

# Influence of Knife Geometry on Selected Factors Pertaining to the Delimiting Process

Ján Melicherčík,\* Jozef Krilek, Ján Kováč, and Pavol Harvánek

Cutting mechanisms and the cutting force are the focus of this article. The cutting force can be determined theoretically or mathematically by statistical analysis. In this work, the cutting speed was compared when changing the diameter of the test wood and when using the three types of angular geometry of delimiting knives. Experimental measurements were conducted on a self-designed experimental pneumatic stand. Empirical relationships and values from the scientific literature were used to determine the input parameters. Based on a regression analysis, conclusions were drawn relative to factors affecting the process of delimiting. The angular geometry of the delimiting knife plays a significant role in the delimiting process. The thicker the knife, the higher the energy consumption in the cutting process and the poorer the quality of the cutting surface of the wood. The quality of chipless separation timber was found to depend on the cutting speed, and the optimal speed was  $2.0 \text{ m s}^{-1}$ .

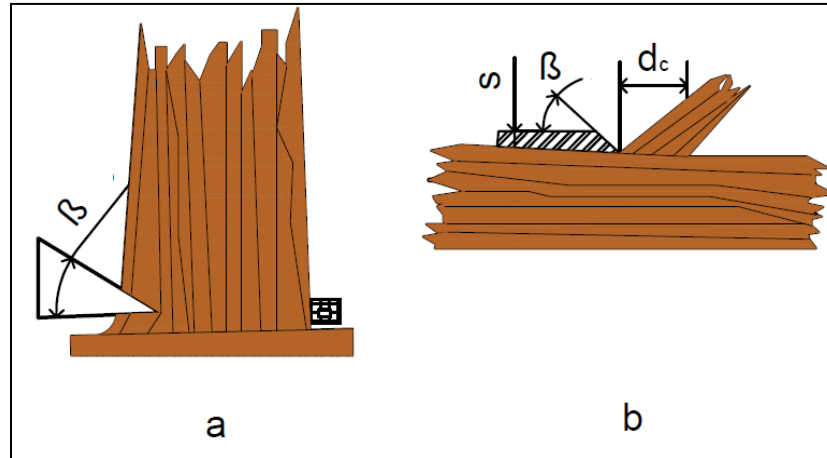
*Keywords:* Cutting force; Cutting speed; Delimiting knife; Branch diameter

*Contact information:* The Technical University in Zvolen, The Faculty of Technology, The Department of Environmental and Forestry Machinery, T. G. Masaryka 24, Zvolen 960 53 Slovakia;

\* *Corresponding author:* [xmelicercikj@tuzvo.sk](mailto:xmelicercikj@tuzvo.sk)

## INTRODUCTION

The chipless wood cutting process, as the object of investigation, is characterized by a number of parameters found to be in close correlation with one another. The geometry of the knife and the cutting force have a significant influence in the delimiting process of wood; they affect a large number of factors, as shown in previous studies (Mikleš and Mikleš 2012; Krilek *et al.* 2018). Delimiting is the technological process in which the tool penetrates the material (wood) and interferes with the interconnection of wood fibers in order to divide it into 2 or more parts (Siklienka *et al.* 2017). The feeding mechanism of the device consists of a pneumatic cylinder, the primary delimiting knife with different geometric shapes, and a different cutting edge angle. Delimiting is a process that is used to cut branches from the trunk during the tree harvesting process. This process can be described as the chipless cutting of green wood (Spinelli *et al.* 2010; Hatton *et al.* 2016). The chipless wood cutting process is a forestry process that is used primarily in machines for delimiting trees. It is a technological process in which a product is produced without the formation of chips (Siklienka *et al.* 2017). This method of cutting is applied to the cutting heads of multi-operation machines (USA, Canada). The free-body diagram of the work of the wedge knife is shown in Fig. 1. The process of chipless wood cutting, with the help of a branching knife, is carried out across the fibers in the wood. This condition causes an increase in the cutting force acting on the pruning knife. Somewhere it is possible to define this process as force cutting. (Marko 1997).



**Fig. 1.** (a) wood cutting with a wedge knife; and (b) wood cutting with a flat knife (Krilek *et al.* 2018)

### Delimiting Knife

A delimiting knife is a cutting tool whose design may have different profiles, *i.e.*, the cutting edge shape and the cutting edge. The cutting edge is the part of the cutting wedge that is to be cut and is the intersection of the face and back of the tool with a knife thickness " $s$ ". With the cutting edge angle  $\beta$  and the back angle  $\alpha = 0$ , the cutting angle is  $\delta = \beta$ . The results of chipless wood cutting research showed that the cutting force at the entrance of the knife into the wood initially increased linearly and then dropped to zero. The maximum force  $F_{\max}$  corresponds to a knife penetration depth of 55% to 80% at the cross sectional area. When chipless cutting wood *via* a wedge knife in a direction that does not correspond to the direction of the wood fibers, considerable cutting forces arise. This results in considerable energy intensity of the cutting process. One of the specific cases of this method is the power cutting of branches, in which knives with a complicated structure are used. The special feature of the knives designed for cutting branches *via* the force method is a combination of effective cutting with copying ability of knives in the process. The magnitude of the cutting force acting in the direction of the velocity vector is the result of all the components of the force of resistance acting on the different parts of the knife, which forms its cutting profile (forehead, back, and cutting edge), (Kováč 2006; Mikleš and Mikleš 2015).

