wood species (beech and spruce), each type of a circular saw, and each cutting and feeding speed. The thickness of the cutting layer (*i.e.* chip thickness) was the same for all circular saws, and it was 5.4 mm.

One purpose of the experiments was to determine the influence of different cutting-edge side rakes on the torque value and compressive force of the cut. The results were analyzed in the CONMES SPIDER program.

RESULTS AND DISCUSSION

The cutting-edge side rake influences cutting resistance and therefore the whole process of crosswise woodcutting. Figure 5 shows a great increase of measured value at the beginning of the tool's penetration of the wood, followed by a decrease as a result of inertia of the circular saw and completion of the cutting process. Afterwards, the cutting process runs at a constant value (the torque value is changed very little), only rotating without any loading at the end of the process. The course of torque M_k during the cutting process of circular saws made of high-speed steel (Fig. 6) is characterized by a rapid increase to a maximum value, a small decrease to an intermediate value, and a rapid decrease as the cut is completed.

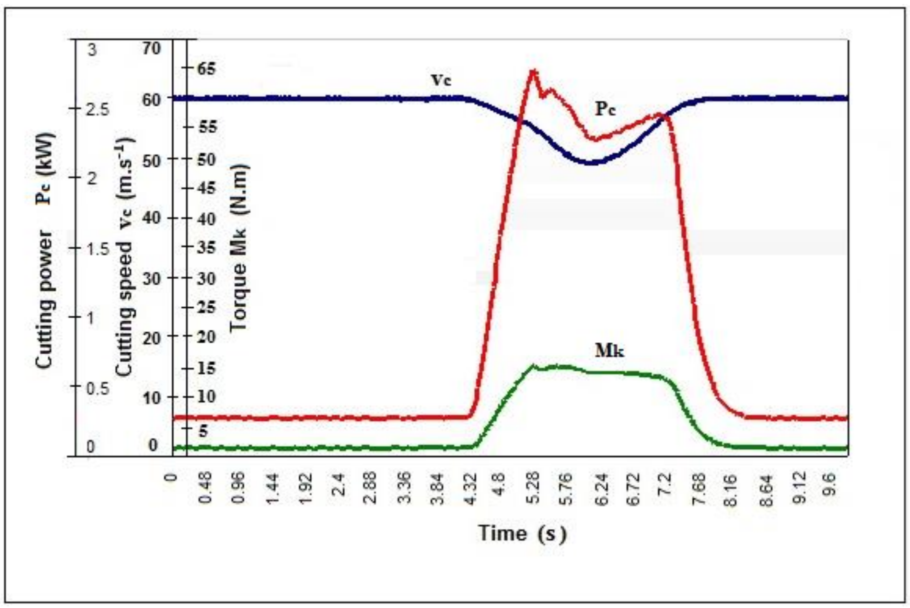

Fig. 5. The course of M_k during the crosscutting process of beech sawn by a circular saw made of cemented carbide plates with a cutting-edge side rake of 20°

The output of the experimental measurement represents measured values of torque recorded during the experiment and are shown in Tables 3 and 4. Obtained values are defined according to different criteria like wood species, cutting-edge side rake, cutting speed v_c, feeding speed v_f, and mean torque values M_k. Mean torque values for individual feeding speeds were calculated from 30 measurements for individual feeding speeds. Graphs were created on the basis of values worked out by ANOVA from the previous measurements. Graphical and statistical evaluations are shown in Figs. 7, 8, 9, and 10.

