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Influence of Moisture Content on Cutting Parameters and Fracture Characteristics of Spruce and Oak Wood

Utjecaj sadržaja vode na parametre piljenja i obilježja loma smrekovine i hrastovine

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ABSTRACT • *The objective of this study was to determine the effect of the moisture content on cutting parameters and fracture characteristics of spruce and oak wood. Samples of Norway spruce (Picea abies (L.) H. Karst.) and English oak (Quercus robur L.) were dried to required moisture content and then used for the machinability test on circular sawblade machine. Results indicate that cutting force and feed force increase with increasing moisture content up to the fiber saturation point (FSP). When the moisture content increases above the FSP, the minimum values of cutting and feed force are achieved. Based on performed experiments, the fracture toughness and shear yield strength were derived. Fracture toughness decreases with increasing moisture content. The minimum values of fracture toughness are achieved at the moisture content level above the FSP. Shear yield strength decreases linearly with increasing moisture content: the decrease is up to 17 % compared to samples with moisture content at the FSP. Based on calculated results, the influence of moisture content and wood species on cutting and fracture characteristics was discussed.*

KEYWORDS: *cutting force; feed force; fracture toughness; shear yield strength; moisture content*

SAŽETAK • *Cilj ovog istraživanja bio je utvrditi utjecaj sadržaja vode na parametre piljenja i obilježja loma smrekovine i hrastovine. Uzorci smrekovine (Picea abies (L.) H. Karst.) i hrastovine (Quercus robur L.) sušeni su do sadržaja vode potrebnoga za ispitivanje obradivosti na kružnoj pili. Rezultati pokazuju da se sila rezanja i posmična sila povećavaju s povećanjem sadržaja vode do točke zasićenosti vlakanaca (TZV). Kada se sadržaj vode poveća iznad TZV-a, postižu se najmanje vrijednosti sile rezanja i posmaka. Lomna žilavost i granica tečenja pri smicanju izvedene su na temelju provedenih istraživanja. S povećanjem sadržaja vode lomna se žilavost smanjuje. Najmanje vrijednosti lomne žilavosti zabilježene su pri sadržaju vode iznad TZV-a. Granica tečenja se pri smicanju linearno smanjuje s povećanjem sadržaja vode: smanjenje je do 17 % u usporedbi s uzorcima sa sadržajem vode pri TZV-u. Na temelju dobivenih rezultata razmatran je utjecaj sadržaja vode i vrste drva na obilježja piljenja i loma.*

KLJUČNE RIJEČI: *sila rezanja; posmična sila; lomna žilavost; granica tečenja pri smicanju; sadržaj vode*

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1 INTRODUCTION
1. UVOD

Wood is the world's most widely available material for a variety of applications in furniture production or timber construction (Moore, 2015). Its advantage over other materials, such as metals or ceramics, is the seemingly easy machinability with both manual tools and industrial machines (Czarniak *et al.*, 2019). Wood is composed of cellulose fibers, hemicellulose and lignin, which all contain a significant amount of free hydroxyl groups (Hartley and Hamza, 2016). Free hydroxyl groups and their amount in wood have an important effect on the fixation of water (Månsson, 1983; Rautkari *et al.*, 2013) and also on the movement of water in wood (Burr and Stamm, 2002; Sperry, 2003). Water in wood has a number of effects, from changes in shape due to swelling and shrinking (Stamm and Tarkow, 1947) to changes in the vast majority of mechanical and physical properties (Kretschmann, 2010). These properties also influence the behaviour of the material during machining, which has been the subject of much research in the past (Naylor and Hackney, 2013), however with inconsistent results in the effect of moisture on cutting conditions. In practice, the theory has long been established that higher humidity results in the fibres moving away from each other, and therefore the cutting force required to break wood with bound water content is smaller (Moradpour *et al.*, 2013a; Lucic *et al.*, 2004), because the mechanical properties of wood also decrease (Kollmann and Côté, 1984). However, this theory failed in many experiments and the measured main (parallel) cutting force was significantly higher with increasing humidity to the limit of fibre saturation (Porankiewicz *et al.*, 2011), which in turn supports the theory, which also takes into account the increasing plasticity of wet wood leading to greater friction during machining (Varkocek *et al.*, 2004), which has already been described in earlier works (McKenzee, 1961). However, the increase in the main cutting force can also be influenced by the higher weight of the evacuated chip, which follows from the work of (Porankiewicz *et al.*, 2011) and also has been taken into account in calculations of (Ratnasingam *et al.*, 1999). Recent research is also more inclined to this theory, but it is not very conclusive and there is not much research directly focused on measuring cutting conditions as a function of humidity by modern methods (Nasir and Cool, 2020). Earlier measurement methods prove to be insufficient for this issue, and therefore this work focuses on the application of a newer calculation method (Orlowski and Ochrymiuk, 2017), which is based on the system of fracture mechanics and was taken from metalworking (Atkins, 2003). The method works with shear strength and fracture toughness in order to determine the cutting force, similarly as in Hlásková *et al.* (2015), where it was applied to saw blade cutting. This method was also successfully applied in wood-based materials processing (Kowaluk *et al.*, 2007). Based on previous experiments, it can also be assumed that the effects of moisture and fibre direction will be different depending on the species and its density (Axelsson *et al.*, 1993a). For example, in Moradpour *et al.* (2013a), woody plants with similar densities, which might affect some variables, were investigated. Therefore, in this work, the effect of moisture content on cutting force was investigated on two species with very different densities, i.e., Norway spruce (*Picea abies* (L.) H. Karst.) and English oak (*Quercus robur* L.).

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Machinability test
2.1. Test obradivosti

The experiments were performed on a research device used for cutting with circular sawblades (Kopecký and Rousek, 2012). The research device simulates the conditions of circular sawing machine in actual operation. The parameters of the cutting process were recorded using sensors installed on the research device. More detailed characteristics are described in the paper of Hlásková *et al.* (2021).

