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Analyses of Shear Angle in Orthogonal Cutting of Pine Wood

Analiza kuta smicanja pri ortogonalnom rezanju borovine

ABSTRACT • *The determination of energy effects for wood machining processes, such as cutting power and cutting forces, is very useful in designing of manufacture process of wooden products. A more accurate prediction of cutting forces requires a correct determination of the shear angle value, which can be determined using various models. In this article, shear angle values for an orthogonal linear cutting process of pine wood are determined. The pine wood analysed was represented by two groups of samples with different moisture content levels, 12 % and 20 %. Three different models were used to determine the shear angle values: the Merchant model, which is based on the rake angle and the angle of friction, model based on chip compression ratios and Atkins model based on material properties (elements of fracture mechanics). The values obtained have been analysed for comparison. Results showed that the values of the shearing angles determined from the chip compression ratios turned out to be higher than the values from Merchant equation. The shear angles determined from the Atkins model are, as expected, lower than those determined from the Merchant model. Furthermore, the shear angle values for moisture content of 20 % are higher than for moisture content of 12 %.*

KEYWORDS: *shear angle; orthogonal cutting; chip compression ratio; pine wood; fracture toughness*

SAŽETAK • *Određivanje energijskih veličina tijekom procesa obrade drva, poput snage rezanja i sile rezanja, vrlo je korisno pri projektiranju procesa proizvodnje drvenih predmeta. Za točnije predviđanje sila rezanja potrebno je ispravno odrediti vrijednost kuta smicanja, što se može postići primjenom različitih modela. U ovom su članku određene vrijednosti kutova smicanja za ortogonalno linearno rezanje borovine. Analizirano borovo drvo predstavljeno je dvjema skupinama uzoraka različitog udjela sadržaja vode, 12 i 20 %. Za određivanje vrijednosti kuta smicanja primijenjena su tri različita modela: Merchantov model utemeljen na prsnom kutu i kutu trenja; model zasnovan na omjerima kompresije strugotine i Atkinsov model, kojemu su glavna polazišta svojstva materijala (elementi mehanike loma). U radu je prezentirana usporedba dobivenih vrijednosti. Na temelju rezultata uočeno je da su vrijednosti kutova smicanja određene iz omjera kompresije strugotine veće od vrijednosti dobivenih Merchantovom jednadžbom. Kutovi smicanja određeni prema Atkinsovu modelu očekivano su niži od onih određenih uz pomoć Merchantova modela. Nadalje, vrijednosti kuta smicanja za uzorke sa sadržajem vode od 20 % veće su od kutova smicanja za uzorke sa sadržajem vode od 12 %.*

KLJUČNE RIJEČI: *kut smicanja; ortogonalno rezanje; omjer kompresije strugotine; borovina; lomna žilavost*

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1 INTRODUCTION
1. UVOD

The determination of energy effects for wood machining processes is a frequently studied issue and the results are very useful for the design of machining processes (Nasir and Cool, 2020; Atanasov and Kovatchev, 2019; Atanasov, 2021). Most of the analytical modelling works aim at producing equations that can determine cutting forces, without any experimental work. This approach is useful since other parameters can be derived by cutting forces, and analysis of tool wear, surface integrity and workpiece quality can be carried out. The problem involved in the determination of the cutting effects ends up in determining a suitable relationship between the shear angle Φ_c, the rake angle γ_f and the friction coefficient μ between a chip and the rake plane A_γ (Markopoulos, 2013). Attempting to find a unique shear angle relationship has long attracted scientific and practical interest. Ståhl *et al*. (2012) report that more than 50 relationships for determining shear angle can be found in the literature in the last 100 years. On the other hand, Markopoulos (2013) cites 13 such functions in his book.

A numerical model for orthogonal cutting using the material point method was applied by Nairn (2016) to woodcutting using a bench plane. The cutting process was modelled by accounting for surface energy associated with wood fracture toughness for crack growth parallel to the grain. The simulations were verified by comparison to an analytical model and then used to conduct virtual experiments on wood planing.

