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The Impact of Design Parameters of a Horizontal Wood Splitter on Splitting Force

Utjecaj projektnih parametara uređaja za horizontalno cijepanje drva na silu cijepanja

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ABSTRACT • *The article deals with the influence of the shape of the splitting wedge on the size and course of splitting force. Today maximum effort is made to search for and use of energy saving solutions in every industry. Such solutions can include a change of the form of the longitudinal splitting wedge for splitting logs. The core of this problem is the experimental detection of powers, followed by analysing the individual effects. For this purpose, an experimental device was designed. The base of equipment consists of a mobile horizontal splitter, which is well adapted to capture the process of splitting force in splitting logs.*
According to the results, the type of wood was the most influencal factor, followed by wood diameter and splitting wedge. When comparing the average values that were generated from repeated measurements, it is possible to follow the reduction of splitting force. The results showed that the splitting force was reduced by approximately 13 % when comparing splitting wedge No. 1 (simple) and No. 2 (refracted). When comparing splitting wedges No. 1 (simple) and No. 3 (concave), it can be observed that the splitting force was reduced by more than 50 %. The experiment also confirmed the effect of different anatomical structures of different species of wood on various physical and mechanical properties of such wood and hence also on the splitting force in splitting wood.

Key words*: *horizontal splitter, energy consumption, splitting force, splitting wedge

SAŽETAK • *U članku se govori o utjecaju oblika klina za cijepanje drva na veličinu i smjer sile cijepanja. U današnje vrijeme ulažu se veliki napori u pronalaženje i primjenu novih riješenja za uštedu energije u svim industrijama. Jedno od takvih rješenja može predviđati i promjenu oblika klina za uzdužno cijepanje trupaca. Za taj problem važno je eksperimentalno odrediti snagu te analizirati pojedinačne utjecajne parametre. Za tu svrhu izrađen je eksperimentalni uređaj za cijepanje drva. Baza opreme sastoji se od mobilnoga horizontalnog razdjelnika, koji je dobro prilagođen praćenju procesa cijepanja i sile za cijepanje trupaca.*
Rezultati su pokazali da najveći utjecaj na silu cijepanja ima vrsta drva, zatim promjer drva i, na kraju, oblik klina za cijepanje. Usporedbom prosječnih vrijednosti dobivenih ponovljenim mjerenjima može se pratiti smanjenje sile cijepanja. Rezultati su pokazali smanjenje sile cijepanja za oko 13 % ako usporedimo cijepanje uz pomoć klina

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1 (jednostavni) i klina 2 (slomljeni). Usporedimo li klinove za cijepanje broj 1 (jednostavni) i broj 3 (konkavni), može se uočiti smanjenje sile cijepanja za više od 50 %. Eksperiment je također potvrdio utjecaj anatomske građe različitih vrsta drva na fizikalna i mehanička svojstva drva, a time i na silu cijepanja pri obradi drva cijepanjem.

***Ključne riječi**: uređaj za horizontalno cijepanje drva, potrošnja energije, sila cijepanja, klin za cijepanje*

1 INTRODUCTION
1. UVOD

Prices of energy have been rising and people are coming back to the oldest method of heating by burning of wood. Every year the number of households using wood mass to produce heat increases. The wood for heat production can be in various forms such as: chips, wood pellets or chopped wood. Chopped wood called fuel wood is obtained by shortening the tribe of the tree to the desired length with subsequent longitudinal splitting to the desired transverse dimension.

Also, production of logs is a necessary and important operation for every forest and wood-processing company (Krilek and Remper, 2012).

For preparing fuel wood, splitters are used working on the principle of chipping or pushing the wedge into the wood in the longitudinal direction. Thus they violate the consistency of wood fibres, which are separated by wedge pressure.

Splitters are mechanical machines designed for splitting wood logs faster and safer than ordinary axes (handle log splitter, wedges). They are safe and easy to operate by moving the splitting wedge controlled by pressure or by moving the lever. Wood is chipped by the action of a compressive force without a rapid kinetic movement of the cutting edge. This is the main reason why working with them is safer than with the classic manual splitting. Splitters are used by small households as well as large forest woodworking companies.

Wood splitters can be divided into groups by performance, position of logs during splitting, maximum strength that they can develop, size, weight, mobility, power, log size that can be chipped and ultimately the productivity. Further improvement of the machine will reduce energy consumption and costs required for preparing fuel wood.

Correct and reliable work of splitters is crucial especially in terms of power, strength, and splitting machine design. The examination of selected dependency and parameters of structure can eliminate necessary splitting force by its draft and thus ensure lower energy consumption while maintaining the same efficiency (Tajboš and Lukáč, 2005).

2 MATERIAL AND METHODS
2. MATERIJAL I METODE

2.1 Theoretical analysis of the problem
2.1. Teorijska analiza problema

Splitting is a process of injection of the cutting tool between the wood fibres in order to pull them away from each other and thus create a divided area parallel to the fibres without violating their length (Kollmann and Côté, 1968). The nature of this process is to break the strength of wood perpendicular to the fibres, as a consequence of a perpendicular pressure action of the cutting wedge on the fibres. Splitting is one of chipless wood machining processes. The direction of injection of the cutting wedge may be parallel or perpendicular to the wood fibres (Blomberg, 2006). The splitting stress is the one in which the forces act normally like a wedge (Figure 1). The plane of cleavage is parallel to the grain, either radially or tangentially (Siklienka and Kminiak, 2013; Record, 2004).