The cutting process was performed with the circular sawblade for longitudinal wood cutting (Flury Systems AG, Arch, Switzerland), with carbide-tipped straight teeth. The construction parameters of the blade are shown in Table 1.

The machine settings were as follows: the optimum operating rotational speed n = 3800 min^{-1} i.e., cutting velocity v_c = 69 m·s^{-1}. The feed rate varied within the range of v_f = 2–22 m·min^{-1} with measuring steps presented in Table 2. This corresponds to the changing feed per tooth f_z and the mean uncut chip thickness h_m. A series of ten measurements were performed for each

Table 1 Parameters of saw blade
Tablica 1. Parametri lista kružne pile

Saw blade diameter *D*, mm *Promjer lista pile D*, mm	350
Teeth number *z* / *Broj zubi z*	28
Saw blade thickness *s*, mm *Debljina lista pile s*, mm	2.5
Kerf width *b*, mm / *Širina propiljka b*, mm	3.6
Tooth height *h*, mm / *Visina zuba h*, mm	10.5
Tooth pitch t_p, mm / *Korak zuba* t_p, mm	39.27
Clearance angle α_f, ° / *Leđni kut* α_f, °	15
Rake angle γ_f, ° / *Prsni kut* γ_f, °	20
Cutting edge radius ρ_0, μm *Radijus rezne oštrice* ρ_0, μm	8

Table 2 Kinematic parameters
Tablica 2. Kinematički parametri

Feed rate v_f, m/min *Posmična brzina* v_f, m/min	$v_f = f_z \cdot n \cdot z$	2	6	10	16	22
Mean uncut chip thickness h_m, mm *Srednja debljina odvojene strugotine* h_m, mm	$h_m = f_z \cdot \sin \varphi_{2m}$	0.011	0.033	0.055	0.089	0.123
Feed per tooth f_z, mm *Pomak po zubu* f_z, mm	$f_z = \frac{v_f}{n\ .\ z}$	0.019	0.056	0.094	0.15	0.207
Cutting speed v_c, m/s *Brzina rezanja* v_c, m/s	$v_c = \pi \cdot D \cdot n$	69.6				
Entry angle ψ_1, ° *Ulazni kut* ψ_1, °	$\psi_1 = arccos\left(\frac{a_e + e}{D/2}\right)$	31.0				
Exit angle ψ_2, ° *Izlazni kut* ψ_2, °	$\psi_2 = arccos\left(\frac{a_e}{D/2}\right)$	42.0				
Mean fiber cutting angle φ_{2m}, ° *Srednji kut zahvata,* φ_{2m}, °	$\varphi_{2m} = \frac{\psi_1 + \psi_2}{2}$	36.5				

feed rate and each type of machined material. Statistical analysis of variance ANOVA was used to assess the effect of the different MC of wood on the cutting parameters when cutting spruce and oak samples for each feed rate used in the experiment. Subsequently, a Scheffé test was performed at each feed rate (StatSoft, Hamburg, Germany). Statistical analyses were performed for a significance level $\alpha = 0.05$.

The rotary movement of the cutting tool and the constant feed rate result in a change of the uncut chip thickness. The model of the cutting is determined based on the technology used by characterizing the individual angles between the wood fiber grain, the tool planes, and the motion vectors. In the case of the longitudinal cutting of wood with a circular saw blade, it is the axial-perpendicular cutting model (φ_1 =90, φ_2 =0–90, φ_3 =0–90). The kinematic parameters are calculated according to the relations given in Table 2.

2.2 Materials
2.2. Materijali

Samples of Norway spruce (*Picea abies*) and English oak (*Quercus robur)* were dried to required moisture content (MC) and then used for the machinability test. The dimensions of the samples, the moisture content levels and densities for given moisture content are presented in Table 3.

The first level of MC (Sample 1) was approximately 5 % and was achieved by leaving the samples under normal room conditions at a temperature of approximately 18 to 20 °C and a humidity of 40 to 60 %. The second, third and fourth levels of MC were achieved by conditioning the samples in the climate chamber Memmert CTC 256 (Memmert GmbH, Schwabach, Germany), the condition setting was to 20 °C and 60 % humidity for the second level of MC (Sample 2); the condition setting was 20 °C and 80 % humidity for the third level of MC (Sample 3); and last temperature was 20 °C and humidity 90 % for the fourth level of MC (Sample 4). These conditions correspond to an approximate wood moisture content of 12 %, 20 % and FSP i.e., approximately 30 % MC. The fifth level of MC (50 %) was achieved by soaking samples in distilled water (Sample 5). The MC was measured after conditioning with the wood moisture meter (HMB-WS25, Merlin Technology GmbH, Ried im Innkreis, Austria), which is used for rapid non-destructive measurements of MC.

Table 3 Specification of machined material
Tablica 3. Specifikacija obrađenog materijala

Wood species *Vrste drva*	**Samples** *Uzorci*	**Dimension L × w × e, mm** *Dimenzije L × w × e,* mm	**Moisture content, %** *Sadržaj vode,* %	**Density, kg·m^{-3}** *Gustoća,* kg·m^{-3}
Spruce *smrekovina*	1	700 x 250 x 20	5.5	534
	2		11.9	542
	3		21.6	558
	4		32.1	571
	5		52.3	666
Oak *hrastovina*	1	700 x 250 x 20	4.7	698
	2		11.3	709
	3		20.2	732
	4		29.6	774
	5		49.3	873

2.3 Methodology for determining fracture parameters
2.3. Metodologija određivanja parametara loma

Using the measured moment of force M_c, and the feed force F_f, other components of the resulting active force (shear force, friction force, thrust force) were calculated based on the Ernst–Merchant circle force diagram (Hlásková *et al.*, 2019).

