Influence of the Shape of the Knife's Cutting Edge on the Cutting Force in the Chipless Cutting of Three Tree Species

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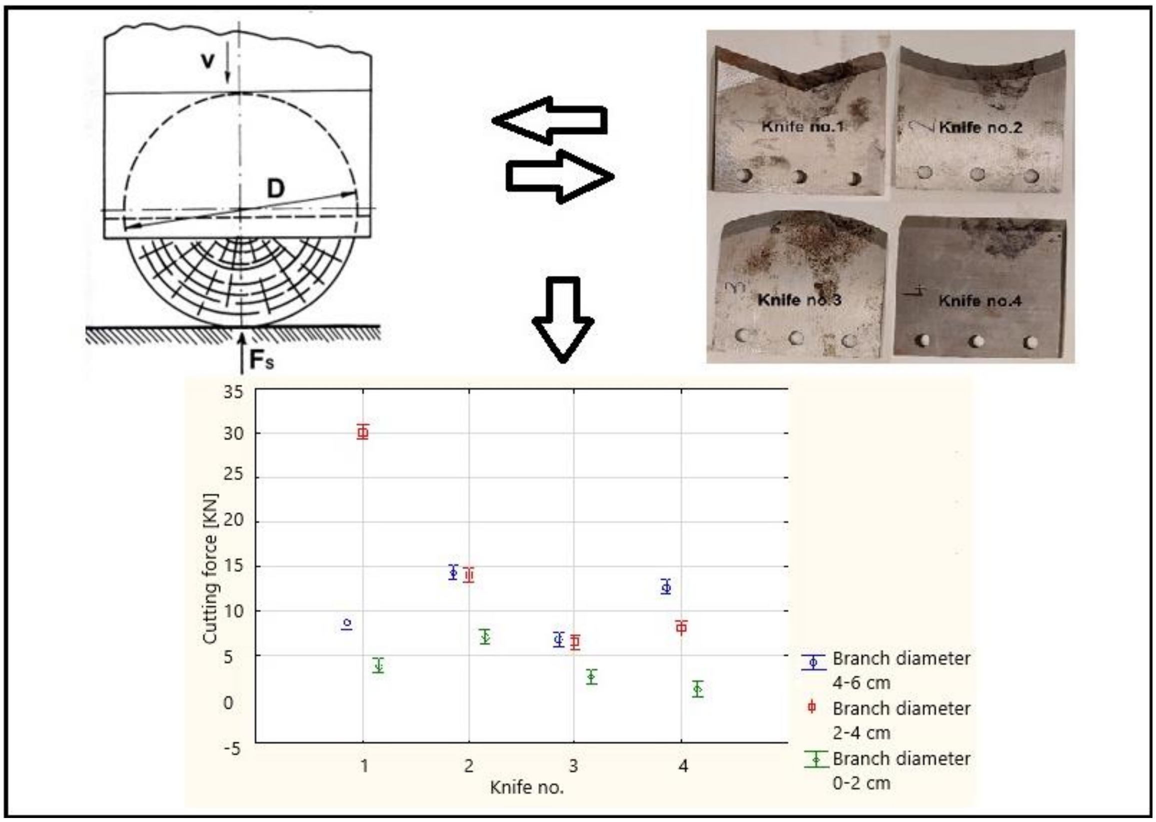
GRAPHICAL ABSTRACT



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Ján Kováč,[a] Tomáš Kuvik,[a,]* Jozef Krilek,[a] and Pawel Tylek [b]

This article presents results obtained for the chipless cutting of wood using different cutting heads. Wood processing in forestry and the demand for firewood are currently increasing, so it is necessary to apply appropriate tools to the existing process, which will be sufficient for fast and high-quality operations. Four groups of cutting knives were used for experimental measurements, where the influence of the cutting knife edge on the cutting process was determined. The cutting knives were always made of the same material and with the same blade angle ∢ 30°. Measurements were made on spruce (*Picea abies*), beech (*Fagus sylvatica*), and willow (*Salix caprea*) trees. The size of the F_c cutting force was selected as the monitored variable, and then the dependent factors (kind of wood, wood diameter, cutting knife) were monitored in terms of their influence on the size of this F_c cutting force and thus also on the energy consumption. Based on the statistical evaluation, the most suitable shape of the cutting edge of the knife was selected, with this shape of the cutting edge, a reduction in the cutting force F_c was achieved for selected woods.