When splitting, the splitting wedge usually pushes the wood fibres on the front of the logs in the parallel direction. In this direction, the wood fibres have the least resistance against being separated from each other. Splitting wedge initially compresses wood fibres and only then penetrates between the fibres and their flanks expand forming a rift, while it rips them from each other by the pressure of the wedge (Figure 1) (Remper and Krilek, 2012).

At the beginning of entering into the wood fibres, the splitting wedge increases the splitting force F_m proportionally to the depth of the wedge penetration. It reaches its maximum when the wedge enters to a depth of l_1, which is in the range from $(1/25 \cdot L)$ to $(1/20 \cdot L)$.

In another penetration of the wedge into the emerging cracks, the force required for F_s decreases to the length of penetration wedge l_2, this F_s being in the range from $(1/8 \cdot F_m)$ to $(1/10 \cdot F_m)$.

The force on the wedge at the average value of F_s is maintained to a depth of penetration wedge l_2, which is in the range from $(1/5 \cdot L)$ to $(1/6 \cdot L)$.

Then again, the force on the wedge significantly decreases and after tearing the log drops to zero. The depth of penetration wedge l_2 and maximum force F_m, in which the log breaks, are very dependent on the front angle of the wedge α, because its increasing power of the depth of penetration decreases. Also, species of trees and condition of wood, as well as the length of the splitting log, have a significant impact on splitting. Forces F_1 derive at the pressure of F acting on both sides of the wedge. When the wedge penetrates into the wood, it must overcome frictional force T, given by:

$$T = f \cdot F_1 \tag{1}$$

where:
f – the coefficient of friction between the tool and wood,
F_1 – the normal force acting on the front of the wedge, N.

The maximum compressive force on the wedge F_m is given by:

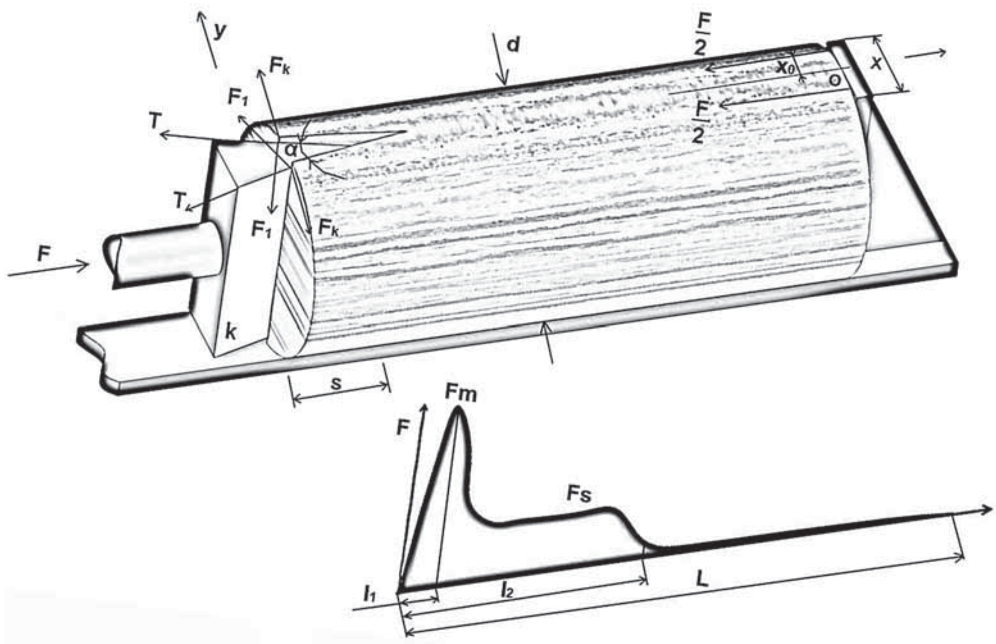

Figure 1 Scheme of forces acting by splitting wood (Remper and Krilek, 2012): *k* – splitting wedge, *o* – support, *d* – diameter of splitting log, *L* – length of splitting log, *F* – pushing force on the wedge, α - front angle of the wedge, F_m – maximum splitting force, F_1 – force perpendicular to the wedge front, F_k – force causing log splitting, *s* – trajectory of a wedge *x* – width of support, x_o – arm of the centre of the supporting reaction, l_1 – length of intrusion wedge with maximum pushing force, l_2 – length of intrusion wedge with the average pushing force, *F*s – average splitting force

Slika 1. Shema djelovanja sila tijekom cijepanja drva (Remper i Krilek, 2012.); *k* – klin za cijepanje, *o* – postolje, *d* – promjer trupca, *L* – duljina trupca, *F* – veličina sile na klinu, α – kut klina, F_m – maksimalna sila cijepanja, F_1 – sila okomita na klin, F_k – sila koja uzrokuje cijepanje trupca, *s* – putanja klina, *x* – širina postolja, x_o – krak središta potporne reakcije, l_1 – duljina prodora klina pri maksimalnoj sili na klinu, l_2 – duljina prodora klina pri prosječnoj sili na klinu, *F*s – prosječna sila cijepanja

$$F_m = 2 \cdot F_1 \cdot \left(f \cdot \cos\frac{\alpha}{2} + \sin\frac{\alpha}{2} \right) \qquad (2)$$

where:
α- the front angle of the wedge (°).

For splitting the log, the front of the wedge exerts force F_k, which is perpendicular to the longitudinal axis of the emerging cracks. This force is given by:

$$F_k = k \cdot d \cdot L \qquad (3)$$

where:
k – the specific splitting resistance of wood, kPa,
d – diameter of splitting log, m,
L – length of splitting log, m.