By cutting with a circular saw blade, the average total cutting power P_{c_T} can be calculated using the cutting forces model published by Atkins (2003, 2005). This model considers the elements of fracture mechanics: shear yield strength τ_γ and fracture toughness R. This methodology was developed for various woodworking technologies by the authors Orlowski, Ochrymiuk and Atkins (2014), Chuchala *et al.* (2020, 2021), Hlásková, Kopecký and Novák (2020) and Sinn *et al.* (2020). The model is expressed in the form of Eq. (1):

$$P_{c\_T} = z_a \cdot \frac{\tau_\gamma \cdot b \cdot \gamma}{Q_{shear}} \cdot h_m \cdot v_c + z_a \cdot \frac{R \cdot b}{Q_{shear}} \cdot v_c + P_{ac} + P_{dull} \quad (1)$$

Where z_a is the number of simultaneously cutting teeth; b is the kerf width; γ is the shear strain along the shear plane; and Q_{shear} is the coefficient of friction correction.

Total power consists of four components. The first component expresses the internal work of plasticity along the shear plane. The shear strain along the shear plane γ is described as:

$$\gamma = \frac{\cos \gamma_f}{\cos(\Phi - \gamma_f) \cdot \sin \Phi} \quad (2)$$

Where γ_f is the rake angle, and ϕ is the shear plane angle, which expresses the orientation of the shear plane.

The second component expresses the internal work required to separate/form a new surface, where the fracture toughness R corresponds to the specific work of separating the material.

The coefficient of friction correction Q_{shear} depends basically on the orientation of the shear plane to the workpiece and represents the effect of the friction between the rake face and the chips. Q_{shear} is expressed in a following form:

$$Q_{shear} = \left[1 - \left(\sin \beta_\mu \cdot \sin \Phi / \cos(\beta - \gamma_f) \cos(\Phi - \gamma_f)\right)\right] \quad (3)$$

Where $\beta_\mu = \tan^{-1}\mu$ is the friction angle, and μ is the coefficient of friction.

The third component expresses the kinetic energy for chip acceleration and its sweep out by the circular sawblade out of point of cutting. The third component does not affect the value of cutting resistance (Kopecký *et al.*, 2014):

$$P_{ac} = \dot{m} \cdot v_c^2 \quad (4)$$

$$\dot{m} = \frac{b \cdot l \cdot v_f \cdot \rho_w}{2} \quad (5)$$

Where l is the cut length, and ρ_w is the wood density.

The effect of chip acceleration power, P_{ac}, on the overall cutting power is negligible. Therefore, P_{ac} was omitted from the analyses performed in this research (Hlásková *et al.*, 2021).

The fourth component, P_{dull}, is the power that considers the dulling of cutting edges. It is important to note that this model assumes perfect cutting-edge sharpness; therefore, the component P_{dull} can be omitted.

The cutting force per single tooth is expressed by the slope of the line in the form:

$$F_c^{1z} = (k) \cdot h_m + q \quad (6)$$

$$F_c^{1z} = \left(\frac{\tau_\gamma \cdot b \cdot \gamma}{Q_{shear}}\right) \cdot h_m + \left(\frac{R \cdot b}{Q_{shear}}\right) \quad (7)$$

Where k corresponds to the slope and q to the intercept of the linear regression line with the y axis. The regression variable is the mean uncut chip thickness h_m. By comparing the regression equation with the experimental data obtained from the machinability tests, it is possible to determine the values of the fracture parameters (fracture toughness $R_{\|\perp}$, and shear yield strength $\tau_{\gamma\|\perp}$).

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Cutting force
3.1. Sila rezanja

Figure 1 shows an almost linear increase in the cutting force per one tooth occurred along with an increasing uncut chip thickness, which confirms the theoretical assumptions (Eq. 6). In addition, Figure 1 shows the coefficients of determination r^2, and the regression equations of the cutting force per one tooth as a function of the uncut chip thickness.

All tests showed statistically significant differences in the mean values of the cutting forces for each feed rate. Therefore, we were able to statistically prove the effect of MC of wood on the value of the cutting force when cutting spruce wood and oak wood with a circular sawblade.

Figure 1 presents the well-known fact that higher cutting force is required when cutting hardwood. When machining spruce samples compared to oak samples, the cutting force is reduced by up to 20 %. When cutting oak samples, the direction of the linear line of regression increases steeper compared to spruce samples. The observed trend is in line with the research of Willinston (1988) and Aguilera and Martin (2001). In the past, many experiments have been focused on the issue of machining softwood and hardwood (Kivimaa, 1950; McKenzie, 1960; Koch, 1964; Goli *et al.*, 2009; Wy-