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Keywords: Chipless cutting wood; Cutting force; Cross-cutting; Cutting edge; Chipless cutting knife

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INTRODUCTION

Wood chipless cutting refers to a technological procedure wherein a single-edge knife works to form the wood into the required shape. Chips are produced when wood is divided into smaller pieces without producing waste (Koreň 1983). In the process of harvesting forests, machinery designed for tree delimbing are the primary users of chipless cutting (Mikleš and Mikleš 2012; Hatton *et al.* 2015, 2017). A single-edge knife is used in a technological process known as "wood chipless cutting" to shape the wood into the desired shape. When wood is cut into smaller pieces without creating waste, no chips are created (Koreň 1983; Mikleš 2011).

Over time, a variety of tool forms have been produced for chipless wood cutting. In general, wood can be cut using all of the geometries that are shown. Nonetheless, the goal of designing contemporary wood processing tools and machinery should be to minimize the energy usage of the procedure (Spinelli *et al.* 2015; Orlowski *et al.* 2020;

Wargula and Kukla 2020; Wargula *et al.* 2022), as well as the effects on the environment (Manzone 2015; Prada *et al.* 2015; Spinelli *et al.* 2018), and machine operators (Magagnotti *et al.* 2014; Gulci *et al.* 2018; Licow *et al.* 2020). The chipless knife is one feature that sets these machines apart. When cutting wood chiplessly, which is becoming more and more common in silviculture thanks to the use of harvesters fitted with specific heads that make it possible to do so, a comparable cutting mechanism is employed (Harvánek *et al.* 2021; Kováč *et al.* 2024). When designing machinery that splits wood into pieces for processing, such as chopping, shredding, cutting, or splitting, two factors pertaining to the cutting mechanism's blade must be traded off. The blade's durability is the first, and its cutting or cutting force is the second. A blade form that decreases cutting force is not very durable, and tools with a shape that increases durability also increase cutting force. The heads of harvesters used for chipless cutting (Bergström and Di Fulvio 2014; Gao *et al.* 2021) or for limbing heads (Mederski *et al.* 2018; Gerasimov *et al.* 2012; Melicherčík *et al.* 2021) are primary locations that are suitable for testing of the cutting device for cutting wood.

To maximise 25 cm log cutting, a knife cutting mechanism with one fixed and one moveable knife, or with two moving floating knives, can be employed, especially in earlier models of chipless cutting heads (Kováč *et al.* 2024). Chipless cutting heads are capable of cutting logs with a diameter of up to 30 cm. The trunk is pushed into the cutting knife by hydraulic control gripping arms during the cutting operation. The cutting wedge (cutting tool) is pushed into the trunk in a transverse direction to the fibre growth in order to operate the chipless cutting head (Fig. 1). Wood splitting directly employs a longitudinal cutting direction (Wegener and Wegener 2013; Minárik and Hricová 2015; Pichler *et al*. 2018).

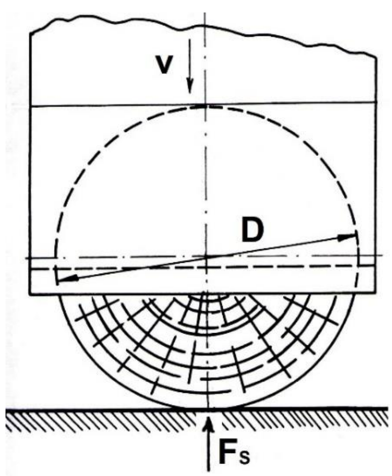

Fig. 1. Schematic of the method of cross-cutting wood

Analysis of the Cutting Process and Determination of its Parameters

Chipless wood cutting in the harvesting process is especially used in the Slovak Republic with machinery for tree delimbing by forest harvesters. This methodology is also used world-wide for multi-operation machines. Wood cutting is a basic technology in forest wood processing. It rapidly affects the organization of production, efficiency, work safety, product quality, and energy consumption (Rousek *et al.* 2010). When designing knife cutting mechanisms, the designer must first of all know the energy and power ratios of the cutting process. One can find clarification of this question in many works, but the analytical calculation of the knife chipless wood cutting process is insufficiently discussed in them

(Kuvik *et al*. 2018) Therefore, in this part, analytical dependencies are derived for determining the energy and power parameters of knife chipless cutting of wood. In doing so, the interdependence of the parameters of the cutting process on the physical-mechanical properties of wood will be taken into account. For the case of transverse cutting of trunk wood, we proceed from the following assumptions:

The division of wood fibers takes place in a plane passing through the cutting edge of the knife parallel to the cutting speed vector.