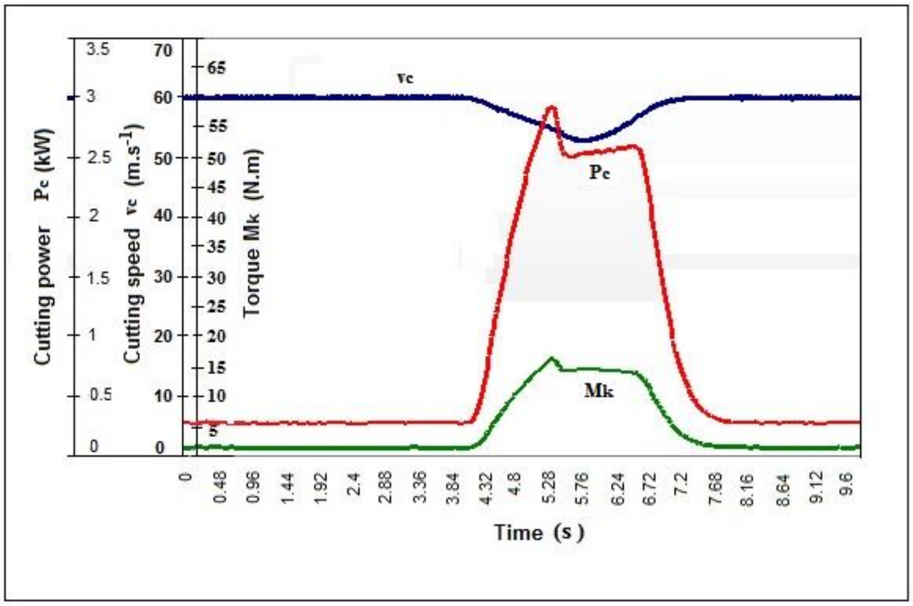

Fig. 6. The course of M_k during the crosscutting process of beech sawn by a circular saw made of high speed steel with a cutting-edge side rake of 20°

The experiment was designed to consider three values of cutting angles (-5°, 0°, and 20°) for evaluating cutting performance because there is thought to be a negative value of cutting angle with the smallest values of M_k.

In Figs. 7 and 8 there is shown an influence of feeding speed v_f on torque M_k in the case of the circular saw blade type. It is clear from the graphs that feeding speed v_f did not exhibit significant influence on the torque M_k during evaluation of individual cutting speeds v_c.

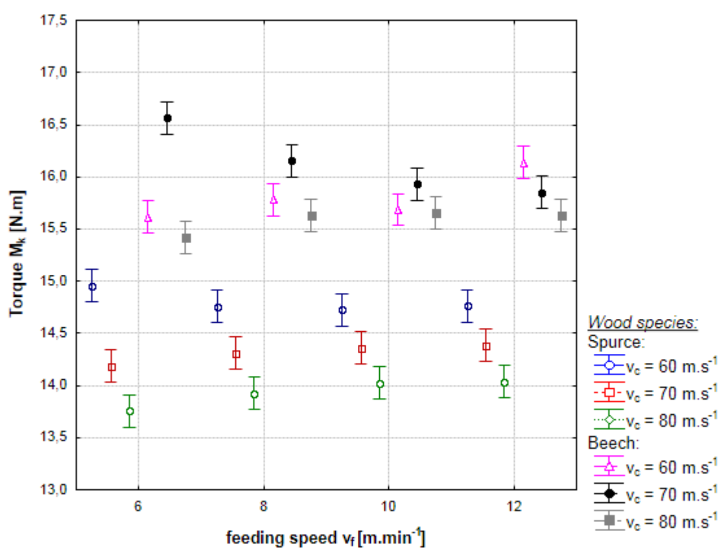

Fig. 7. The influence of feeding speed v_f on torque M_k for different wood species

Table 3. Measured Values of Torque during Wood Crosscutting Process Performed by Circular Saw Made of High Speed Steel (HSS)

No.	Wood species	Cutting-edge side rake [°]	Cutting speed v_c [m.s^{-1}]	Feeding speed v_f [m.min^{-1}]	Mean torque values M_k [N.m]	No.	Wood species	Cutting-edge side rake [°]	Cutting speed v_c [m.s^{-1}]	Feeding speed v_f [m.min^{-1}]	Mean torque values M_k [N.m]
1.	Beech	-5	60	6	15.805	37.	Spruce	-5	60	6	15.398
2.				8	14.825	38.				8	16.003
3.				10	14.712	39.				10	16.022
4.				12	15.002	40.				12	15.948
5.			70	6	18.173	41.			70	6	15.295
6.				8	14.91	42.				8	15.583
7.				10	14.158	43.				10	15.567
8.				12	14.405	44.				12	15.903
9.			80	6	14.845	45.			80	6	14.808
10.				8	15.122	46.				8	15.367
11.				10	14.603	47.				10	15.437
12.				12	14.515	48.				12	15.6
13.		0	60	6	15.605	49.		0	60	6	15.592
14.				8	15.612	50.				8	16.068
15.				10	15.185	51.				10	15.942
16.				12	15.338	52.				12	15.862
17.			70	6	16.477	53.			70	6	14.602
18.				8	16.198	54.				8	15.105
19.				10	16.378	55.				10	15.357
20.				12	16.012	56.				12	15.203
21.			80	6	14.478	57.			80	6	14.17
22.				8	15.18	58.				8	14.285
23.				10	15.203	59.				10	14.39
24.				12	15.745	60.				12	13.975
25.		20	60	6	15.367	61.		20	60	6	17.058
26.				8	15.663	62.				8	13.65
27.				10	15.617	63.				10	13.342
28.				12	15.715	64.				12	13.697
29.			70	6	17.083	65.			70	6	13.692
30.				8	16.655	66.				8	13.45
31.				10	16.79	67.				10	13.37
32.				12	15.768	68.				12	13.392
33.			80	6	15.888	69.			80	6	13.528
34.				8	15.555	70.				8	13.593
35.				10	15.575	71.				10	13.905
36.				12	15.347	72.				12	14.06