### Forces Acting on the Forehead of a Knife Cutting Branch

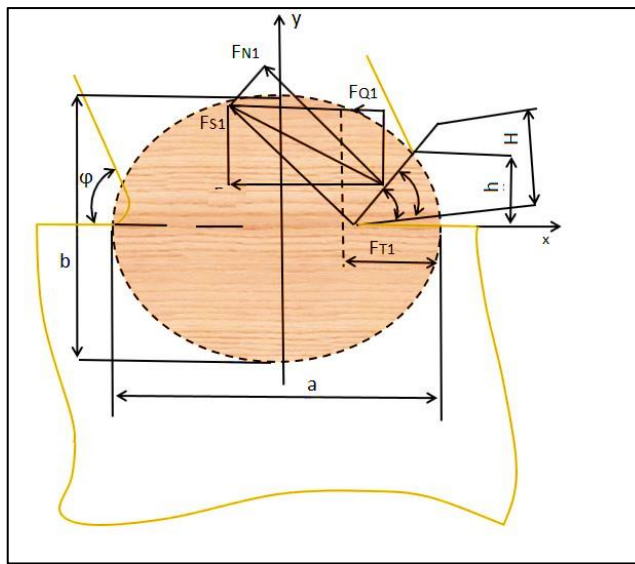
Chipless cutting is characterized in particular by the fact that, up to the moment of removal of the branch from the forehead knife, it penetrates the wood only *via* the compressing the wood and pushing it out of the cutting zone in a volume equal to that of the protruding portion of the knife. This is illustrated by the fact that a branch that has a long enough length is characterized by major resistance to shearing along the fibers, and therefore the vertical force  $F_{Q1}$  is not able to overcome this resistance. Therefore, chips are not formed, and the branch subsequently observed a characteristic decrease in cutting resistance. The cutting resistance is constantly increasing, reaching the maximum at the moment when the over-cut branch begins to separate from the forehead knife, after which the opposite process takes place. The nature of the growth and decrease of the cutting resistance must ideally be the same. It follows that the maximum force acting from the wood on the forehead of the knife must be counted out based on the condition of energy

consumption for pressing the wood. Here the authors assume that the relative pressure, caused by the cut-off branch on the forehead of the knife is in direct dependence of the volume of the wood extruded by the forehead in the cutting process.

The measuring pressure on the entire area in contact with the forehead knife being evenly distributed is most likely to cause chipless cutting. The principle is that in the given method, the over-cut part of the branch does not leave the forehead knife but is attached to it until the conditions are maintained and the relationship applies, as shown in Eq. 1,

$$F_{Q1(a-z)} \leq \frac{1}{32} \cdot \pi \cdot (a-z)^2 \cdot b \cdot \sigma_{OH} [N] \quad (1)$$

where  $F_{Q1}$  is the pressure of the wood (N),  $a$  is the longer axis slit branch (mm),  $z$  is the depth of the knife penetration (mm),  $b$  is the shorter axis slit branch (mm), and  $\sigma_{OH}$  is the timber strength of the branch along the fibers (MPa).



**Fig. 2.** Forces acting on the front of the knife (Mikleš and Mikleš 2015)

When calculating the forces  $F_{S1}$ ,  $F_{Q1}$ , and  $F_{P1}$ , the deformation is caused by the pressing of the front edge of the knife into the wood. When this occurs, the normal force  $F_{N1}$ , acting on the forehead of the knife, can be determined from the following relationship, as shown in Eq. 2,

$$F_{N1} = q \cdot V_1 \quad (2)$$

where  $q$  is the specific compression force, per unit of volume of the compressed wood ( $N \cdot mm^{-3}$ ), and  $V_1$  is the volume of the wood, knife – crush out ( $mm^3$ ).

The resultant force  $F_{S1}$  is obtained as the geometric sum of the forces  $F_N$  and  $F_I$  as shown in Eq. 3,

$$F_{S1} = q \cdot V_1 \cdot \sqrt{1 + f_1^2}, N \quad (3)$$

where  $V_1$  is the volume of the wood, knife – crush out ( $mm^3$ ),  $f_1$  is the coefficient of friction between the knife and the tree trunk, and  $F_{S1}$  is the resultant force (N).

These values can be applied to Eqs. 4 and 5,

$$F_{P1} = F_{S1} \cdot \sin(\delta + \arctg f_1), N \quad (4)$$

$$F_{Q1} = F_{S1} \cdot \cos(\delta + \arctg f_1), N \quad (5)$$

where  $F_{PI}$  is the pressure force (N).

The maximum value of the  $F_{Rmax}$  cutting force, according to Mikleš (2009) and Hatton *et al.* (2015), is directly proportional to the square diameter of the "dc" of the cut branch in the bark, as shown in Eq. 6,

$$F_{Rmax} = a_1 \cdot d_c^2, N \quad (6)$$

where  $a_1$  is the coefficient of proportionality, which is dependent on the parameters of the knife, the wood, and the angle of the ingrowth of the branches. This relationship shows that  $F_{Rmax}$  is directly proportional to the cutting surface of branch  $S$ , as shown in Eq. 7,

$$F_{Rmax} = k \cdot S, N \quad (7)$$

where  $k$  equals  $F_{spMAX}$ , which is the proportionality ratio corresponding to the maximum nominal cutting force, which includes the influence of the geometric characteristics of the knife ( $N \cdot mm^{-2}$ ), and  $S$  is the cutting surface of the branch ( $mm^2$ ).