The specific splitting resistance depends on the type of tree species, condition of wood, diameter and length of the log, as well as on the front angle of the wedges:

$$k = k_z \cdot k_d \cdot k_s \cdot k_v \cdot k_k \qquad (4)$$

where:
k_z – the basic value of the splitting resistance, N·mm^{-2}
k_d – wood factor (for example pine = 1, birch = 1.1 – 1.2)
k_s – wood factor status (dry = 1, crude = 1.1 – 1.2)
k_v – factor of the splitting log shape (logs = 1, prism = 1.25 – 1.3)
k_k – factor of the blunting wedge (normal = 1.1 – 1.2).

Apart from the need for a pull force of the wedge for splitting the log as much as possible, it is also necessary to provide low resistance wood of small diameter and length, as well as a small angle wedge with a flat front surface. The support of splitting machines must be wide (Remper and Krilek, 2012).

2.2 Experimental measuring equipment
2.2. Oprema za provedbu eksperimenta

Experimental measuring equipment (Figure 2) is designed to fluently record the process and the size of splitting force in the longitudinal splitting of wood. Its principle is based on the construction of horizontal splitter (1) with the pressure plate and fixed splitting wedge (2), which is removable. Linear hydraulic engine (3) creates compressive force on the plate which moves the log (5) against wedge (2). Pressure of hydraulic oil is produced by a hydraulic unit (6), and the control of the process is provided by a control panel (7).

In order to be able to determine the course of splitting force, an actuator was inserted between rods of the linear hydraulic engine and printing plates of the splitting machine. The use of a standard load cell was not appropriate because of its size, as the priority was to preserve the maximum length of splitting. For this reason, the idea of using a strain gauge applied to a selected part of the machine was carried out with the intention of monitoring the power of the splitting process. A ball bearing eye was chosen as the deformation member, and screwed into the internal thread rod. Cylindrical clamping part of the loop was sufficiently large and its shape was suitable for the application of strain gauges according to Figure 3, and it had several advantages.

The arrangement with two longitudinal and two transverse compensated strain gauges is the most popular to determine the axial load (Figure 2, 3).

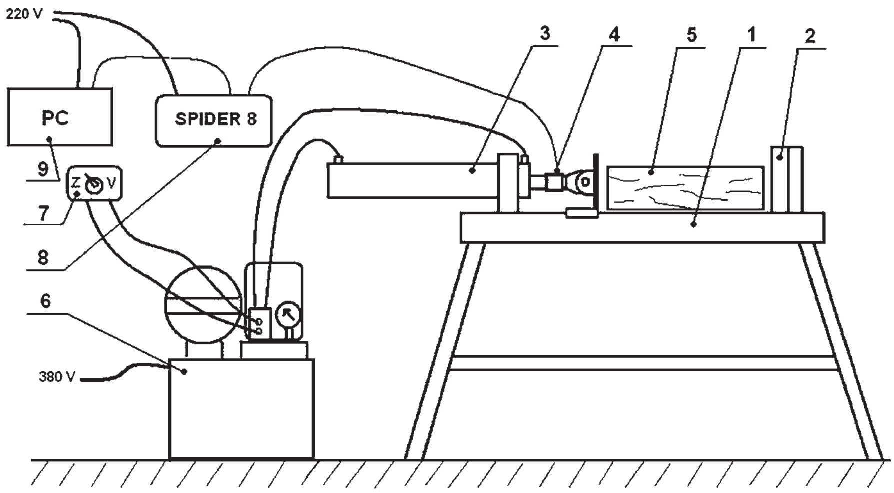

Figure 2 Horizontal splitter with measuring chain (1 – frame of horizontal splitter, 2 –splitting wedge, 3 – straightforward hydraulic engine, 4 – strain gauges, 5 – splitting log, 6 – hydraulic unit, 7 – control panel, 8 – logger, 9 – personal computer (pc)
Slika 2. Uređaj za horizontalno cijepanje drva s mjernim uređajima: 1 – okvir uređaja za cijepanje, 2 – klin za cijepanje, 3 – jednostavni hidraulički motor, 4 – mjerni instrumenti, 5 – trupac koji se cijepa, 6 – hidraulički uređaj, 7 – kontrolna ploča, 8 – kreiranje datoteka s podacima, 9 – računalo

Dependence is shown below:

$$\frac{U_v}{U_n} = \frac{K \cdot \varepsilon \cdot (1+\mu)}{2 + K \cdot \varepsilon \cdot (1-\mu)} \tag{5}$$

where:
U_v – output voltage, V
U_n – supply voltage, V
K – coefficient of deformation sensitivity of strain gauge,
ε – strain,
μ – Poisson's number.

This version provides very good temperature compensation, because the strain guages are in all adjacent arms of bridge. Both strain gauges are located in the adjacent arms of bridge. In comparison with the version of half Wheatstone bridge, involvement output is greater by a coefficient (1 + μ) and characteristics of output are linear.

Calibration of strain gauges is performed using the universal testing machine Testometric M500-100 CT.

Complete calibration consists of loading in the longitudinal direction of the eye (removed from the piston rod) clamped in among the grips of the testing machine. The functionality and precision of strain gauge bridge applications were verified by calibration.

The output signal is transmitted to the measurement amplifier SPIDER 8, modified and subsequently deposited on the hard disk of a PC using the program Conmes Spider, in txt format. The measured values of splitting force were evaluated in Statistics 11.0 program by means of analysis of variance (Scheer, 2007). Estimates were made of the zero hypothesis H_0 that says that the mean squares of measured values of splitting power are equal, and alternative hypothesis H_1 that says that the mean squares are not equal. In order to determine the interaction of several factors affecting the change in the splitting process, ANOVA (multifactorial analysis of variance) was used. Reciprocal statistical dependency was found out among maximum splitting force (dependent variable) and wood, splitting wedges, diameter of splitting logs (independent variables).