Experimental works compared to modelling of the wood cutting process is a larger group. The strain associated with orthogonal cutting with and against the grain of hinoki (*Chamaecyparis obtusa*) was measured by Matsuda *et al*. (2019). A digital image correlation (DIC) method has been used in a number of published works to measure strain distribution (Matsuda *et al*., 2018, 2019; Ohtani and Iida, 2015; Radmanović *et al*., 2017).

The values of shear angles determined based on the Atkins model (Atkins, 2005) for sawing wood on a frame sawing machine, a band sawing machine and a circular sawing machine have been published in the papers of Orlowski *et al*. (2013, 2014).

The goal of this work was to demonstrate how the method of determination of shear angle can affect the obtained values while pine wood (*Pinus sylvestris* L.) is cut in the orthogonal process. The new features in this paper is that the experimental values of shear angles, determined in a function of the chip compression ratio (Grzesik, 2017, 2018; Ståhl *et al*., 2012), are compared to the values calculated from the Merchant equation (Merchant, 1945) and the values of shear angles computed based on the Atkins model

(Atkins, 2005), which incorporate realistic effects of cut material properties.

2 THEORETICAL BACKGROUND
2. TEORIJSKE OSNOVE

Orthogonal cutting represents a two-dimensional mechanical problem with no side curling of the chip considered. It represents only a trickle of machining processes. Nevertheless, it is widely used in theoretical and experimental work due to its simplicity. The case of free orthogonal cutting occurs when (Grzesik, 2016, 2017; ISO 3002-4, 1984):
- cutting speed v_c is perpendicular to the cutting edge,
- the cutting edge S is rectilinear,
- tool cutting edge angle is $\kappa_r = 90°$, and inclination angle is $\lambda_s = 0°$,
- the width of the cut layer (sample width) W_s is much greater than the uncut thickness h,
- the length of the active cutting edge is greater than the cutting width.

2.1 Prediction of shear angle with Merchant model
2.1. Predviđanje kuta smicanja Merchantovim modelom

The engineering approach to the description of plastic deformation in the cutting zone is simplified, including: replacing curvilinear boundaries by straight lines (shear zone is in the shape of the fan) proposed by Zorev (1966), parallel-sided shear band inclined at shear angle (Oxley, 1989), and one shear plane proposed by Merchant (1945) as presented in Figure 1. Although this 2D single shear plane model is criticised, it is usually discussed in machining handbooks due to
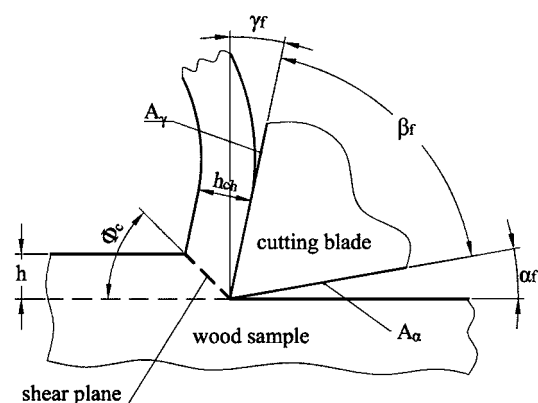

Figure 1 Geometry of chip forming zone with one shear plane. Legend: A_α - flank face, A_γ - rake face, h – uncut chip thickness, h_{ch} – chip thickness, Φ_c – shear angle, α_f – side flank (clearance) angle, β_f - side wedge angle, γ_f – rake angle
Slika 1. Geometrija zone nastanka strugotine s jednom ravninom smicanja (A_α – leđna površina, A_γ – prsna površina, h – debljina neodvojene strugotine, h_{ch} – debljina strugotine, Φ_c – kut smicanja, α_f – leđni kut, β_f – kut klina, γ_f – prsni kut

its simplicity and it is the basis for calculating several process parameters, e.g. cutting forces (Grzesik, 2017; Markopoulos, 2013).