## EXPERIMENTAL

### Materials

This study deals with the comparison of various cutting speeds with respect to the cutting resistance of different delimiting knife geometries. To analyze these different geometries, a special device was built to allow the cutting process to be monitored in laboratory conditions and to measure the cutting forces, which results in recording the energy intensity of the delimiting process. The authors experimented with a pneumatic cylinder. For evaluating the delimiting process, knives with different geometric parameters were used (Table 1). The geometry of the cutting wedge delimiting knife is shown in Fig. 3. The purpose of this paper was to determine the optimal geometry of the knife. Under the same cutting conditions (a delimiting speed of  $4 \text{ cm} \cdot \text{s}^{-1}$ ), the maximum cutting force was determined (or measured cutting force).

The experimental measurements were carried out by professional employees of the school forestry company. Wood sampling took place in the course of a logging operation in the forest. The samples were always brought on the day of the experimental measurement, and during the measurement they were stored in an open hangar to maintain the necessary conditions and properties of the wood. The moisture content of the samples was measured by the gravimetric method, always before the start of the experimental measurements. The diameters of the sampling woods used in the experiment were from 10 to 55 mm. A larger diameter sample was inserted into the experimental stand, from which the delimiting branch is based. When measuring a change in the type debranching blade, 27 specimens were studied. The number of specimens was determined by a basic statistical set.

For chipless wood cutting applications in woodland harvesting, further refinement of the cutting tool was necessary. The incompleteness of the design of the cutting tool and the cutting mechanism did not allow for a good cutting surface, especially when cutting frozen wood (in the splitting process wood is shredded and longitudinal cracks emerge from the forehead), and also causes large cutting forces, which cause considerable load on the whole mechanism.

The theory of chipless wood cutting processes is based on analysis of works by foreign authors (Gerasimov *et al.* 2012; Hatton *et al.* 2015; Orłowski *et al.* 2018) and the author's previous research (Kováč and Alexi 2004; Krilek *et al.* 2018). That work involved an analysis to determine the impact of various parameters on cutting, and found that the parameter with the greatest impact on the cutting resistance upon entering the wood was the thickness of the knife ( $s$ ). The greater the thickness of the knife, the higher the energy consumption in the delimiting process and the worse the quality of the cutting surface. Therefore, a reduction in the thickness of the knife can cause a significant impact in terms of tool optimization. For the laboratory pruning tests, 3 knives with a constant thickness ( $s = 15$  mm), the geometry of these knives was the most appropriate according to the results of the initial chipless separation measurements. The effective cutting edge width for all knives was 130 mm. The tool steel DIN C45W was used for the production of the test knives. All knives were hardened to a hardness of 52 HRC to 56 HRC and were machined to a surface roughness of  $R_a = 0.8$   $\mu\text{m}$ . The technical parameters of the blades are shown in Table 2.

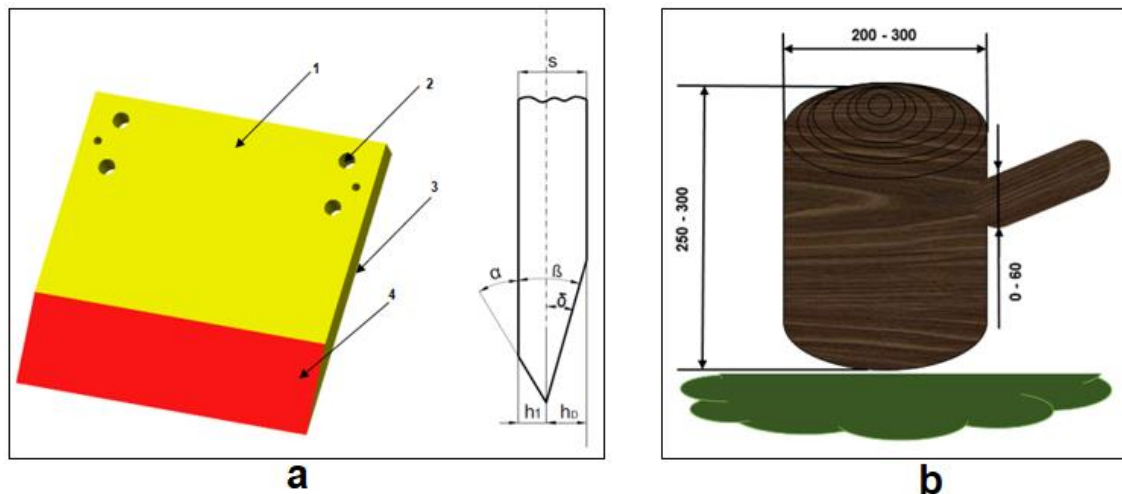


**Fig. 3.** Experimental device for testing delimiting knives

The experimental equipment was constructed of profiled steel and shaped elements by means of welded joints. The device had dimensions of 1404 x 500 mm, and the branching knife was 400 mm away from the sample material. The air tank was located on a profile stand, which included a barometer, by which to monitor the air pressure and a pressure reducing valve to adjust the air flow in the system. A pneumatic double-acting cylinder was mounted by screws, with parameters according to ISO 6431. The HBM S9 strain gauge was located on the piston rod of the cylinder by means of the proposed