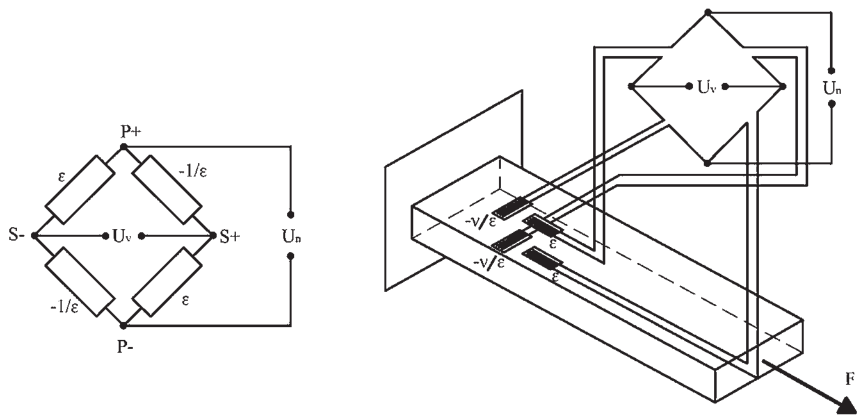

Figure 3 Beam tensile stress - pressure – full bridge with complete compensation (Hoffmann, 1989)
Slika 3. Vlačno i tlačno naprezanje u gredi – puni most s potpunom kompenzacijom (Hoffmann, 1989.)

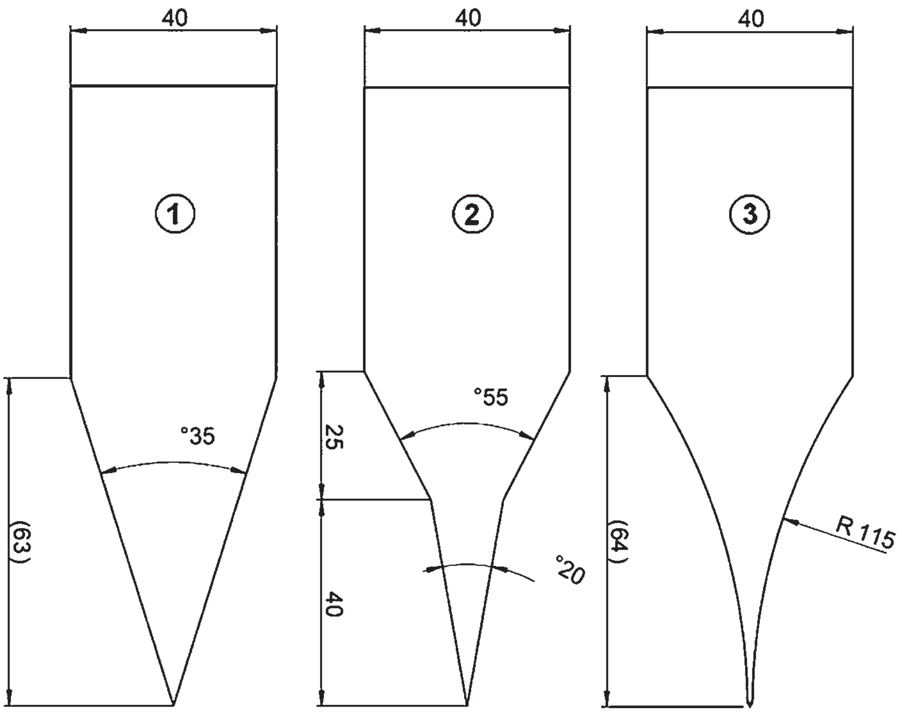

Figure 4 Various shapes of splitting wedges (1 – simple splitting wedge, 2 – refracted splitting wedge, 3 – concave splitting wedge)
Slika 4. Različiti oblici klina za cijepanje: 1 – jednostavni klin, 2 – slomljeni klin, 3 – konkavni klin

2.3 Methods of measurement
2.3. Mjerne metode

During the measurement, three types splitting wedges were used (Figure 4). Based on the survey, three types of splitting wedges were designed with different geometric shapes and sizes. The experiment samples were made of beech wood (*Fagus sylvatica* L.) and spruce wood (*Picea abies* L.). Cuts were sawn to length L = 85 cm, log diameter ranged between 27 and 36 cm and wood moisture content was ~ 34 %.

4 RESULTS AND DISCUSSION
4. REZULTATI I RASPRAVA

The criteria used for analysis are maximum splitting forces. As the criterion of statistical significance (p) F-test was used, although it is probable that the factor does not have statistical influence. It was assumed that individual parameters influence each other.

For each variation of three factors, there were two groups of diameters of splitting logs (27-31 cm and 32-36 cm) x two types of wood (BE – beech wood (*Fagus sylvatica* L.) and SP - spruce wood (*Picea abies* L.) x three different splitting wedges (simple, refracted and concave splitting wedge) = making a total of twelve variations. The representing of values of the tested item F - splitting force was filtered out. For each physical item, the results were statistically evaluated by three-factor analysis of variance.