Table 4. Measured Values of Torque during Wood Crosscutting Process Performed by Circular Saw Made of Cemented Carbide Plates (CCP)

No.	Wood species	Cutting-edge side rake [°]	Cutting speed v_c [m.s^{-1}]	Feeding speed v_f [m.min^{-1}]	Mean torque values M_k [N.m]	No.	Wood species	Cutting-edge side rake [°]	Cutting speed v_c [m.s^{-1}]	Feeding speed v_f [m.min^{-1}]	Mean torque values M_k [N.m]
1.	Beech	-5	60	6	16.133	37.	Spruce	-5	60	6	14.967
2.				8	16.19	38.				8	15.627
3.				10	16.305	39.				10	15.39
4.				12	16.417	40.				12	14.985
5.			70	6	16.342	41.			70	6	14.968
6.				8	17.	42.				8	15.375
7.				10	17.28	43.				10	15.282
8.				12	17.168	44.				12	15.343
9.			80	6	16.277	45.			80	6	14.81
10.				8	16.38	46.				8	14.83
11.				10	16.702	47.				10	14.775
12.				12	16.748	48.				12	15.025
13.		0	60	6	14.802	49.		0	60	6	14.603
14.				8	16.47	50.				8	15.097
15.				10	16.412	51.				10	15.32
16.				12	18.413	52.				12	15.235
17.			70	6	16.015	53.			70	6	14.487
18.				8	16.658	54.				8	14.272
19.				10	16.5	55.				10	14.293
20.				12	16.922	56.				12	13.96
21.			80	6	16.163	57.			80	6	12.713
22.				8	16.248	58.				8	13.132
23.				10	16.775	59.				10	13.343
24.				12	16.668	60.				12	13.408
25.		20	60	6	15.963	61.		20	60	6	12.128
26.				8	15.933	62.				8	12.093
27.				10	15.883	63.				10	12.323
28.				12	15.95	64.				12	12.832
29.			70	6	15.297	65.			70	6	12.058
30.				8	15.51	66.				8	12.065
31.				10	14.478	67.				10	12.295
32.				12	14.828	68.				12	12.517
33.			80	6	14.883	69.			80	6	12.503
34.				8	15.303	70.				8	12.348
35.				10	15.077	71.				10	12.302
36.				12	14.758	72.				12	12.157

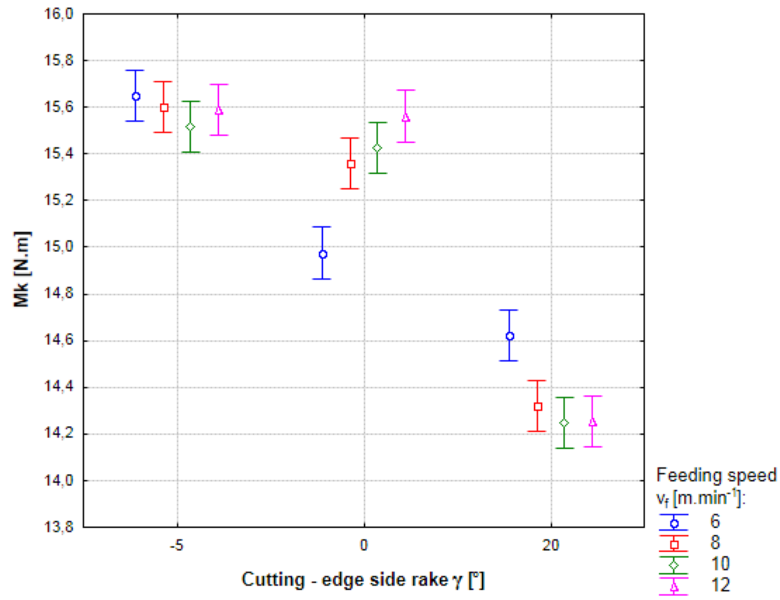

Fig. 8. The influence of cutting-edge side rake on torque M_k for varying feeding speeds v_f

Figures 9 and 10 present statistical dependency of torque M_k on the type of the circular saw blade, wood species, cutting speed v_c, and cutting-edge side rake.

In Fig. 9 it is clear that the values of torque measured in the case of spruce cut by circular saw made of high speed steel (HSS) were higher than values of torque M_k measured at beech cut by circular saw made of cemented carbide plates (CCP). This difference was attributed to faster tool wearing.

Figure 10 shows the influence of circular saw blade type on the cutting-edge side rake on torque M_k. This case represents the most suitable cutting-edge side rake angle, having a value of 20°.