fastening jigs. Starting the double acting cylinder provided movement of the pneumatic actuator, which was provided with a check valve and a silencer. The sensor was powered by connecting cables to the Quantum MX 840 measuring unit, which was an 8-channel measuring control panel. The advantage of the measuring unit is compatibility with HBM devices. The cutting device consisted of a flat delimiting knife, which was located on the piston rod and was detected by a pin. After the piston rod is extended, the knife moves towards the wood sample, while there is a transverse division of the wood - delimiting. The sample material was secured against ejection by a pressure cylinder, which was controlled by a separate pneumatic control unit, which consisted of a pneumatic actuator, a throttle valve, a trigger valve, and an exhaust valve at the outlet of the pressure cylinder.

Spruce (*Picea excelsa*) was used for the experimental measurements, and the chosen wood samples had the maximum specific cutting resistance that was processed. The delimiting branches of fresh spruce branches had a moisture content of 40% to 70%. Individual measurements were carried out *via* pneumatic measuring; the primary part the measuring device consisted of a pneumatic cylinder on which the authors fastened the selected delimiting knives, according to Table 2.



**Fig. 4.** a.) The geometry of the cutting wedge delimiting knife ( $s$  is the thickness of the knife;  $\alpha$  is the angle of the knife;  $\delta$  is the cutting angle;  $h_1$  is the depth the knife penetrates the wood; and  $h_0$  is the thickness of the cut layer) b.) Sampling trees with the average groups used in the experiment

**Table 2.** Technical Parameters of the Knives Intended for Experimental Tests

Knife Number	Cutting Angle ( $\delta$ ) (°)	Back Angle of Knife ( $\alpha$ ) (°)	Knife Thickness ( $s$ ) (mm)
1	20	7	15
2	15	4	15
3	20	4	15

For the sake of evaluation, the authors compiled a measurement chain from individual sensors. To measure the speed, the authors used a single axis SA I/L acceleration sensor, which measured the acceleration of the knife for a certain time unit, which allows for the calculation of the delimiting speed after conversion. The growth of the HBM Force sensor pressure transducer was within a pressure range of 25 to 60 MPa. The process and the individual measurement results were displayed using Conmes Spider (version8) from

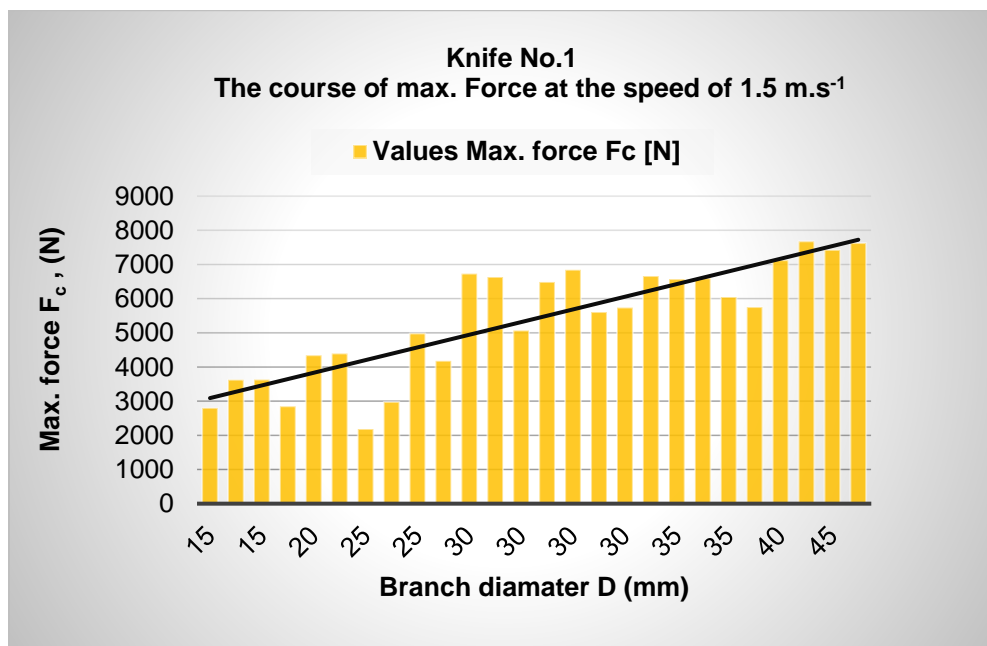


HBM. The experimental delimiting measurements investigated the maximum cutting force and speed relative to the cutting resistance. The tested cutting knife speeds were 1.5, 2.0, and 2.5  $\text{m}\cdot\text{s}^{-1}$ , with three different knives (the knife parameters are shown in Table 2). The relative moisture content of the samples ranged from 21% to 46%. Basic statistical characteristics were performed in the STATISTICA statistical program (STATISTICA12 software, TIBCO Software Inc., Palo Alto, CA, USA), and the results are shown in Table 3

## RESULTS AND DISCUSSION

The primary goal of this experiment was to compare the cutting speed, with consideration to the cutting resistance and the delimiting knife geometry, *via* changing the parameters that characterized the cutting process. When cutting a branch at the point of its emergence, the character of the cutting force acting in the direction of the knife displacement is a close-up shape of a triangle with a cut off vertex, with the speed of the cutting knife being a mirror image of the action of the cutting force. When the depth of the cut when the knife enters the branch increases, the cutting force increases linearly and the cutting speed decreases linearly; this pattern coincides with the shape of the typical curve of total wood deformation. The linear dependence of the cutting power and cutting speeds usually changes only at a depth of penetration of the tool equal to approximately  $0.5 d_c$  (Mikleš and Mikleš 2010), or slightly less than half the branch diameter. The individual laboratory results of the maximum cutting force measurements at different speeds were processed in tabular form with the STATISTICA program.