In the cutting process, compression occurs by the surfaces of the wedge part of the knife. The specific pressure when compressing the wood is distributed equally on each of the plane surfaces of the knife's contact with the wood. The cross-section of wood with a knife is based on the wood's ability to deform. The blade of the knife compresses the wood fibers in the transverse direction, while the fibers bend and expand. When taking into account the different degree of possible deformation of the fibers in the transverse and longitudinal direction until their failure occurs, it can be assumed that the failure of the fibers before the knife edge occurs essentially at the expense of their expansion. During cutting, the values of specific pressures, compressive stresses and friction coefficients are taken as being constant. Wood exhibits relatively little resistance to deformation when a cutting wedge is pressed into it. In order to carry out the wood cutting process, it is necessary that the cutting edge be acted upon by a force F_S acting in the direction of the wood fibers. In doing so, the cutting edge breaks the bonds between the fibers in the plane (Mikleš and Mikleš 2012; Harvánek *et al.* 2021).

The method of cutting wood in a process that does not change the nature of the movement of the cutting tool or the cut wood (it is rectilinear) is called static. Figure 2 shows diagrams of basic cutting methods.

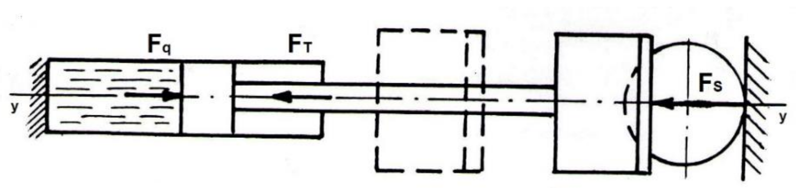

Fig. 2. Schemes of basic cutting methods

The movement of the knife and cutting is carried out using a hydromotor with linear movement. In this case, the forces acting on the knife balance each other. For the scheme in Fig. 2a (horizontal movement), one can express the balance equation of the forces acting on the knife in the cutting process, which has the form,

$$F_q + F_s + F_T = 0 \tag{1}$$

where Fs is the shear force (resistance) during static shearing (N), F_T is the friction force in the line (N), and F_Q is the force exerted by the hydraulic motor (N). Adjusting the equation leads to Eq. 2.

$$F_s = F_q - F_T \tag{2}$$

Methodology

The laboratory measurements were carried out on the hydraulic stand of the workshop at the Technical University in Zvolen (Fig. 3). Cutting knives with different cutting edge shapes and geometric parameters were gradually attached to the stand. Since these were laboratory conditions, the size of the shearing blades was smaller compared to the shearing blades of commercial chipless shearing heads.

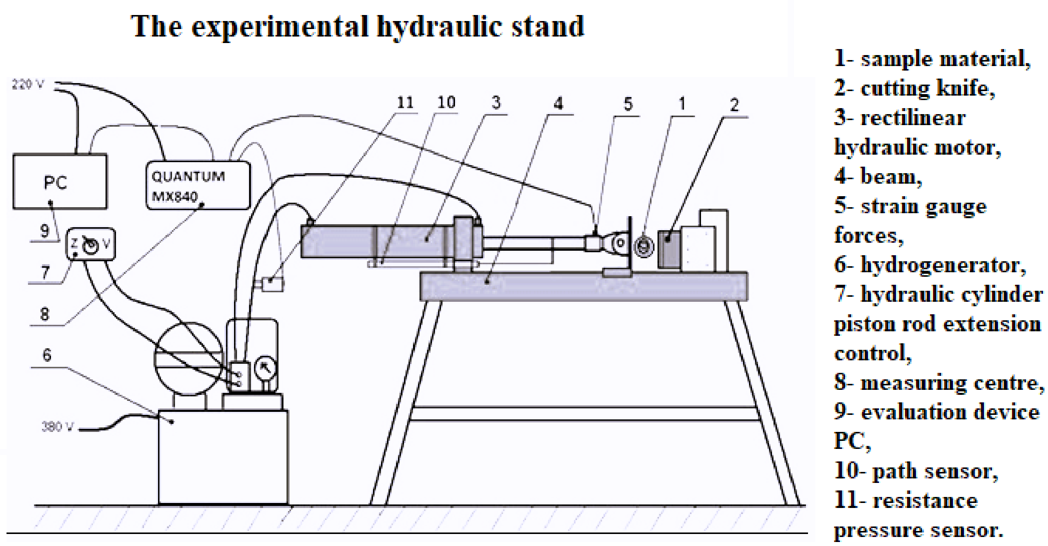

Fig. 3. The experimental stand

The tested material and measurement methodology was previously described (Harvánek *et al.* 2021; Kováč *et al.* 2024). The measurements were evaluated on a personal computer using the STATISTICA 12 software, which made it possible to clearly state whether the use of different variations of screening knives in the chipless screening process is statistically significant (Harvánek *et al.* 2021; Melicherčík *et al.* 2021; Kováč *et al.* 2024).