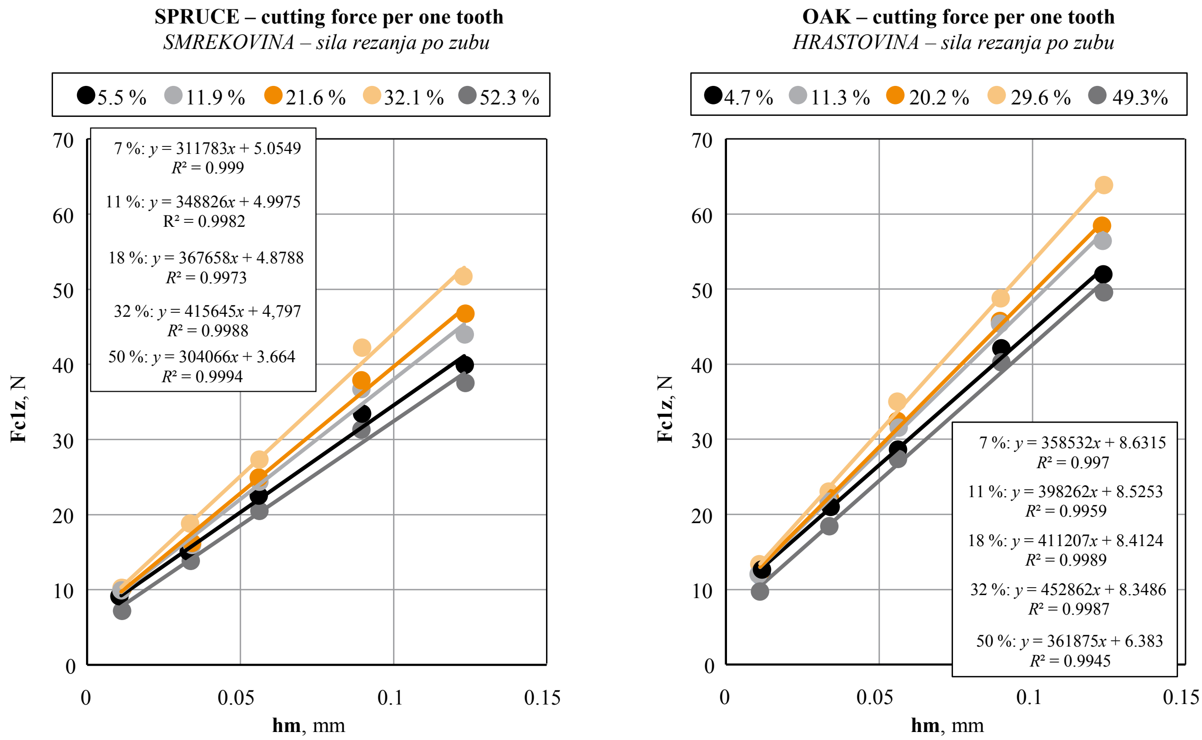

Figure 1 Dependence of average value of measured cutting force per one tooth as a function of mean uncut chip thickness
Slika 1. Ovisnost prosječne vrijednosti sile rezanja po jednom zubu kao funkcije srednje debljine neodvojene strugotine

eth, Goli and Atkins, 2009; Cristóvão *et al.*, 2011; Moradpour *et al.*, 2013b). The results of our experiment confirm their claim that the cutting force depends on the wood species.

Moreover, Figure 1 indicates the effect of the MC on the value of the cutting force. The values of cutting force increase with increasing wood moisture content up to the FSP. If the wood cell lumens are filled with free water, the values of the cutting force decrease significantly - by 22 % compared to the samples with MC at the FSP for oak, and by 27 % for spruce. The highest value of cutting force was observed when machining oak and spruce samples at FSP. Wood saturated with free water had the lowest cutting force values. Cristóvão *et al.* (2011), Moradpour *et al.* (2013b) and Lucic *et al.* (2004) state in their publications that the increasing MC up to the FSP results in a deterioration of the mechanical properties of the wood and thus causes a reduction in the cutting force. Our results are contrary to the assumption of the above authors, but they are in accordance with the following researchers: Increasing the MC of wood to FSP results in an increase in the distance between the cellulose chains (Kollmann and Côté, 1984) and thus the wood swells, resulting in increased friction between the tool and workpiece kerf sides and greater gripping at the cutting point. In the range of bound water, we must also consider the degree of elastic deformation, which increases with higher moisture content. As a result of these deformations, the cutting tool is gripped in the cut (Varkocek *et al.*, 2004), which leads to an increase in the value of the cutting force. Postnikov (1965) and Mikolašik (1981) stated that cutting force and power requirements increase with increasing MC of wood, despite the decrease in mechanical properties of wood. They explained this effect by saying that, for a workpiece with a higher moisture content, the friction between the tool, the chips and both workpiece kerf sides increase the cutting force more than the decreasing mechanical properties of the wood. The effect of MC on the value of the cutting force may vary depending on the observed wood species (Cristóvão *et al.*, 2011; Moradpour *et al.*, 2013b). Axelsson *et al.*, 1993a claim that the MC can affect the cutting force positively or negatively depending on the cutting direction and wood temperature. Porankiewicz *et al.* (2011) argued that the parallel cutting force increases with the MC from 8 % to 30 % and then, decreases slightly with a further increase in MC up to 133 %.

The MC above the FSP contains free water, which helps to reduce the friction at the tool rake, acts as a lubricant in the cut, and consequently reduces the cutting force (Siklienka *et al.*, 2017).

3.2 Feed force
3.2. Posmična sila

Figure 2 shows that the force required to feed the workpiece in the sawblade at a speed of 2–22 m/min ranges from 10 N to 35 N for oak samples and from 8 to 31 N for spruce samples. The higher feed force is needed for machining hardwood than softwood; when machining oak samples, the increase in the feed force is up to 15