Merchant (1945) proposed to calculate the shear angle Φ_c considering the rake angle γ_f of and the angle of friction β_μ. The latter depends on the coefficient of friction μ between the rake face and the chip. The relationship by Merchant is as follows:

$$\Phi_c = \frac{\pi}{4} - \frac{1}{2}\left(\beta_\mu - \gamma_f\right) \qquad (1)$$

Where: β_μ is a friction angle determined as $\beta_\mu = \tan^{-1}\mu$.

The coefficients of friction are going to be taken on the basis of the measured cutting forces.

2.2 Shear angle as a function of chip compression ratio
2.2. Kut smicanja kao funkcija omjera kompresije strugotine

Knowledge of the chip compression ratio λ_h that takes place enables the shear angle Φ_c to be computed with the use of the relationship (Merchant, 1945; Grzesik, 2017, 2018; Ståhl *et al*., 2012):

$$\tan\Phi_c = \frac{\cos\gamma_f}{\lambda_h - \sin\gamma_f} \qquad (2)$$

The chip compression ratio λ_h could be calculated as follows (Merchant, 1945; Ståhl *et al*., 2012):

$$\lambda_h = \frac{h_{ch}}{h} \qquad (3)$$

To determine the chip thickness h_{ch} (Figure 2), the chips were collected after each test and immediately measured with a calliper. The digital calliper by GEDORE company was applied (GEDORE Werkzeugfabrik GmbH & Co. KG, Remscheid, Germany).

2.3 Prediction of shear angle with Atkins model
2.3. Predviđanje kuta smicanja primjenom Atkinsova modela

Atkins (2003) stated that sensible material-dependent predictions for Φ_c are obtained when proper magnitudes of separation work are incorporated in the minimisation. According to Atkins (2003) for least cutting force F_c, the shear angle Φ_c satisfies:

$$\left[1 - \frac{\sin\beta_\mu \sin\Phi_c}{\cos(\beta_\mu - \gamma_f)\cdot\cos(\Phi_c - \gamma_f)}\right]\cdot\left[\frac{1}{\cos^2(\Phi_c - \gamma_f)} - \right.$$

$$\left. - \frac{1}{\sin^2\Phi_c}\right] = -\left[\cot\Phi_c + \tan(\Phi_c - \gamma_f) + Z\right]\cdot \qquad (4)$$

$$\cdot\left[\frac{\sin\beta_\mu}{\cos(\beta_\mu - \gamma_f)}\left\{\frac{\cos\Phi_c}{\cos(\Phi_c - \gamma_f)} + \frac{\sin\Phi_c \sin(\Phi_c - \gamma_f)}{\cos^2(\Phi_c - \gamma_f)}\right\}\right]$$

in which $Z = \dfrac{R}{\tau_\gamma \cdot h}$ is the parameter which makes Φ_c material dependent, where: R is specific work of sur-

face separation/formation (fracture toughness), and τ_γ is the shear yield stress (along the shear plane). The nonlinear equation (4) (further called the Atkins Model – AM) can be solved with Newton's method (Wanat 1994), which is one of the iterative methods, in which the roots can be found.

The cutting process is a simple and exceptional way for simultaneously measuring toughness and shear yield stresses (Atkins, 2005). Cutting forces can be expressed as a linear regression function (Atkins, 2003; Orlowski and Atkins, 2007; Orlowski *et al*., 2013; Chuchala *et al*., 2021):

$$F_c(h) = b \cdot h + a \qquad (5)$$

In this case, *a* and *b* correspond to the intercept and slope, respectively. From the value *a,* the value of fracture toughness *R* could be determined (Orlowski and Atkins, 2007; Chuchala *et al*. 2021), and from the value of the slope *b,* the value of shear yield stresses τ_γ might be computed (Orlowski and Atkins, 2007).