The monitored factors show the following results: statistically the type of wood has the most significant influence, followed by diameters of wood and

Table 1 Univariate Tests of Significance for F_{max}
Tablica 1. Jednosmjerni testovi značajnosti za F_{max}

Effect	*SS*	*DF*	*MS*	*F*	*p*
Intercept / *Presjek*	3.615E+10	1	3.62E+10	1857.8	0.000
Group diameter of wood / *Skupina promjera drva*	3.983E+08	1	3.98E+08	20.5	0.000
Group types of woods / *Skupina vrste drva*	6.286E+08	1	6.29E+08	32.3	0.000
Group splitting wedge / *Skupina klina za cijepanje*	4.575E+08	2	2.29E+08	11.8	0.000
Group diameter of wood * types of wood *Skupina promjer drva * vrsta drva*	2.727E+06	1	2.73E+06	0.1	0.709
Group diameter of wood * splitting wedge *Skupina promjer drva * klin za cijepanje*	3.035E+08	2	1.52E+08	7.8	0.001
Group types of wood * splitting wedge *Skupina vrsta drva * klin za cijepanje*	7.674E+07	2	3.84E+07	2.0	0.147
Group diameter of wood * types of wood * splitting wedge *Skupina promjer drva * vrsta drva * klin za cijepanje*	1.215E+08	2	6.08E+07	3.1	0.050
Error / *Pogreška*	1.323E+09	68	1.95E+07		

Legend / *Legenda* (Scheer, 2007): *SS* – Summary of squares / *zbroj kvadrata*, *DF* – Degree of freedom / *stupanj slobode*, *MS* – Variance / *varijanca*, *F*– Critical value of Fischer Test / *kritična vrijednost Fišerova testa*, *p*– Level of significance / *razina značajnosti*

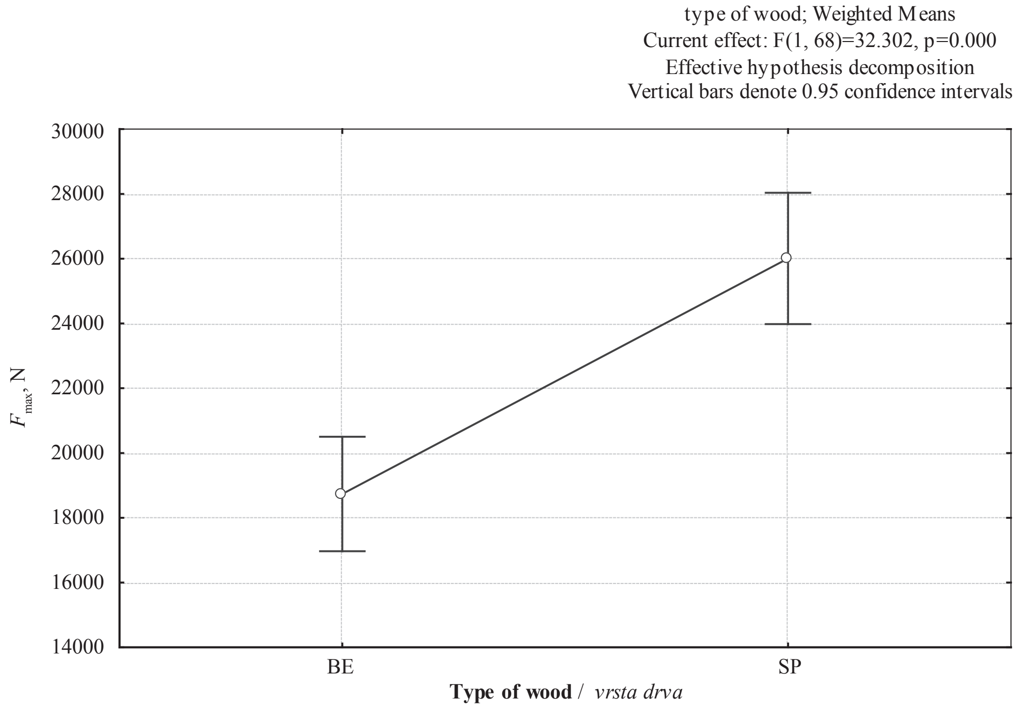

Figure 5 Graph of 95 % confidence interval for mean values of splitting force depending on wood species (beech wood and spruce wood)
Slika 5. Prikaz 95 %-tnog intervala pouzdanosti za srednjevrijednosti sile cijepanja u ovisnosti o vrsti drva (bukovina i smrekovina)

splitting wedge. The impact of splitting wedges is statistically significant, but among the monitored factors, its significance is the smallest.

The graph of splitting wedge - splitting strength in Figure 5 shows that the splitting force for sprucewood is significantly higher than for beechwood. This means that the sum of the averages of splitting forces measured are higher for sprucewood than for beech wood. The impact of the splitting wedge is included among random factors. Therefore, confidence intervals overlap (Figure 6), although the basic Table 1 analysis of variance shows that the effect of the splitting wedge