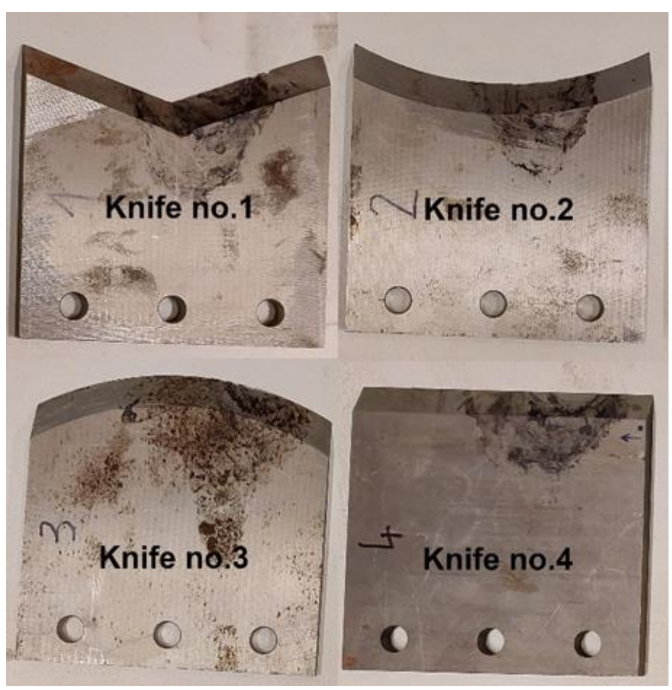

Fig. 4. Cutting knives with different cutting edges

All measurements were performed with the following selected parameters: (a) cutting speed: 0.1 m·s^{-1}; (b) types of wood (with a circular (elliptical) cross-section with a diameter of up to 60 mm with a maximum sample length of 200 mm, in the diameter groups 0 to 20 mm, 20 to 40 mm, and 40 to 60 mm): Norway spruce (*Picea abies*), beech (*Fagus sylvatica*), and sea buckthorn willow (*Salix caprea*); (c) felling knives: shading knife with a thickness of s = 8 mm, and (d) knives with different cutting edges: a straight cutting edge (Fig. 4, knife no. 4), a convex blade (Fig. 4, knife no. 3), a concave blade (Fig. 4, knife no. 2), and a V-shaped blade (Fig. 4, knife no. 1). The wood samples were selected not only from the branches of the trees of the mentioned woody plants, but also during thinning harvesting to remove unwanted growths.

The moisture content of the types of trees should correspond to freshly cut wood, *i.e.*, well above the saturation point of wabs fibres. = 30%. The entire process of recording the moisture content of the samples was carried out in the MEMMERT UF 30 PLUS dryer in the workshops of the Technical University in Zvolen. The measurement was based on the STN EN 13183-1 standard and accurate laboratory scales.

The measured values from the QuantumX MX840 measurement center were processed using a spreadsheet for the statistical software STATISTICA 12.

At the beginning of the experiment, it was necessary to make test measurements. To determine a sufficiently large sample set (number of measurements), empirical relationships (Harvánek *et al.* 2021; Melicherčík *et al.* 2021; Kováč *et al.* 2024) were used. Based on the calculation under the given conditions, approx. 350 measurements were made per knife for all types of wood.

Factor analysis of variance (ANOVA) was used within the programme. In the two-factor ANOVA experiment, the influence (effect) of two different factors *A* and *B* on the values of the studied property *X* was sought. More specifically, the effect of two different factors *A* and *B* on any sample was named μij, (i = 1,...,k; j = 1,...,l) of any k*l samples. In the case of two-factor variance analysis, a single $xijp$ measurement can be viewed as (p = 1,...,n),

$$x_{ijp} = \mu + a_i + b_j + c_{ij} + e_{ijp} \tag{3}$$

where μ is the virtual total mean of all levels of the two factors examined, a_i is the only effect of the i^{th} level of the investigated factor A, b_j is the only effect of the j^{th} level of factor B under study, c_{ij} is the effect of the interaction between the i^{th} level of factor *A* under investigation and the j^{th} level of factor B under investigation, and e_{ijp} is the error (random deviation) of the fifth repeated measurement at the i^{th} level of factor *A* and the j^{th} level of factor *B*.