3 MATERIALS AND METHODS
3. MATERIJALI I METODE

3.1 Materials
3.1. Materijali

Scots pine (*Pinus sylvestris* L.) was used to prepare the samples. One log was randomly chosen among others in the sawmill yard. From the middle part of the 4 m long log, rectangular samples with dimensions W = 60 mm × H = 60 mm × L = 600 mm (width × height ×length, respectively) were cut. Then, ten prepared samples were dried and conditioned under laboratory conditions assuring constant air temperature of 20 °C and relative humidity of 65 % for three months. They were divided into two group - one of the final moisture content MC obtained at the level around 20 %, and the other of about 12 % *MC*. The moisture content values were determined by use of the dryer-weight method. The 12 % MC level represents dry wood and 20 % *MC* represents wet wood but bellow the value of fibre saturation point (FSP). The density of the tested wood was 549 kg/m³ for final *MC* of 20 %, and 536 kg/m³ for final *MC* of 12 %. The examined pine wood was characterised by an average width of annual rings of 2.12 ±0.4 mm and an average width of the late wood in annual rings of 0.44 ±0.05 mm. These rectangular samples were sawn on the sash gang saw PRW15M into lamellae about 5 mm in thickness. The obtained lamellae were the raw material for the preparation of small samples with dimensions W_s = 5 mm × H_s = 30 mm × L_s = 50 mm (width × height ×length, respectively). The dimensions of small samples were determined by the material holder of the microtome.
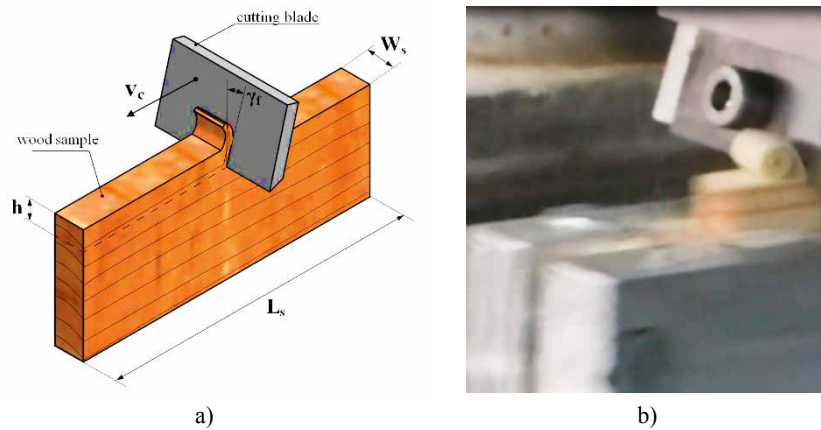
a)

b)

Figure 2 Orthogonal cutting process on sliding microtome: a) process kinematics and b) formed chip while cutting. Legend: L_s – sample length, W_s – sample width, h – uncut chip thickness, v_c – cutting speed

Slika 2. Proces ortogonalnog rezanja na kliznome mikrotomu: a) kinematika procesa, b) strugotina nastala tijekom rezanja; L_s – duljina uzorka, W_s – širina uzorka, h – debljina neodvojene strugotine, v_c – brzina rezanja

3.2 Orthogonal cutting tests
3.2. Eksperimentalno ortogonalno rezanje

The orthogonal cutting process was conducted on the sliding microtome (Figure 2a and 2b) (R. Jung AG, Heidelberg, Germany) at the laboratory of the University of Natural Resources and Life Sciences (BOKU) in Vienna (Austria). The investigated linear cutting process was performed in longitudinal direction to wood fibres (direction 90°−0° according to Kivimaa (1950)) (Figure 2a). The average cutting speed v_c was equal to 0.05 m·s^{-1}, and the uncut chip thickness h was set at 4 levels: 0.075 mm, 0.1 mm, 0.15 mm and 0.2 mm. 5 repetitions were made for each h level of the uncut chip thickness. Brand new sharp knife blades made of tungsten carbide (HW) (Leitz GmbH & Co KG, Oberkochen, Germany) were applied for cutting. Tool side rake angle (tool-in machine system) γ_f was equal to 15°, and tool wedge angle was $\beta_f = 55$°.