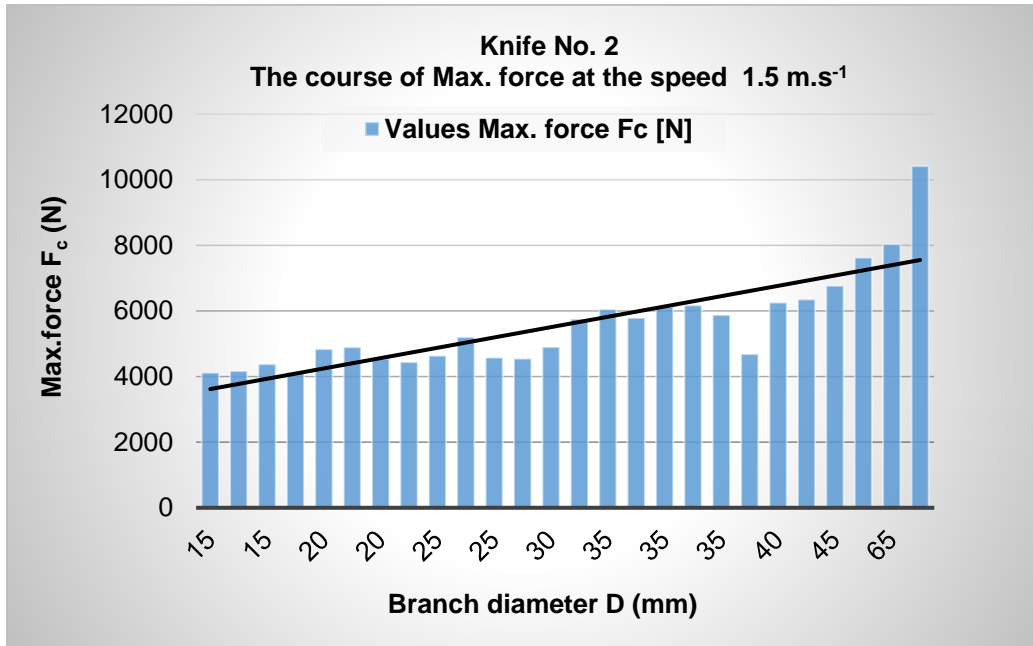
### Statistical Curves of Maximum Cutting Force During the Delimiting Process Using the Delimiting Knives Described in Table 2



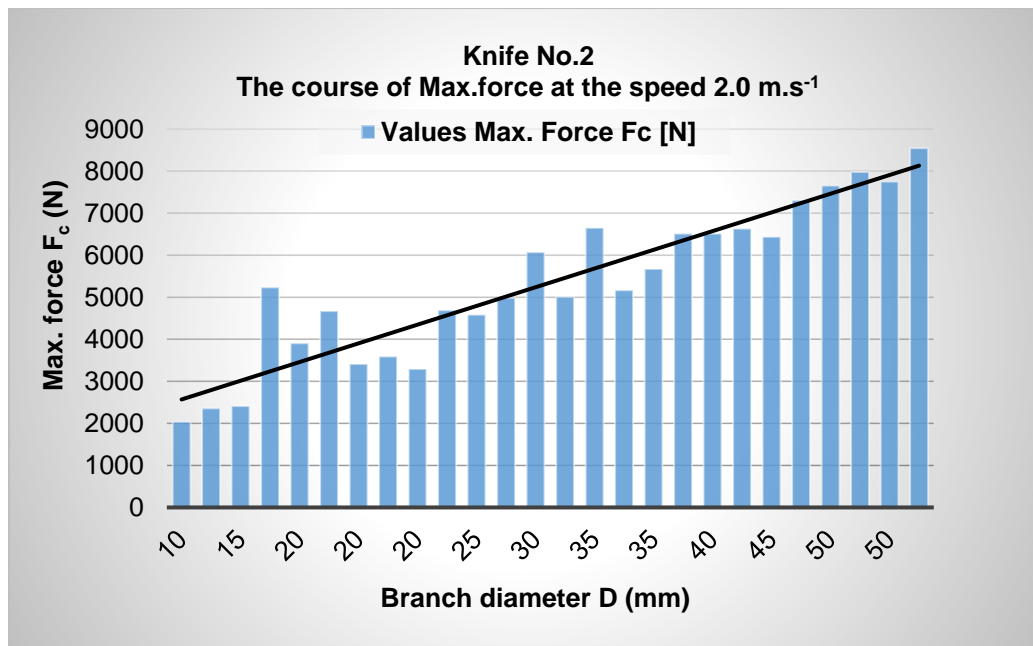
**Fig. 5.** The maximum cutting force when processing the spruce wood branch at a cutting speed of  $1.5 \text{ m}\cdot\text{s}^{-1}$