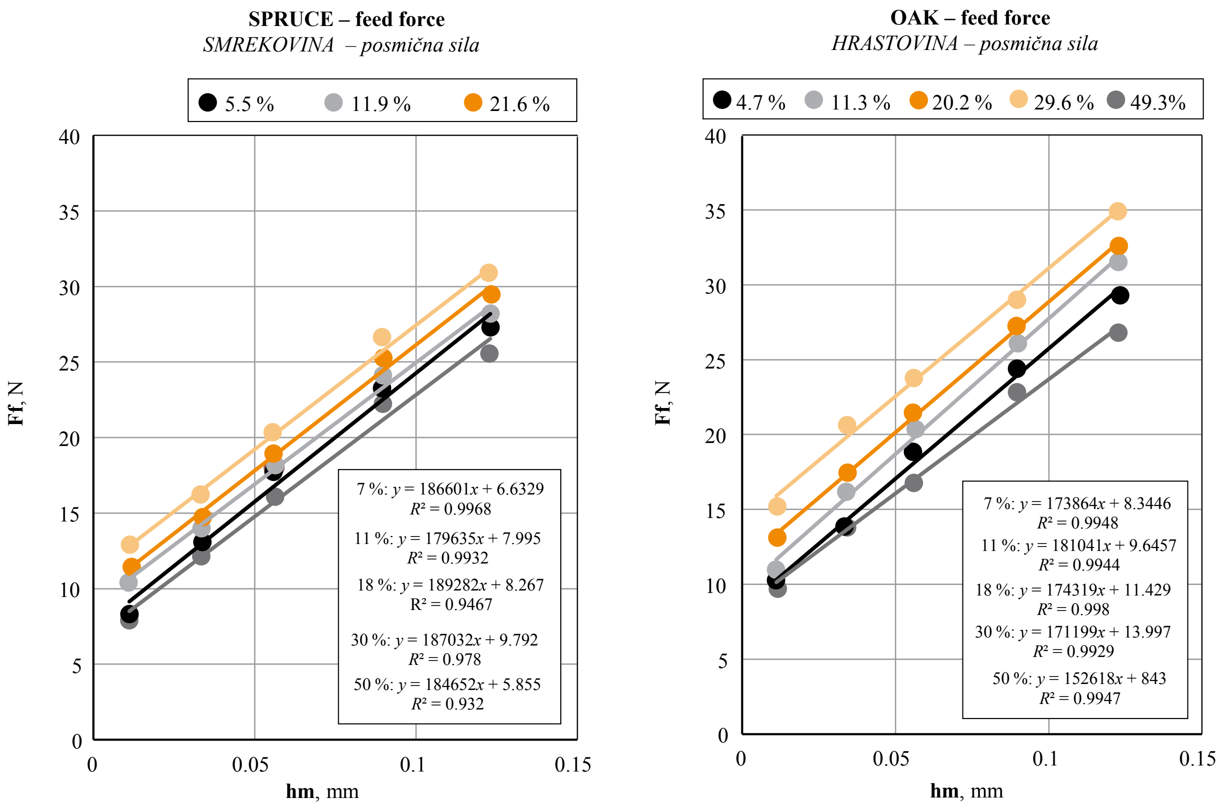

Figure 2 Dependence of average value of feed force as a function of mean uncut chip thickness
Slika 2. Ovisnost prosječne vrijednosti posmične sile kao funkcije srednje debljine neodvojene čestice

% compared to spruce samples. The dependence is linear with a high coefficient of determination. Koch (1964), Moradpour *et al.* (2013b), Kminiak and Kubs (2016) found that cutting force increases with feed speed. Increasing the feed speed (connected with increasing uncut chip thickness) is generally associated with higher cutting force and power (Axelsson *et al.*, 1993b; Cristóvão *et al.*, 2011; Aguilera and Martin, 2001) (Axelsson *et al.,* 1993, Vazquez-Cooz and Meyer, 2006; Aguilera, 2011a; Cristóvão *et al*., 2012).

We have also found that, as the MC increases, the feed force increases in the range of bond water. Significant elastic deformations occur in the saw kerf and in gripping the cutting tool at the cutting point by sides of saw kerf, thus increasing the feed force. At MC above the FSP, the feed force decreases. At this MC level, the values of the feed force are the lowest during machining with the circular saw blade. The decrease in feed force of oak samples compared to sample no. 4 (at the FSP) was 25 % and up to 20 % for spruce samples. Due to the presence of free water, which acts as a lubricant, the feed mechanisms do not require such a large feed force, as is the case with dry wood.

3.3 Fracture parameters
3.3. Parametri loma

Based on the experiments performed, the input parameters (ϕ, μ, β_μ, γ, Q_{shear}) for the axial-perpendicular model were calculated for cutting with the circular sawblade (b = 3.5 mm, φ_{2m} = 36.5°). The characteristic data were estimated according to Atkins (2005). The main parameters of the model were determined based on regression analysis; the fracture toughness, $R_{\parallel\perp}$ from the intercept; the shear yield strength, $\tau_{\gamma\parallel\perp}$ from its slope. The shear yield strength values $\tau_{\gamma\parallel\perp}$ were calculated for the uncut chip thickness, h_m > 0.12 mm, when the cutting resistance was practically constant (Orlowski and Palubicki, 2009). The values of the fracture parameters are given in Table 4. Fracture toughness and shear yield strength are given in the literature for the individual directions of loading and for the main directions of crack propagation. However, our results represent a combination of these basic directions because the machining was performed in the axial-perpendicular direction of cutting. The values of the fracture parameters are relevant only for a given cutting edge, and therefore cannot be considered as the material constants (Hlásková *et al.*, 2020).

Figure 3 summarizes the fracture toughness and shear yield strength in boxplots to illustrate the influence of the wood species and MC on fracture parameters.

Fracture toughness of spruce samples is up to 42 % lower compared to oak samples. Ashby *et al.* (1985) claim that the fracture toughness of dry wood depends on the density. The statement is justified by the fact that higher density samples provide greater resistance to crack propagation due to higher wood mass concentra-

Table 4 Fracture parameters
Tablica 4. Parametri loma

Wood species *Vrsta drva*	w, %	μ	β_μ, °	ϕ, °	γ	Q_{shear}	$\tau_{\gamma\|\|\perp}$, MPa Mean Score ± SD	$R_{\gamma\|\|\perp}$, J/m² Mean Score ± SD
Spruce *smrekovina*	5.5	0.46	25.23	42.63	1.468	0.797	50.23 ± 0.891	1404.14 ± 86.835
	11.9	0.33	23.72	45.63	1.457	0.745	46.48 ± 0.959	1388.19 ± 100.646
	21.6	0.41	22.51	43.75	1.484	0.711	45.11 ± 0.939	1355.22 ± 105.631
	32.1	0.40	21.88	44.06	1.479	0.716	43.43 ± 1.206	1332.5 ± 90.396
	52.3	0.43	23.06	43.47	1.489	0.705	42.21 ± 1.846	1017.77 ± 133.523
Oak *hrastovina*	4.7	0.68	34.26	37.866	1.608	0.625	61.11 ± 1.179	2397.64 ± 90.454
	11.3	0.56	29.29	40.31	1.549	0.656	57.02 ± 1.204	2368.14 ± 91.315
	20.2	0.53	28.19	40.91	1.536	0.665	55.32 ± 1.436	2336.77 ± 121.679
	29.6	0.54	28.75	40.62	1.542	0.661	51.397 ± 1.251	2319.06 ± 79.739
	49.3	0.64	32.59	38.71	1.586	0.636	50.62 ± 1.969	1773.06 ± 119.767