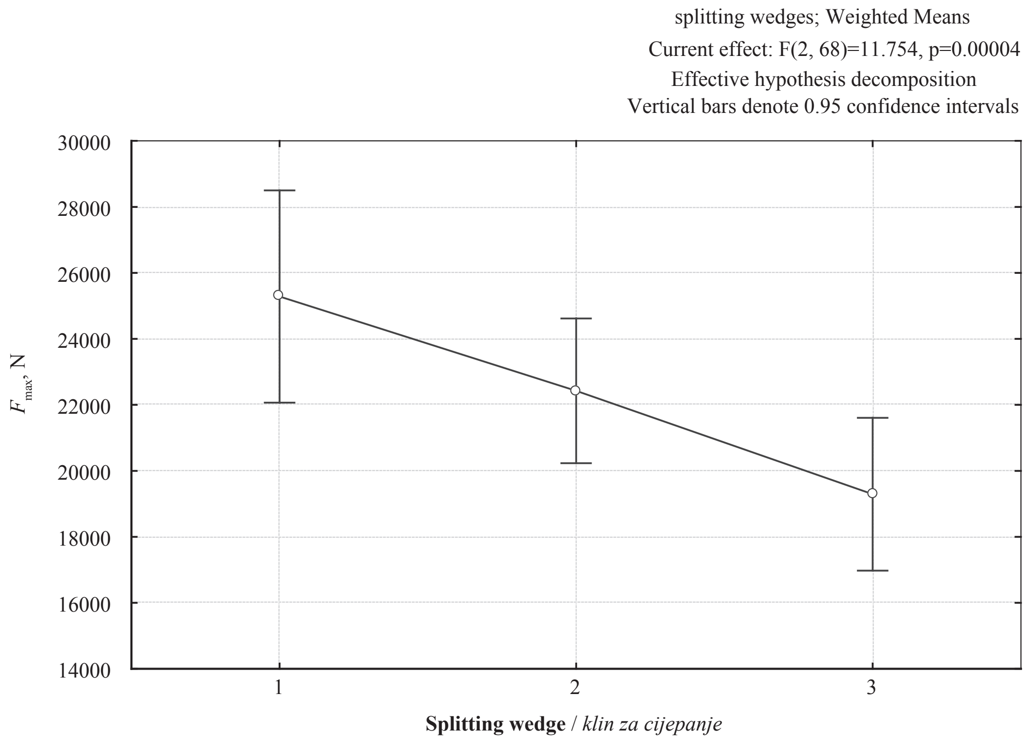

Figure 6 Graph of 95 % confidence interval for mean values of splitting force depending on the type of splitting wedges
Slika 6. Prikaz 95 %-tnog intervala pouzdanosti za srednje vrijednosti sile cijepanja u ovisnosti o obliku klina za cijepanje

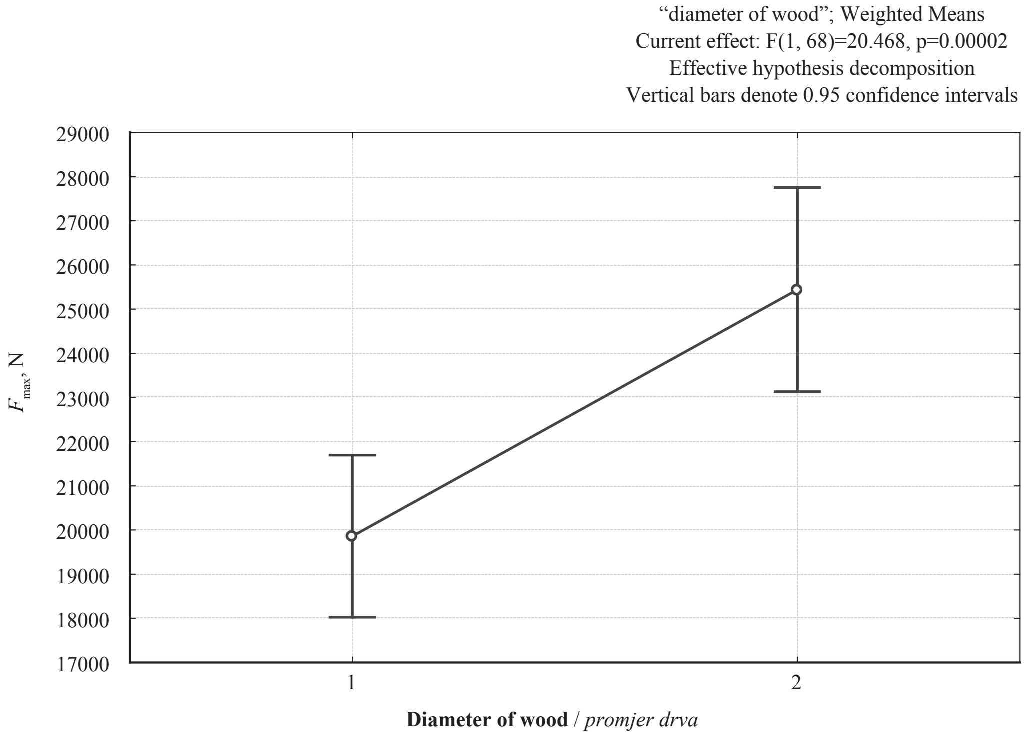

Figure 7 Graph of 95 % confidence intervals for mean values of splitting force depending on diameter of wood
Slika 7. Prikaz 95 %-tnog intervala pouzdanosti za srednje vrijednosti sile cijepanja u ovisnosti o promjeru drva

is statistically significant, i.e. the sum of the averages of splitting forces are the smallest for splitting wedge 3. Figure 7 shows clearly that the diameter of wood is statistically significant, i.e. the bigger diameter of the wood, the higher is the splitting force.

With the use of a simple splitting wedge (Figure 4), with maximum angle of 35°, maximum splitting force is produced compared to other wedges. With wedge No. 1, maximum force significantly increases linearly up to a value when the log tearing and cracking begins to grow faster than the splitting wedge. Subsequently F_{max} decreases to a value, which is needed for the distribution of fibres in the whole length of tribe. This force is many times less than the force F_{max}. When using refracted (degree) splitting wedge (Figure 4), with maximum angle of 20°, less splitting force is needed than with the simple wedge. Smaller maximum angle provides easier penetration of the wedge into tribe and its wider part provides the subsequent increase in the force required for splitting wood. The course of forces in the this splitting is more oscillating because splitting parts rub the edges of the wedge generating vibrations and causing the deformation of splitting force.