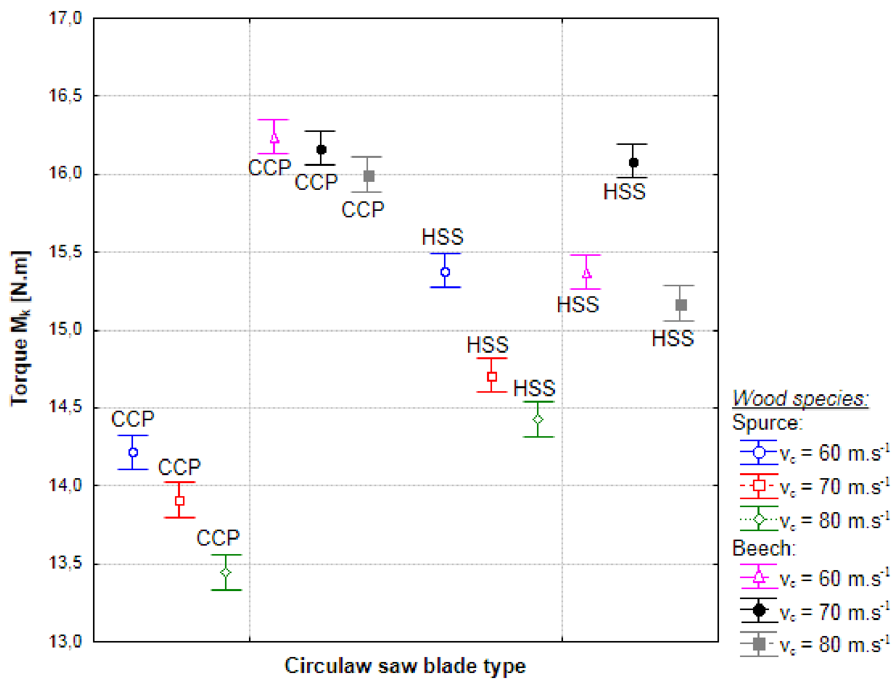

Fig. 9. The influence of circular saw type on torque M_k for different wood species

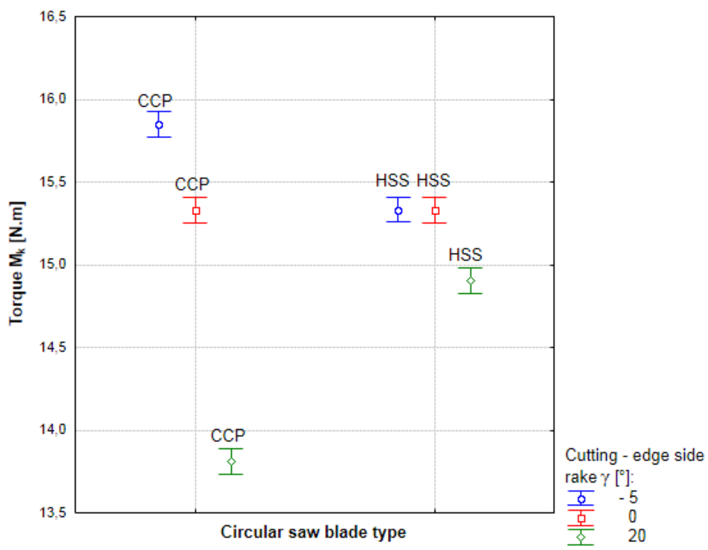

Fig. 10. The influence of circular saw type on torque for different cutting-edge side rakes

The mentioned statistical evaluations of torque M_k for individual measurement variables show that the most convenient cutting-edge side rake for crosscutting wood by circular saw blades made of HSS and CCP is a positive value (20°). These results are supported by other authors (Siklienka *et al.* 2013) and a tool producer PILANA Saw Bodies, Ltd. (1999).

CONCLUSIONS

1. The cutting rake angle (*e.g.* 20^{o}) of a circular saw is an important factor influencing torque M_k.
2. Changing circular saw type (with the same geometry) had the biggest influence on torque M_k of all tested factors.
3. Feeding speed v_f has a significant influence on torque M_k. For deciduous wood, it is more suitable to use a higher feeding speed at positive cutting angles. For coniferous wood, it is more suitable to use slower feeding speeds due to the presence of reaction wood.
4. According to the research, the cutting speed v_c has more significant influence on torque M_k in the cutting of spruce than beech. It is sure that torque M_k decreases when cutting speed v_c increases. This result was found to be valid for both observed types of circular saw blades *i.e.* a circular saw made of high speed steel (HSS) and a circular saw made of cemented carbide plates (CCP).

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