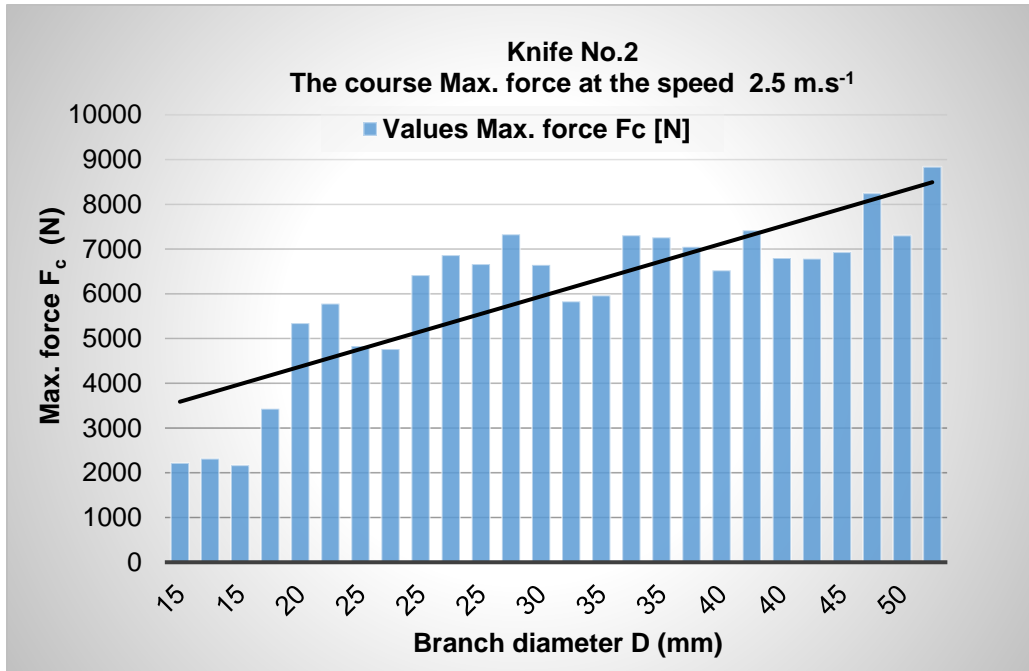




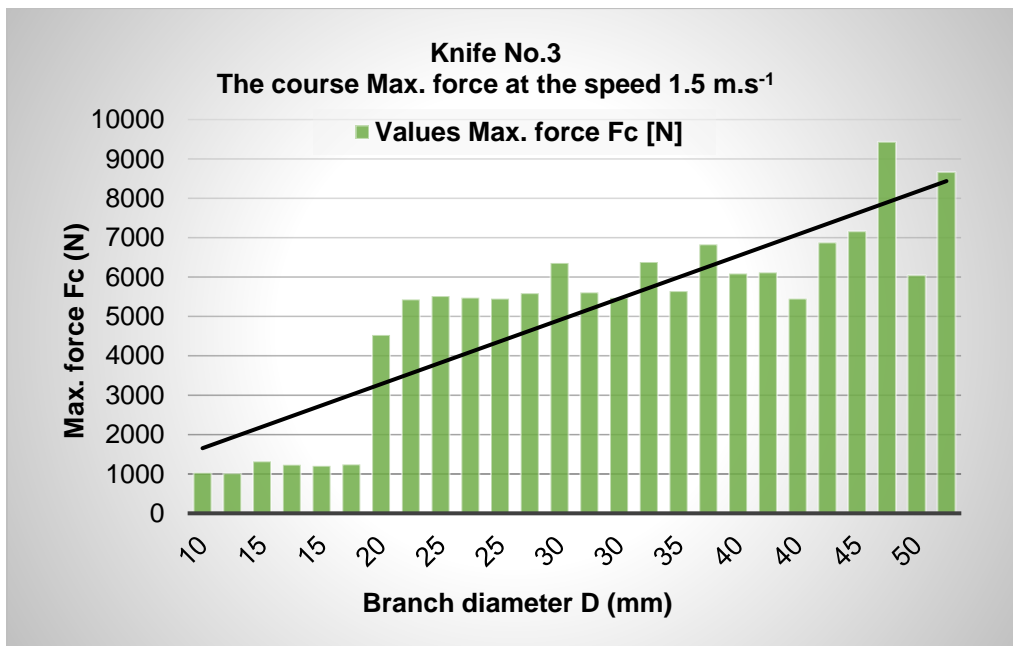
**Fig. 8.** The maximum cutting force when processing the spruce wood branch at a cutting speed of 1.5 m·s<sup>-1</sup>