When using a concave splitting wedge (Figure 4), less splitting force is needed similarly as with refracted wedge. The maximum force is, relative to its force, almost 2/3 lower when using a simple wedge. Similarly as in the second case, forces are oscillating because splitting parts of the riven side rub the edges of the splitting wedge. In this case saving of splitting force is considerable, and in order to optimize it, the splitting force must be reduced as much as possible.

Three-factor analysis shows that splitting force of beech wood decreases with each splitting wedge and diameter of wood. With spruce wood, the mean values of splitting force are higher for the category wood diameter 1 (d = 27-31 cm).

For better evaluation of the measured data, categorized scatter plots were used (Figure 9). Figure 9 shows that when using beech wood of the increasing wood diameter, the mean splitting force increases, and with the splitting wedges 1 and 2, splitting force decreases. With spruce wood, the simple splitting wedge - 1 proved unsuitable for large diameter trees. For small diameter spruce wood, diameter factor proved to be opposite of splitting wedges 1, 2, 3, which explains the higher mean values of splitting force for wedge 2 and 3 for diameter of wood 1 (d = 27-31 cm) (Figure 8).

This is caused by physical and mechanical properties, and moisture of the spruce wood fibre saturation point (~ 34 %). The wedge is pushed deeper into the wood, thereby increasing contact zone of the splitting wedge, which results in a higher splitting force (Čadež *et al*., 2002). The weakest link is modullary rays that weaken wood and therefore splitting force is lower in beech wood (Antonović *et al*., 2007). Modullary rays consist exclusively of living parenchymatous cells with thin lignified walls, particularly at the point of connection to blood vessels or tracheids (Blomberg, 2006).

The results are similar to results of other authors (Stefanson, 1995; Tabarsa and Chui, 2000; Tabarsa and Chui, 2001), who say that the cleavability increases with the deformation in wood under compression. Siklienka and Kminiak (2013) say that in terms of

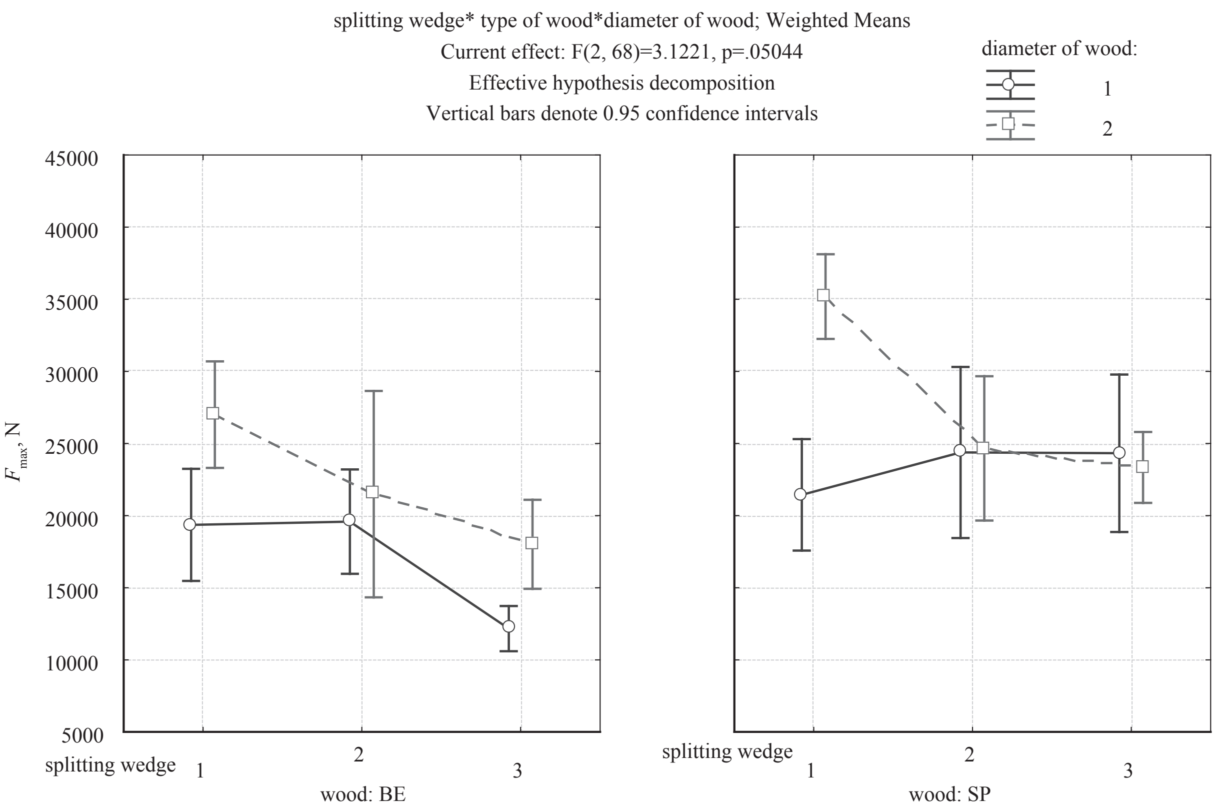

Figure 8 Graph of 95 % durability intervals for the mean values of splitting force for all input factors depending on wood diameter impact
Slika 8. Prikaz 95 %-tnog interval pouzdanosti srednjih vrijednosti sile cijepanja za sve ulazne parametre s obzirom na utjecaj promjera drva