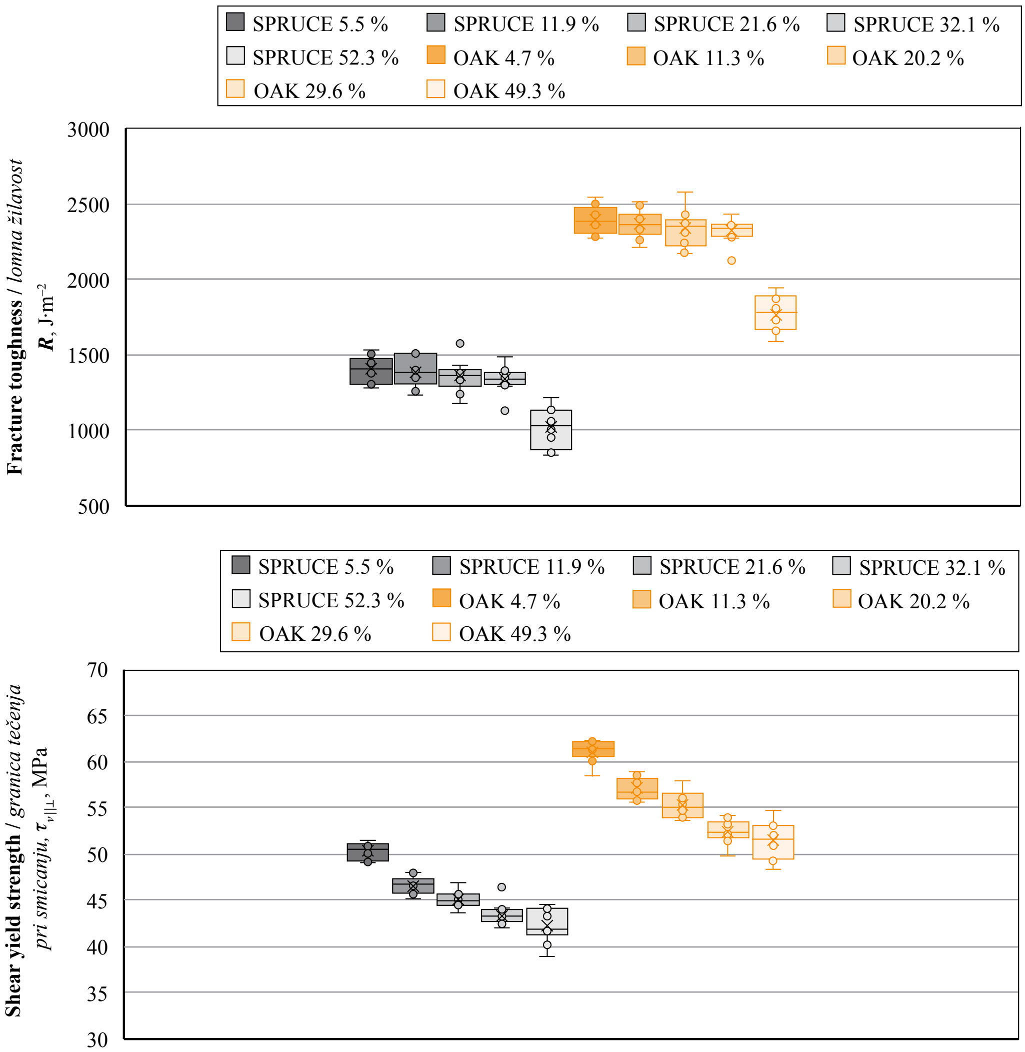

Figure 3 Fracture toughness and shear yield strength for all moisture content levels
Slika 3. Lomna žilavost i granica tečenja pri smicanju za pojedine sadržaje vode

tion (Petterson and Bodig, 1983). The same conclusion was published by Leicester (1974), Kretschmann *et al.* (1990) and Gibson and Ashby (1997).

Few previous investigations have considered the dependency of fracture behavior on moisture content (Majano-Majano *et al.*, 2012). Kretschmann (2010) states that there is only limited information on the effect of MC on fracture toughness. This information suggests that fracture toughness is either insensitive to MC or increases with decreasing wood MC. Petterson and Bodig (1983) report that fracture toughness decreases with increasing MC for various wood samples. Our results agree with the literature and confirm that higher MC level negatively affects the mechanical properties of wood. Fracture toughness decreases with increasing moisture content: the decrease for oak samples is up to

28 % and for spruce samples up to 26 %. The minimum values of fracture toughness are achieved at the MC level above FSP for spruce ($R_{\gamma\parallel\perp}$ = 1018 J·m^{-2}) and oak samples ($R_{\gamma\parallel\perp}$ = 1773 J·m^{-2}). Nikitin (1966) explains this claim by the penetration of water into the crystal structure of cellulose microfibrils. This leads to a reduction in crystallinity and a consequent reduction in fracture toughness. The maximum values are reached at MC of approximately w = 5 %, for spruce ($R_{\gamma\parallel\perp}$ = 1404 J·m^{-2}) and oak samples ($R_{\gamma\parallel\perp}$ = 2398 J·m^{-2}). According to Conrad *et al*. (2003), the fracture toughness of solid wood reaches a maximum between 6 to 8 % MC.