3.3 Shear angle
3.3. Kut smicanja

The shear angle values were determined using three methods:
- Merchant model (Eq. 1);
- chips compression ratio model (Eq. 2);
- Atkins model (Eq. 4).

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

The obtained experimental results of cutting forces F_c in orthogonal cutting process on the sliding microtome in longitudinal direction to pine wood fibre (direction 90°−0° according to Kivimaa (1950)) at two levels of MC equal to 12 % and 20 % are presented in Figure 3.

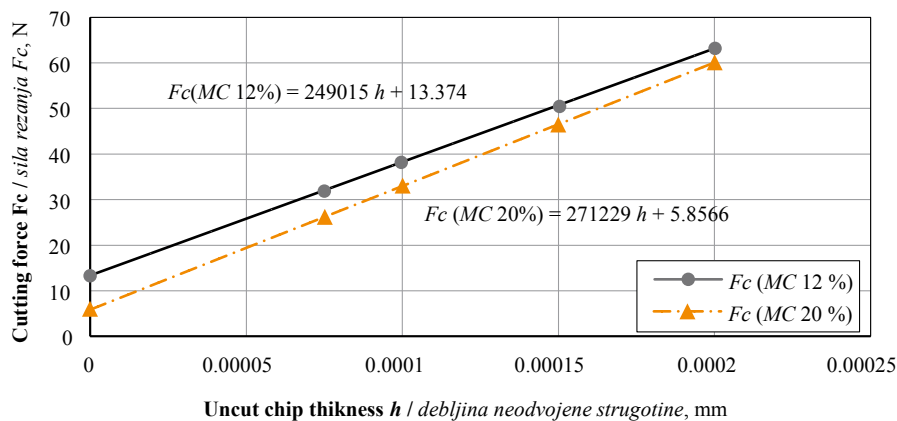On the assumption that the cutting model includes work of separation (fracture toughness) in addi-

$Fc(MC\ 12\%) = 249015\ h + 13.374$

$Fc\ (MC\ 20\%) = 271229\ h + 5.8566$

Figure 3 Cutting forces F_c in a function of uncut chip thickness h and moisture content MC while cutting on sliding microtome in longitudinal direction to pine wood fibres

Slika 3. Sile rezanja F_c u funkciji debljine neodvojene strugotine h i sadržaja vode MC tijekom rezanja na kliznome mikrotomu u smjeru vlakanaca borova drva

Table 1 Fracture toughness R, shear yield stresses τ_γ and average friction coefficients μ between rake face and chip for pine wood in a function of MC
Tablica 1. Lomna žilavost R, naprezanje smicanja τ_γ i prosječni koeficijenti trenja μ između prsne površine i strugotine borovine u ovisnosti o sadržaju vode

MC, %	R, J/m²	τ_γ, MPa	μ
12	2674.80	17.21	0.72
20	1171.32	20.03	0.63

tion to plasticity and friction in the case of cutting pine wood on the sliding microtome, examined values of fracture toughness R and shear yield stresses τ_γ have been computed from linear functions given in Figure 3. The results of computations of R and τ_γ together with determined average friction coefficients μ between the rake face and the chip are presented in Table 1.

Cutting forces for pine wood of 12 % MC in a function of the uncut chip thickness are slightly higher than in the case of cutting pine of 20 % MC (Figure 3), and this phenomenon could be caused by differences in friction coefficient, which is smaller for pine wood of

20 % MC. Moreover, as the values of the uncut chip thickness increases, the differences in force values decrease. The obtained values of friction coefficients (Table 1) are in agreement with the statement that intermediate moisture content may range from 0.5 to 0.7 (Simpson and TenWolde, 1999).