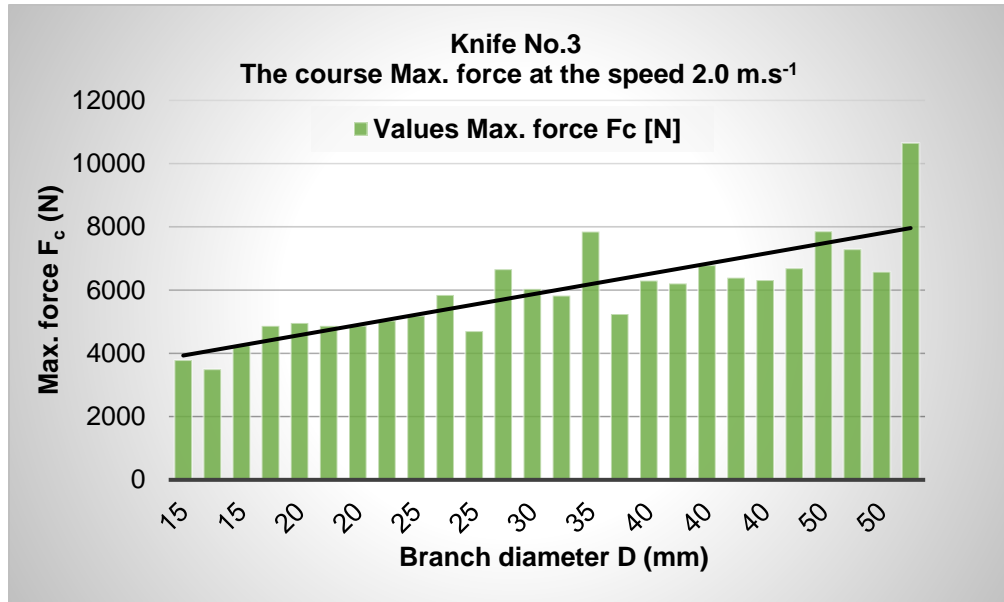
**Fig. 9.** The maximum cutting force when processing the spruce wood branch at a cutting speed of 2.0 m·s<sup>-1</sup>



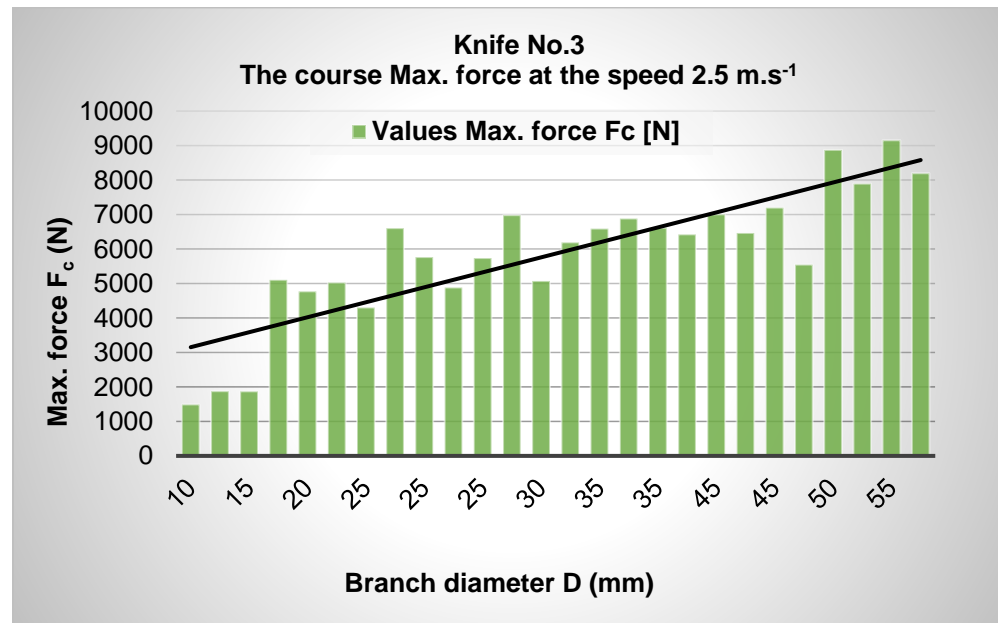
**Fig. 10.** The maximum cutting force when processing the spruce wood branch at a cutting speed of 2.5 m·s<sup>-1</sup>



**Fig. 11.** The maximum cutting force when processing the spruce wood branch at a cutting speed of 1.5 m·s<sup>-1</sup>



**Fig. 12.** The maximum cutting force when processing the spruce wood branch at a cutting speed of 2.0 m·s<sup>-1</sup>



**Fig. 13.** The maximum cutting force when processing the spruce wood branch at a cutting speed of 2.5 m·s<sup>-1</sup>

Covariance multifactor analysis was used to determine the mutual statistical dependence between maximum cutting force (as a dependent variable) and cutting speed. Different knife types and branch diameters (variables in the statistics) represent quantities influenced by another factor to specify the state of statistical significance that was performed for each knife type, knife speed, and branch diameter, as confirmed by the Duncan test. Results of statistical processing of experiments of statistical characteristics, for the dependence of maximum cutting force from the cutting speed, the type of knife and the diameter of the branch are graphically shown in Figs. 5 to 13.

The intervals of the investigated variables, *e.g.*, maximum cutting force, cutting speed, and branch diameter, as a low energy intensity indicator gave the authors greater insight into the assessment of these parameters in terms of the quality and energy intensity of the chipless woodcutting process. It is clear from the graphs that the plots are linear with an increasing tendency in certain places with a large increment, *i.e.*, where the cutting force of knife sample 3 is constant due to its 20 mm diameter.