Due to the fibrous structure, wood has different shear yield strengths in three perpendicular directions. Our method of breaking the workpiece is most closely approached by shear in the transverse plane, where the forces act perpendicular to the fibers in the radial or tangential direction. This type of failure is often called "cutting fibers" or "shear strength" (Pozgaj, 1993). Shear yield strength for oak samples is up to 23 % higher compared to spruce samples. Values of the shear yield strength are higher for oak samples than for spruce samples at all moisture content levels. Shear yield strength decreases linearly with increasing moisture content: the decrease for oak samples is up to 17 % and for spruce samples up to 16 %. The minimum values of shear yield strength are achieved at the moisture content level above FSP: for spruce samples ($\tau_{\gamma\parallel\perp}$ = 42 MPa) and for oak samples ($\tau_{\gamma\parallel\perp}$ = 51 MPa). The maximum values are reached at moisture content of approximately w = 5 %, for spruce ($\tau_{\gamma\parallel\perp}$ = 50 MPa) and oak samples ($\tau_{\gamma\parallel\perp}$ = 61 MPa). Naylor *et al.* (2012) claim that a linear decrease in shear strength was observed with an increase in moisture content in the range 6.5–35 %. The three hardwoods studied showed the highest values, and they were approximately 45 % higher than those of softwoods.

4 CONCLUSIONS
4. ZAKLJUČAK

Contrary to the opinion of some authors, the results have shown that, during circular sawing, the cutting force and feed force increased with increasing MC up to the FSP. As the MC increases above the FSP, the cutting and feed forces significantly decrease (reaching the minimum values). For a workpiece with a higher moisture content, the tool is gripped in the saw kerf and the friction between the tool, the chips and both workpiece kerf sides increase the cutting force more than the decreasing mechanical properties of the wood. If the wood contains free water, the cutting and feed force are reduced because the free water acts as a lubricant in the cut and helps to reduce friction at the tool rake.

On the basis of the measurements, the basic relationships for calculating fracture toughness and shear yield strength of spruce and oak samples were derived without the need to perform complex fracture tests. The values of fracture parameters are only suitable for the axial-perpendicular cutting model and cannot be considered as material constants. It can be concluded that the moisture content of wood affects the fracture toughness $R_{\parallel\perp}$, and shear yield strength $\tau_{\gamma\parallel\perp}$. As the moisture content increases, the values of these parameters decrease. The minimum values of fracture parameters are achieved at the moisture content level above FSP.

5 REFERENCES
5. LITERATURA

1. Ahmet, K.; Dai, G.; Jazayeri, S.; Tomlin, R., 1999: Experimental procedures for determining the equilibrium moisture content of twenty timber species. Forest Products Journal, 49: 88-93.
2. Barkas, W. W., 1936: Wood-water relationships, 2: The fibre saturation point of beech wood. Proceedings of the Physical Society, 48: 576-588. https://doi.org/10.1088/0959-5309/48/4/305
3. Böhner, G., 1996: Überlegungen und Ergänzungen zum „Keylwerth-Diagramm". Holz als Roh-und Werkstoff, 54: 73-79. https://doi.org/10.1007/s001070050139
4. Box, G. E. P.; Draper, N. R., 2007: Response surfaces, mixtures, and ridge analyses, 2nd ed. Wiley Series in Probability and Statistics. Wiley, Hoboken, NJ, USA.
5. Browning, B. L., 1966: The chemistry of wood. Interscience Publishers Inc., New York, USA.
6. Brunner, R., 1987: Die Schnittholztrocknung, 5th ed. Brunner-Hildebrand GmbH, Hannover, Germany.
7. Chatterjee, S.; Hadi, A. S., 2013: Regression analysis by example, 5th ed. Wiley, Somerset, UK.
8. Côté, W. A., 1964: Anatomy and ultrastructure of reaction wood. In: Cellular Ultrastructure of Woody Plants. Presented at the Advanced Science Seminar, Syracuse University Press, Upper Saranac Lake, New York.
9. Côté, W. A.; Day, A. C.; Timell, T. E., 1969: A contribution to the ultrastructure of tension wood fibers. Wood Science and Technology, 3: 257-271. https://doi.org/10.1007/BF00352301
10. Felten, J.; Sundberg, B., 2013: Biology, chemistry and structure of tension wood. In: Cellular Aspects of Wood Formation, Plant Cell Monographs. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 203-224. https://doi.org/10.1007/978-3-642-36491-4_8
11. Fengel, D.; Wegener, G., 1983: Wood: Chemistry, ultrastructure, reactions. Walter de Gruyter, Berlin. https://doi.org/10.1515/9783110839654
12. Glass, S. V.; Zelinka, S. L.; Johnson, J. A., 2014: Investigation of historic equilibrium moisture content data from the Forest Products Laboratory (No. FPL-GTR-229). Forest Products Laboratory, Madison, WI, USA.
13. Groover, A., 2016: Gravitropisms and reaction woods of forest trees – evolution, functions and mechanisms. New Phytol, 211: 790-802. https://doi.org/10.1111/nph.13968
14. Hailwood, A. J.; Horrobin, S., 1946: Absorption of water by polymers: analysis in terms of a simple model. Transactions of the Faraday Society, 42: B084. https://doi.org/10.1039/tf946420b084
15. Hernández, R. E., 2007: Moisture sorption properties of hardwoods as affected by their extraneous substances,