The shear angle Φ_c, considering the rake angle γ_f and the angle of friction β_μ, computed with the use of the Merchant model (Eq. 1), for pine wood of 12 % MC was equal to $\Phi_c = 34.65°$, and in case of pine wood of 20 % MC the shear angle $\Phi_c = 36.44°$. The obtained results are in agreement with machining theory (Grzesik, 2018; Markopoulos, 2013; Ståhl *et al.*, 2012), since lower cutting forces are observed for larger values of the cutting angle (Figure 3). The calculated shear angle Φ_c values with the Merchant model are presented in Figure 4a and 4b as ϕ_MER.

Some collected pine chips from the orthogonal cutting on the sliding microtome in longitudinal direction to pine wood fibres are shown in Figure 5.

Measured with callipers, the chip thickness values allowed the determination of the chip compression ratio
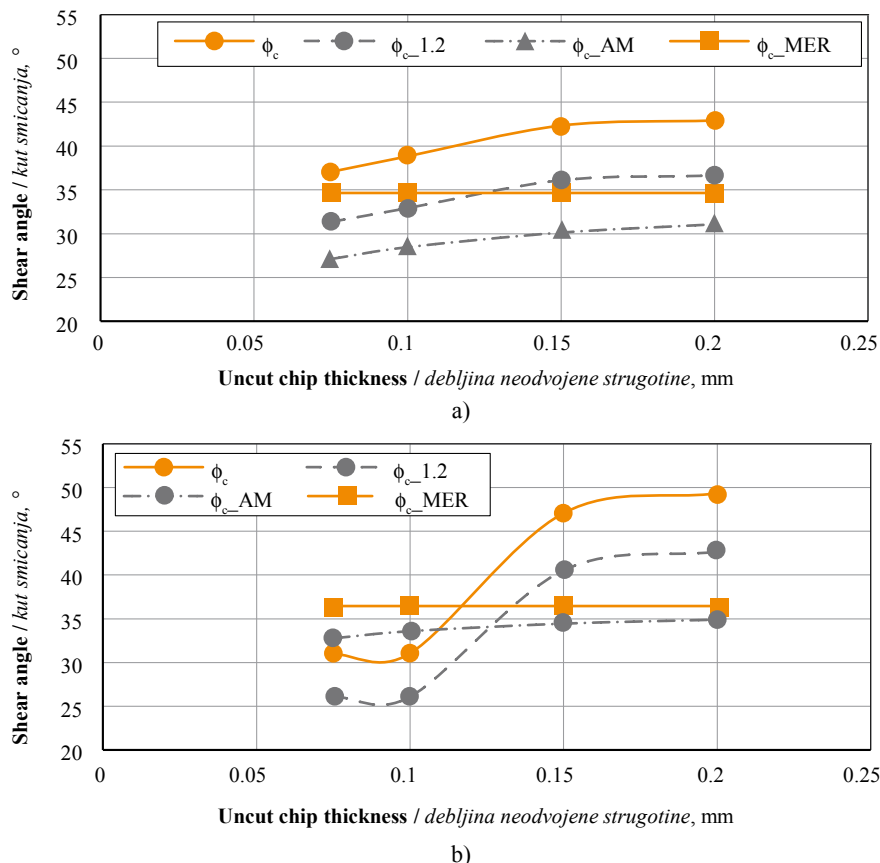

a)

b)

Figure 4 Shear angles Φ_c while cutting on sliding microtome in longitudinal direction to pine wood fibres for $MC = 12$ % (a) and $MC = 20$ % (b) in a function of uncut chip thickness h. Legend: ϕ_c – shear angle determined in a function of chip compression ratio λ_h, ϕ_c_1.2 – shear angle computed in a function of chip compression ratio λ_h while measured chip thickness h_{ch} was enlarged by 20 %, ϕ_c_AM – shear angle obtained from Atkins model, ϕ_c_MER – shear angle calculated with Merchant model
Slika 4. Kutovi smicanja Φ_c tijekom rezanja na kliznome mikrotomu u smjeru vlakanaca borovine pri (a) $MC = 12$ % i (b) $MC = 20$ % u funkciji debljine neodvojene strugotine h (ϕ_c – kut smicanja određen u funkciji omjera kompresije strugotine λ_h, ϕ_c_1.2 – kut smicanja izračunan u funkciji omjera kompresije strugotine λ_h, a izmjerena debljina strugotine h_{ch} povećana je za 20 %, ϕ_c_AM – kut smicanja dobiven iz Atkinsova modela, ϕ_c_MER – kut smicanja izračunan prema Merchantovu modelu)