The main objective of the two-factor ANOVA experiment is to determine the significance of the influence of two factors *A*, *B* and their interaction on the values of the investigated property *X*. The hypothesis will show us whether any factor or interaction will affect a particular property of the composite. To solve this question, the null hypothesis H_0 is formulated, which indicates that the variances of the diameters of a particular property of the composite are equal to the alternative hypothesis H_1, which indicates that the variances of the diameters of a particular property of the composite are not equal.

$$H_0: \mu_1 = \mu_2 = \cdots = \mu_k \tag{4}$$

$$H_1: \mu_1 \neq \mu_2 \neq \cdots = \mu_k \tag{5}$$

To determine whether one hypothesis is to be rejected in favor of the other hypothesis, the Levene test was used for this, specifically a p-level with a significance level of α = 0.05. If the Levene test shows a p-level value greater than 0.05, it means that the H_1 hypothesis is to be rejected in favor of H_0. If the Leven test shows a p-level value of less than 0.05, it means that the H_0 hypothesis is to be rejected in favor of H_1.

RESULTS AND DISCUSSION

The main task in performing laboratory measurements was monitoring and recording the maximum cutting force "F_c" of a chipless felling knife when changing the type of wood and the size of the diameters of this wood. This process of chipless wood cutting took place in the presence of changing parameters (cutting force, shape of the cutting edge, type of wood and diameter of the wood. However, it was mostly possible to observe a change in the size of the cutting force when changing the wood sample, as well as when changing the group of diameters. The result of the experimental research was a change the size of the cutting force, which ranged from 1.1 to 59.55 kN. For the sake of clarity, Fig. 5 shows the process of chip-free chipping of a sample of all types of wood in the diameter range of 40 to 60 mm with a chopping knife number 2. By setting the piston rod of the hydraulic cylinder in motion, the cutting tool was recorded, which has a linear course as the hydraulic stand is oversized.

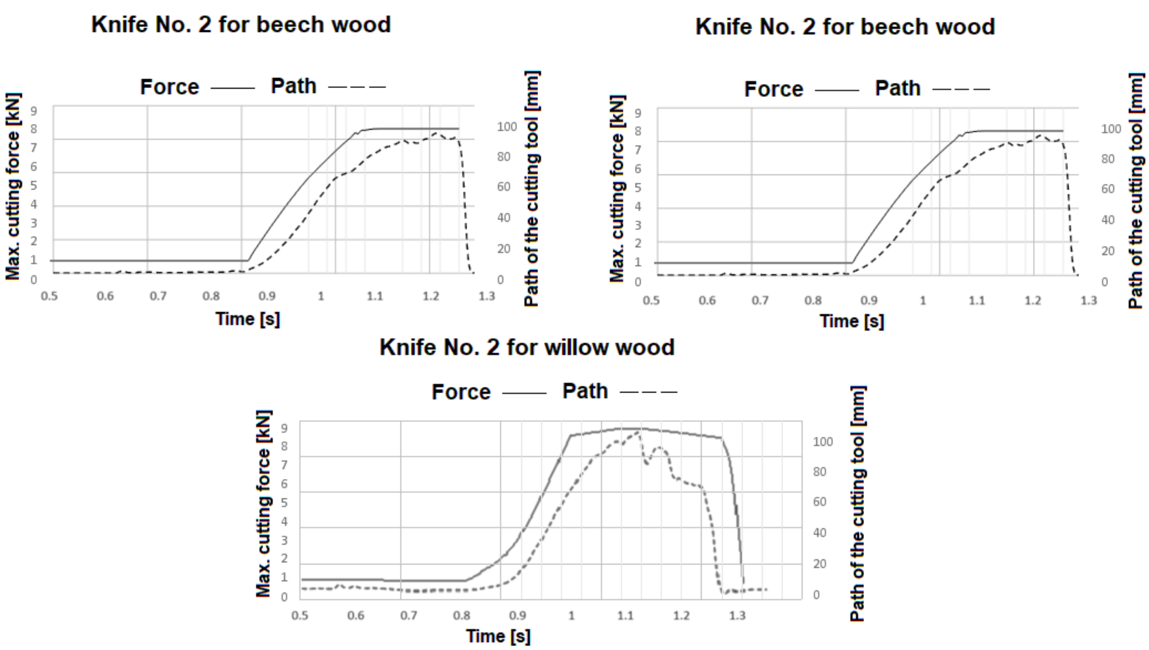

Fig. 5. Courses of cutting forces when measuring with knife No. 2 and uniform woods

Duncan's test of significance was performed to evaluate statistically significant interactions. Not only do individual factors have a statistically significant influence, but also interactions of two factors (knife*wood, *etc*.) and at the same time interactions of all three factors. Figures 6, 7, and 8 show graphs of 95% confidence of cutting force as a function of knife shape, types of trees, and wood diameter. There was no significant difference between the knife shapes (Fig. 8), but knife number 2 with a concave blade needed less cutting force than the other blade shapes (except willow wood). As expected, the cutting force increased with increasing wood diameter. Among the wood species (Fig.