wood density and interlocked grain. Wood and Fiber Science, 39: 132-145.
16. Jankowska, A., 2018: Assessment of sorptive properties of selected tropical wood species. Drvna industrija, 69: 35-42. https://doi.org/10.5552/drind.2018.1733
17. Jankowska, A.; Drożdżek, M.; Sarnowski, P.; Horodeński, J., 2016: Effect of extractives on the equilibrium moisture content and shrinkage of selected tropical wood species. BioResources, 12: 597-607. https://doi.org/10.15376/biores.12.1.597-607
18. Jannot, Y.; Kanmogne, A.; Talla, A.; Monkam, L., 2006: Experimental determination and modelling of water desorption isotherms of tropical woods: afzelia, ebony, iroko, moabi and obeche. Holz als Roh- und Werkstoff, 64: 121-124. https://doi.org/10.1007/s00107-005-0051-2
19. Klement, I.; Vilkovská, T.; Uhrín, M.; Barański, J.; Konopka, A., 2019: Impact of high temperature drying process on beech wood containing tension wood. Open Engineering, 9: 428-433. https://doi.org/10.1515/eng-2019-0047
20. Klement, I.; Vilkovská, T.; Vilkovský, P.; Hýsek, Š., 2020: Structural differences between reaction wood and opposite wood with different drying temperatures. BioResources, 15: 4407-4416. https://doi.org/10.15376/biores.15.2.4407-4416
21. Kojs, P.; Malik, I.; Wistuba, M.; Stopka, R.; Trabka, K., 2012: Mechanizmy wzrostu ekscentrycznego i formowania się drewna reakcyjnego w kontekście badań dendrogeomorfologicznych – wprowadzenie do nowej hipotezy / Model of eccentric growth and reactive wood formation in the context of dendrogeomorphological research – introduction to a new hypothesis. Studia i Materiały Centrum Edukacji Przyrodniczo-Leśnej, 14: 147-156.
22. Kollmann, F., 1936: Technologie des Holzes, 1st ed. Springer, Berlin.
23. Kúdela, J.; Čunderlík, I., 2012: Bukové drevo, štruktúra, vlastnosti, použitie / Beech wood, structure, properties, use. Technická univerzita vo Zvolene, Zvolen.
24. Langrish, T. A. G.; Walker, J. C. F., 1993: Transport processes in wood. In: Primary Wood Processing: Principles and Practice. Springer Netherlands, Dordrecht, pp. 121-152. https://doi.org/10.1007/978-94-015-8110-3_5
25. Majka, J.; Olek, W., 2013: The influence of equilibrium moisture content data on accurate control of timber kiln drying intensity. In: Procedings of 4th European Drying Conference (EuroDrying'2013), European Federation of Chemical Engineering, Paris, France.
26. Popper, R.; Niemz, P., 2009: Wasserdampfsorptionsverhalten ausgewählter heimischer und überseeischer Holzarten. Bauphysik, 31: 117-121. https://doi.org/10.1002/bapi.200910017
27. Popper, R.; Niemz, P.; Croptier, S., 2009: Adsorption and desorption measurements on selected exotic wood species: Analysis with the Hailwood-Horrobin model to describe the sorption hysteresis. Wood Research, 54: 43-56. https://doi.org/10.3929/ethz-a-006104740
28. Redman, A. L.; Bailleres, H.; Turner, I.; Perré, P., 2016: Characterisation of wood-water relationships and transverse anatomy and their relationship to drying degrade. Wood Science and Technology, 50: 739-757. https://doi.org/10.1007/s00226-016-0818-0
29. Salin, J.-G., 2011: Inclusion of the sorption hysteresis phenomenon in future drying models. Some basic considerations. Maderas: Ciencia y Tecnologia, 13: 173-182. https://doi.org/10.4067/S0718-221X2011000200005
30. Scurfield, G., 1973: Reaction wood: Its structure and function. Science, 179: 647-655. https://doi.org/10.1126/science.179.4074.647
31. Scurfield, G.; Wardrop, A., 1962: The nature of reaction wood. VI. The reaction anatomy of seedlings of woody perennials. Australian Journal of Botany, 10: 93. https://doi.org/10.1071/BT9620093
32. Simón, C.; Esteban, L. G.; de Palacios, P.; Fernández, F. G.; Martín-Sampedro, R.; Eugenio, M. E., 2015: Thermodynamic analysis of water vapour sorption behaviour of juvenile and mature wood of *Abies alba* Mill. Journal of Materials Science, 50: 7282-7292. https://doi.org/10.1007/s10853-015-9283-7
33. Simpson, W. T., 1973. Predicting equilibrium moisture content of wood by mathematical models. Wood and Fiber Science, 5: 41-49.
34. Skaar, C., 1988: Wood-water relations. Springer-Verlag, Berlin; New York.
35. Spalt, H., 1958: Water vapor sorption by wood. Forest Products Journal, 8: 288-295.
36. Tarmian, A.; Perré, P., 2009: Air permeability in longitudinal and radial directions of compression wood of *Picea abies* L. and tension wood of *Fagus sylvatica* L. Holzforschung, 63: 352-356. https://doi.org/10.1515/HF.2009.048
37. Tarmian, A.; Remond, R.; Dashti, H.; Perré, P., 2012: Moisture diffusion coefficient of reaction woods: compression wood of *Picea abies* L. and tension wood of *Fagus sylvatica* L. Wood Science and Technology, 46: 405-417. https://doi.org/10.1007/s00226-011-0413-3
38. Tarmian, A.; Remond, R.; Faezipour, M.; Karimi, A.; Perré, P., 2009: Reaction wood drying kinetics: tension wood in *Fagus sylvatica* and compression wood in *Picea abies*. Wood Science and Technology, 43: 113-130. https://doi.org/10.1007/s00226-008-0230-5
39. Tulik, M.; Jura-Morawiec, J., 2011: Drewno reakcyjne a architektura korony drzewa / Reaction wood and tree crown architecture. Sylwan, 155: 808-815.
40. Wardrop, A.; Davies, G., 1964: The nature of reaction wood. VIII. The structure and differentiation of compression wood. Australian Journal of Botany, 12: 24. https://doi.org/10.1071/BT9640024
41. Weichert, L., 1963: Untersuchungen über das Sorption- und Quellungsverhalten von Fichte, Buche und Buchen-Preßvollholz bei Temperaturen zwischen 20 ° und 100 °C. Holz als Roh-und Werkstoff, 21: 290-300. https://doi.org/10.1007/BF02610962
42. Wengert, E. M., 1976: Predicting average moisture content of wood in a changing environment. Wood and Fiber Science, 7: 264-273.
43. ***Wood Handbook, 2010: Wood as an Engineering Material. General Technical Report No. FPL-GTR-190, Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI, USA.

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