Scientific papers involving the chipless cutting of wood, or delimiting itself, are focused on the overall energy and the quality of the machine or device (Hatton *et al.* 2015). Such research is important in terms of the operating life, mechanical performance, and economic performance of the machine. However, in order to focus purely on the delimiting mechanism, it is necessary to understand the issues associated with branch cutting from the tree trunk and the factors that affect the life of the knives (McEwan *et al.* 2016). Industrial damages are caused by different rounding of the wood, which is related to the maintenance of the delimiting machine and, in particular, ensuring a sufficiently sharp cutting edge of the knife (Gerasimov *et al.* 2012). Delimiting is an expensive wood harvesting operation, which usually reduces the net amount of renewable biomass (Watson *et al.* 1993). The delimiting mechanism, which is usually a knife, serves to deflect the tree trunk. These are basically hyperbolically shaped knives stored in the collecting head or telescopic shoulder. Delimiting knives should be able to copy the trunk shape as best as possible (Hatton *et al.* 2015). The cutting resistance and cutting speed of a significant part affects the delimiting process and therefore interferes with the energy intensity of the machine (Orlowski *et al.* 2014; Pathak *et al.* 2017). In order to detect the impact of cutting speed, force, and cutting resistance, the Department of Environmental and Forestry Engineering developed and constructed a measuring stent whose functionality was secured by a pneumatic cylinder.

In a report by Siklienka and Šustek (2007) the cutting force, or the required work and performance, was used as the only tool for expressing the cutting edge condition. By assessing the influence of the factors examined on the quality of the deviation from the analyses performed, it was determined that the main quality criterion with the greatest impact on the tear and branching balance was the cutting speed and geometry of the cutting knife, on the basis of which the most favorable cutting speed was  $2.0 \text{ m}\cdot\text{s}^{-1}$ . At a cutting speed of  $1.5 \text{ m}\cdot\text{s}^{-1}$ , in terms of the quality of the cut, there were no major branch shoots on the total track path of the branch. The maximum tear value occurred with knife no. 2 (Table 2), which reached 11 mm. At a cutting speed of  $2.0 \text{ m}\cdot\text{s}^{-1}$ , the cutting surface of the tree branch was smooth enough when compared to a cutting speed of  $1.5 \text{ m}\cdot\text{s}^{-1}$  of the residual values of the branches after cutting, ranged from 0 to 5 mm, although max. the balance was up to 8 mm. The greatest influence on the cutting force was the selection of the correct geometry of the delimiting knife, with the optimal geometry of the blade having the following parameters:  $\delta = 20^\circ$ ,  $\alpha = 4^\circ$ ,  $h = 2 \text{ mm}$ ,  $s = 15 \text{ mm}$ , and  $\rho = 0.02 \text{ mm}$  (Melicherčik *et al.* 2020). All effects that acted on the cutting force (with a far greater effect than dullness) made it impossible to compare the results. The relative moisture content of the wood affected the quality of the delimiting process (branch residue and winding). With an increased relative humidity, the cutting speeds, ranging from  $1.5$  to  $2.5 \text{ m}\cdot\text{s}^{-1}$ , resulted in visibly better results in terms of tear and branch remnants. This study can provide accurate data that affects the machine life and process quality.

## CONCLUSIONS

1. This article compared the cutting speed with respect to the cutting resistance and the geometry of the blade during the process of cutting chipless wood (delimiting). The primary part of the separating machine was a knife, which was tested with different geometries. Statistical courses precisely define the branching procedure for specific types of knives, which is the basis for conclusions about the respective angular geometry.
2. In terms of the quality and speed of the delimiting knife, it is necessary to choose the most optimal knife geometry with the following parameters:  $\delta = 20^\circ$ ,  $\alpha = 4^\circ$ ,  $h = 2$  mm,  $s = 15$  mm, and  $\rho = 0.02$  mm was evaluated by experimental measurements which are statistically evaluated.
3. Under the same cutting conditions, the maximum cutting force  $F_{c \max} = 10$  kN (or measured cutting force) was determined according to empirical relationships in the area of chipless wood cutting.
4. The thickness of the knife has the greatest influence on the wood processing process. It affects the cutting force, which in the present case ranged from 1.1 to 9.0 kN, due to the specified cutting speed and type of wood. The most optimal knife thickness was 15 mm. A greater thickness of the tool leads to higher energy intensity of the cutting process and poorer quality of the cutting surface.
5. The quality of the processed wood and the reduction of energy intensity had the greatest impact of the optimal delimiting speed of  $2.0 \text{ m}\cdot\text{s}^{-1}$ .

## ACKNOWLEDGMENTS

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## Symbols

$\beta$  – cutting angle edge ( $^\circ$ )

$\delta$  – cutting angle ( $^\circ$ )

$\alpha$  – back angle ( $^\circ$ )

$d_c$  - distance of the knife from the cut branch (mm)

$s$  – branch thickness (mm)

$F_{Q1}$  – vertical force (N)

$\phi$  - angle attachment of the branch the trunk ( $^\circ$ )

$F_{S1}$  - maximum cutting tool force (N)

$F_{P1}$  - force for determining the cutting resistance (N)

$Q$  – specific pressure (Pa)

$V_1$  - volume, determined (bounded) on the area ( $\text{m}^3$ )

$F_{R\max}$  – the cutting force depended on the diameter of the branch (N)

$S$  – cutting surface of the branch (mm)

$\sigma_{OH}$  – strength of wood along the fibers (MPa)

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