6), the lowest cutting force was found for willow, because it is a soft wood, whereas the highest force was for beech.

It also follows that cutting of the mentioned types of wood was problematic with high demands on the entire process, which was mainly caused by the structure of the wood and its properties above the fiber saturation point, where the willow and spruce samples were characterized by the so-called high toughness and reaction value of wood. There was no change in strength during the process.

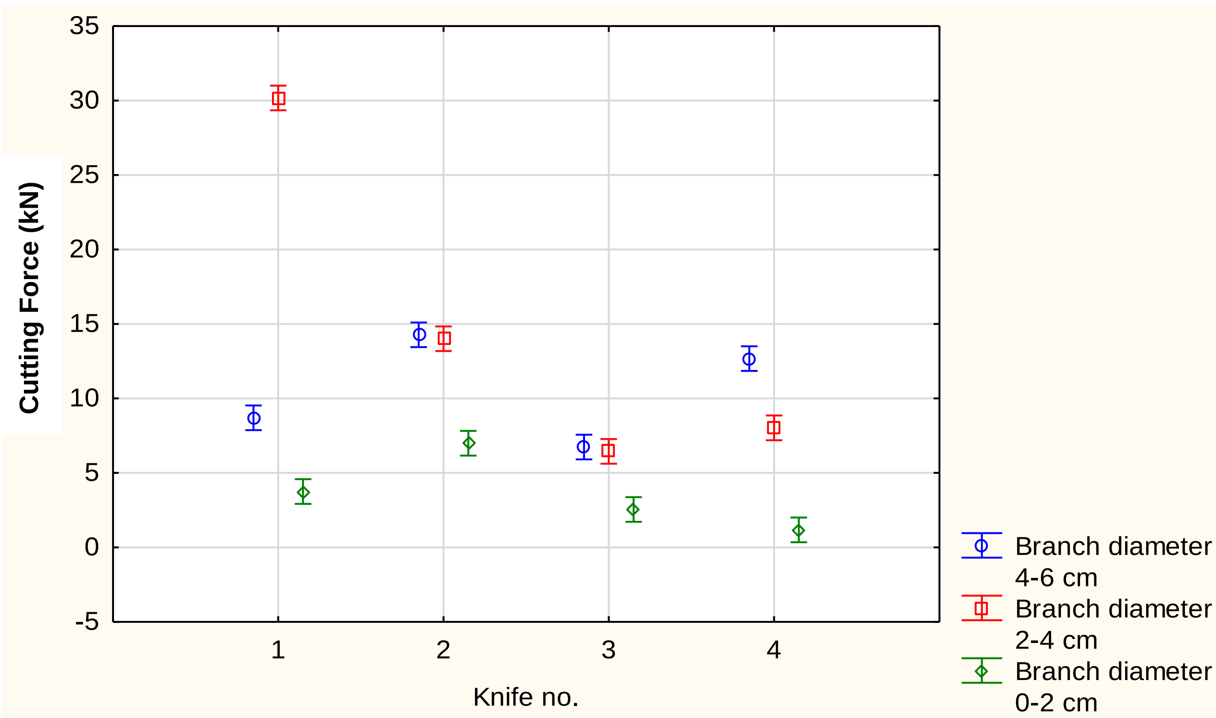

Fig. 6. Influence of willow wood diameter on cutting force

The relationships described in the literature are based on the research methodology for machines and tools, or in patent descriptions. Operated tools used to split wood are mainly proposed or tested for work with cross-cutting wood (Mutin 1994; Päivinen and Heinimaa 2009; Gregg 2015; Wargula and Kukla 2020). Most commercial machine feeling heads with a chipless knife were also proposed and tested in that regard (Albright 2006; Biberger 2012; Kováč *et al.* 2024). Tests for chipless cross-cutting wood to the fibres are mainly conducted on the heads of harvesters used for chipless cutting (Bergström and Di Fulvio 2014; Gao *et al.* 2021) or for delimbing heads (Gerasimov *et al.* 2012; Mederski *et al.* 2018; Melicherčík *et al.* 2021).