Figure 5 Exemplary collected chips from orthogonal cutting on sliding microtome in longitudinal direction to pine wood fibres; chips were created during cutting process with set uncut chip thickness h = 0.15 mm
Slika 5. Primjeri strugotine skupljene pri ortogonalnom rezanju na kliznome mikrotomu u smjeru vlakanaca borovine; strugotina je nastala tijekom procesa rezanja uz definiranu debljinu neodvojene strugotine h = 0,15 mm

(Eq. 3), and then the determination of shear angle Φ_c from Eq. (2). The results of the shear angle Φ_c (courses Fic) for pine wood of 12 % MC are shown in Figure 4a, and for pine wood of 20 % MC in Figure 4b. For both courses, it is noticeable that the obtained values are larger than shear angles determined with the use of the Merchant model (ϕ_c_MER). These results are contrary to the data presented in the literature, where the values of the shear angles obtained experimentally are below the values of the Merchant model (Ståhl *et al*., 2012). The reason for this phenomenon may be local compression of thin chips by the callipers during measurement. An additional simulation was carried out for chip thicknesses increased by 20 %, and the resulting shear angles (Figure 4a, b, plots ϕ_c_1.2) were found to be lower, although, for higher uncut chip thickness values, still above those of the Merchant model. Although the resolution of a digital calliper is 0.01 mm, its measurement error for external dimensions can be ±0.03 mm for a calliper with a measurement range of up to 150 mm (Mitutoyo, 2018). This measurement error may be another additional source of overshooting shear angle values. It is presumed that much better results could be achieved by using vision techniques in chip thickness measurement as it was done in case of wood cutting (Matsuda *et al*., 2019; Ohtani and Iida, 2015; Radmanović *et al*., 2017), and has also proved its worth in metal cutting (Venkata Ramana *et al*., 2021).

In prediction of the shear angles with the Atkins model (Eq. 4), which makes Φ_c material dependent, the values of fracture toughness R and shear yield stresses τ_γ, and values of friction coefficients μ presented in Table 1 were applied in numerical computations. The results of these calculations are shown in Figure 4a and 4b. The values obtained from the Atkins model ϕ_c_AM are lower than the values from the Merchant model (ϕ_c_MER) over the entire range of change. Moreover, a decrease in the cutting angle is observed for smaller values of uncut chip thickness, whereas, in the Merchant model the shear angle is constant. Furthermore, it is evident that differences between shear angles from the Merchant model and the Atkins model are larger for pine wood of 12 %.

4 CONCLUSIONS
4. ZAKLJUČAK

The novel experimental analyses of shear angles proposed here provide a unique opportunity to assess the effect of the method of determining shear angles on their values.

For pine wood (*Pinus sylvestris* L.) with a moisture content of *MC* = 20 %, lower values of the friction coefficient μ between the chip and the rake face were observed during orthogonal cutting along the wood fibre than for a moisture content level of *MC* = 12 %. The difference is equal to 14.2 %. As a consequence of this difference, lower values of the cutting force F_c were recorded over the entire range of variations in the uncut chip thickness.

The values of the shearing angles determined from the chip compression ratios turned out to be higher than the values from Merchant equation. This can be explained by the measurement error resulting from the use of digital callipers.

The shear angles determined from the Atkins model are, as expected, lower than those determined from the Merchant model. Furthermore, the shear angle values for 20 % *MC* are higher than for moisture content 12 % *MC*.

The area of shear angle analysis for wood machining processes requires deeper analysis at both modelling and experimental verification levels. Accurate determination of the shear angle for wood machining processes would allow a fairly accurate prediction of the energy demand for these cutting processes, resulting in a reduction of material waste.

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