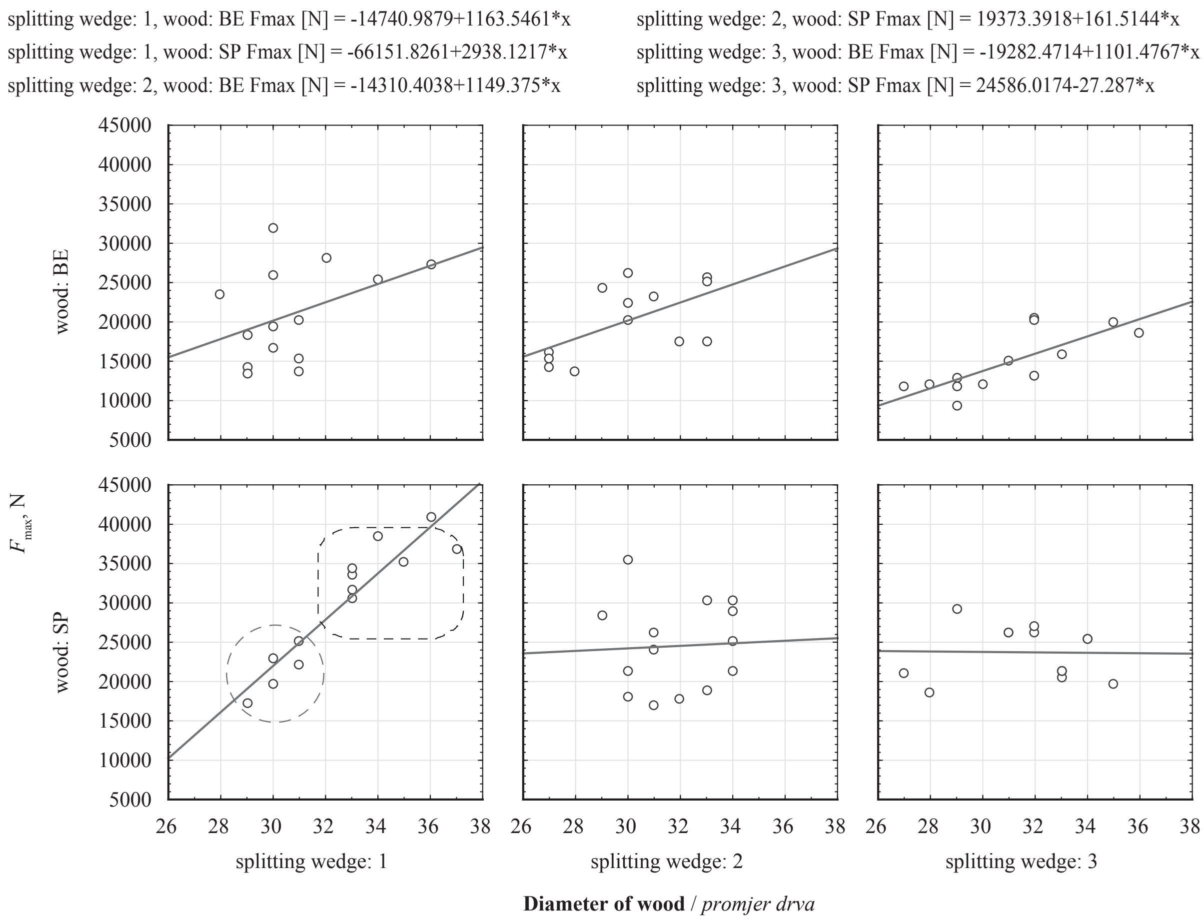

Figure 9 Dependence of splitting force by type of wood on diameter of wood and splitting wedges
Slika 9. Ovisnost sile cijepanja prema vrsti drva o promjeru drva i obliku klina

cleavability, an increase in water content in softwoods results in lower cleavability.

The above said is also shown by the monitorred length of wedge intrusion with the maximum splitting force l_1, in spruce wood higher by 30 % than in beechwood.

In the beech wood l_1 for splitting wedge 3, the length of intrusion is by 30 % shorter and for splitting wedge 2 by 56 % shorter.

In spruce wood, no influence has been demonstrated of splitting wedges 1, 2, and 3 on the length of wedge intrusion with the maximum splitting force l_1.

5 CONCLUSION
5. ZAKLJUČAK

The above theoretical analysis and the implementation of the experiment show that properly designed splitting wedge greatly influences the energy splitters.

When comparing the average values of the five repeated measurements, a decrease of splitting force can be observed. When comparing splitting wedges No. 1 and No. 2, splitting force ranges around 13 %, and when comparing splitting swedges No. 1 and No. 3, splitting force is over 50 %. However, it should be added that in terms of reducing the splitting force of the wedge, No. 3 is highly efficient.

Splitting wedges do not affect the splitting force in splitting spruce wood.

In terms of durability, it is less suitable because its thin and long blade is prone to dulling and bending and thereby requires the use of high strength steel. Increased complexity also requires re-sharpening of blunt wedge considering its concave shape. Further to the above, it can be concluded that the concave shape of the wedge is highly suitable for longitudinal splitting of logs, but its design and the need to use quality material have a negative impact on its economic aspect, and therefore nowadays it can only be seen on some splitters of reputable manufacturers.

It should be noted that it is necessary to take into consideration its life or durability.

Another option to reduce energy consumption is to reduce friction between the tool and logs, e.g. the method of surface coating, which can lead to further research of reducing adhesion and thus also the splitting forces.

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