Preliminary scientific research dealing with similar issues (Kováč *et al*. 2024; Kuvik *et al*. 2018; Reichel *et al*. 2020) has described the methodology according to which the authors proceeded in the experimental measurements. From the above research based on chipless wood cutting, it can be said that the size of the cutting force is influenced by the type of wood, the diameter of the wood, and the thickness and shape of the delimbing knife. The interaction of wood diameter and cutting speed on the resulting force does not have a statistically significant effect. Marko (1996) found that for chipless wood cutting, it is most advantageous to use a felling knife with a cutting-edge angle of 30°. During his research, felling knives with a thickness from 1 mm to 8 mm with a cutting-edge angle from 25° to 60° were tested.

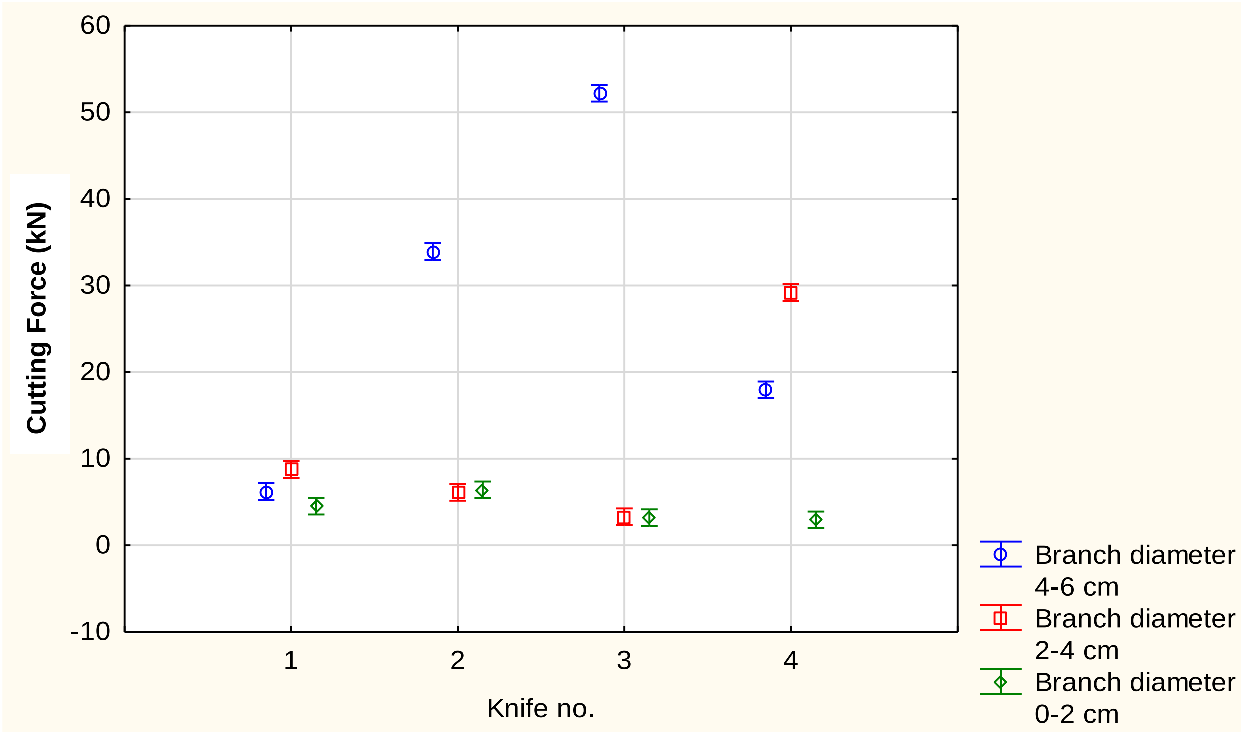

Fig. 7. Influence of spruce wood diameter on cutting force

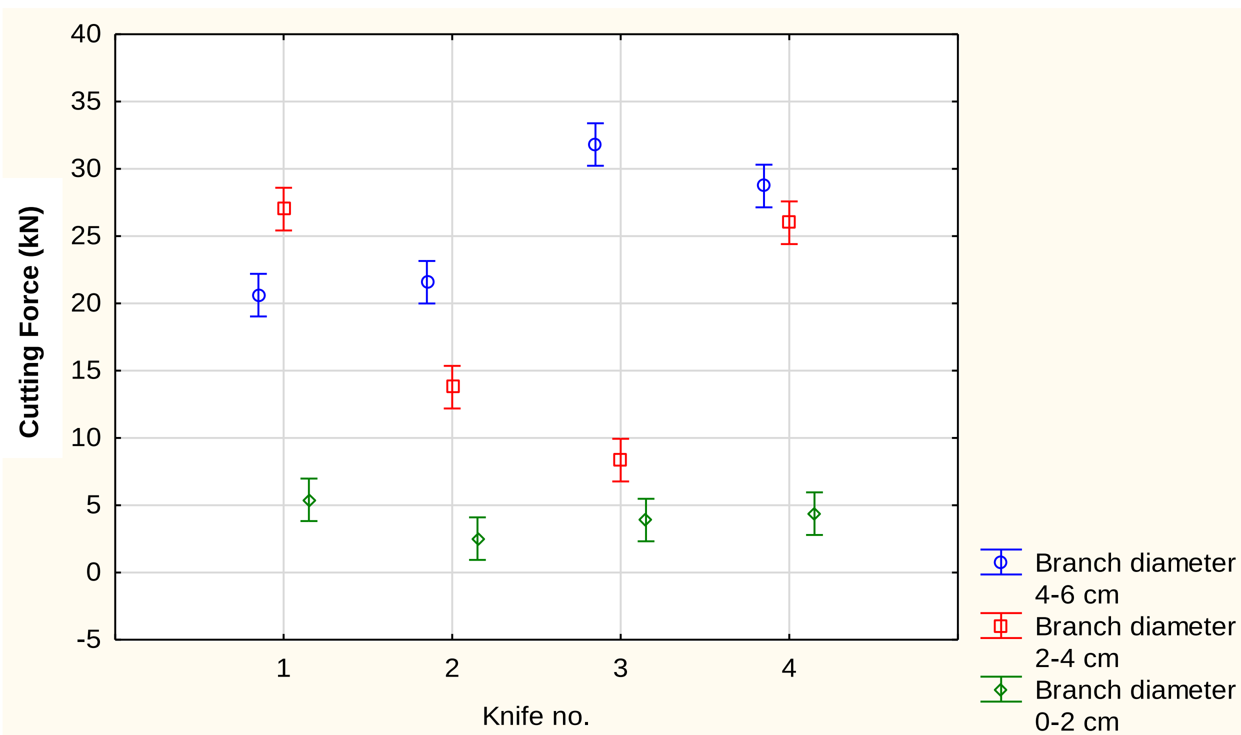

Fig. 8. Influence of beech wood diameter on cutting force

Two indirect methods were examined to measure the value of the cutting force F_c. Tensometric measurement with a deformation sensor on the piston rod eye was also researched by the authors in their scientific studies (Lapkova *et al*. 2014; Machelski 2018; Skorupka and Sobieszek 2018). To supplement and check the correctness of the measured data, the experimental device was also equipped with a pressure sensor in the hydraulic rectilinear hydromotor (Bellin and Fiorotto 1995; Albrecht *et al.* 2005). This value was presented only as a control one and, after being converted to the drilling area of the rectilinear hydromotor, it could be checked with the measured force from the tensometric force sensor. The paper is focused on the research of chipless wood processing and thus primary wood harvesting. The cutting force can be determined theoretically if it is broken down into individual components. The multifaceted nature of the types of cutting mechanisms confirms that, in their work, various authors were sometimes based on incorrect considerations.

The topic of chip-free shading of wood is a current and resolved issue in the field of primary processing of wood. The achieved results in the field of energy efficiency can be considered as a contribution to the field of wood processing in forestry. The authors began to deal more intensively with this issue mainly in the 90s of the last century, where the most advantageous angle of the cutting wedge of a chipless pruning knife was found. Based on the findings of Harvánek *et al.* (2021) from the above results, it is possible to claim that the most advantageous is the use of a pruning knife with a thickness of 8 mm. Thanks to the new materials, measuring technique and evaluation procedure, the processed issue was improved and other factors that influence the process of chipless screening of wood were discovered.

CONCLUSIONS

1. Based on the statistics, it was possible to gradually arrive at the final version of the knife, knife no. 2 (concave cutting edge), which achieves lower values of the cutting force F_c in the process of chipless wood cutting compared to commonly used knives.

2. The determined values of the cutting forces, the proposed parameters of the cutting tools, constitute directly realizable results for the design of the cutting tools, the dimensioning of the functional parts, and the determination of the necessary power input of the cutting heads of the cutting tool to be used in forest machines. The obtained results and knowledge can also be applied when designing the working mechanisms of the cutting heads of forest machines.

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