ACTA FACULTATIS XYLOLOGIAE ZVOLEN, 63(1): 75−83, 2021
Zvolen, Technická univerzita vo Zvolene
DOI: 10.17423/afx.2021.63.1.07

COMPARISON OF THE FRACTURE TOUGHNESS OF PINE WOOD DETERMINED ON THE BASIS OF ORTHOGONAL LINEAR CUTTING AND FRAME SAWING

Daniel Chuchała – Kazimierz A. Orłowski – Gerhard Sinn – Aleksandra Konopka

ABSTRACT

In this paper, the values of the fracture toughness of Scots pine determined by cutting tests are presented. The cutting tests were carried out using the samples of Scotch pine (*Pinus sylvestris* L.) from Pomeranian Region, Poland. These experiments were carried out on two research stands: orthogonal linear cutting tests were conducted using the microtome instrument and the frame saw PRW-15M was used for sawing tests. The values of the fracture toughness were determined following the recorded values of cutting power during the cutting tests (PRW-15M) and cutting forces (microtome instrument) with the use of models based on the elements of fracture mechanics. It was observed that the fracture toughness values determined following the orthogonal linear cutting tests were significantly lower, what could be caused by bending the wood fibers under the pressure of the cutting force.

Key words: fracture toughness, orthogonal cutting, cutting force, cutting power, frame sawing, pine wood

INTRODUCTION

The Atkins model (2003, 2005, 2009) of cutting forces (cutting power) takes into account the geometry of cutting tool, the friction conditions in the cutting zone and mechanical properties (fracture toughness R and the shear yield stress in the cutting zone τ) of the raw material of the workpiece. This model was applied to determine the mechanical properties of wood on the basis of experimental cutting tests (ORLOWSKI and ATKINS 2007, ORLOWSKI and PAŁUBICKI 2009, CHUCHALA and ORLOWSKI 2016, HLASKOVA *et al.* 2018, 2019, 2020). The methodology compiled by ORLOWSKI and ATKINS 2007, and further developed by Orlowski *et al*. (2017), ORLOWSKI and OCHRYMIUK (2017), SINN *et al.* (2020), was used successfully to forecast the cutting forces (cutting power) for different sawing processes of wood (CHUCHALA *et al.* 2020, OTTO and PARMIGIANI 2015, ORLOWSKI *et al.* 2020, SINN *et al.* 2020). The fracture toughness R is a material property representing the fracture mechanics in discussed models and defines an internal specific work required for the formation of a new surface. BEER *et al*. (2005) also adopted Atkins model (2003, 2005, 2009) to determine the value of fracture toughness from orthogonal cutting processes with the use of the microtome instrument. This investigation showed that microtome instrument is suitable for determination of the fracture toughness for wood composite materials like particle-boards. Moreover, the study conducted by KOPECKY *et al*. (2014) and HLASKOVA *et al*. (2020) also showed that the fracture toughness values for wood-based-materials can be determined following the circular saw machining tests. On the other hand, ATANASOV and KOVATCHEV (2019) proposed a model of the cutting power for the particleboard milling process based only on the feed speed and cross-section of the cutting layer.

The fracture toughness is one of the mechanical properties of the material on which the Atkins model of cutting forces is based. Therefore, it indirectly enables optimization of the cutting process by forecasting the power and/or cutting forces based on this model. NASIR and COOL (2019, 2020 and 2021) showed that optimization of the cutting process has a large impact on the machining quality.

The goal of this study was to investigate differences of the fracture toughness values which were determined using the methods based on element of fracture mechanics in two separate cutting tests (orthogonal and semi-orthogonal) for pine wood (*Pinus sylvestris* L.). The mentioned material property could be useful for the proper estimation of the cutting forces (cutting power) demand.

MATERIALS AND METHODS

Materials

Scots pine (*Pinus sylvestris* L.) species were used to prepare the samples. One log was randomly selected among others at the yard in the sawmill. The middle part (2 m length) of 4 m long log was cut into rectangular samples with dimensions $W = 60$ mm × $H = 60$ mm × $L = 600$ mm (width × height ×length, respectively). The prepared ten samples were dried and conditioned under laboratory conditions assuring constant air temperature of 20°C and relative humidity of 65 % by three months. The final moisture content MC was obtained at the level around 12 %. The density of the tested wood was 536.34 ±7.1 kg·m^{-3} for final MC 12 % (416.4 kg·m^{-3} under oven dry conditions). The structure of the examined pine wood was characterized by an average width of annual rings 2.12 ±0.4 mm and an average width of the late wood in annual rings 0.44 ±0.05 mm. These rectangular samples were used in sawing tests conducted using a frame saw. Lamellas with the thickness of around 5 mm resulted from the sawing process using the frame saw. Lamellae were used to prepare small samples with dimensions $W_s = 5$ mm × $H_s = 30$ mm × $L_s = 50$ mm. Sample dimensions were adapted to the material holder of the microtome instrument.

Frame sawing tests

The dried ten samples were sawn using the frame saw PRW-15M equipped with a hybrid dynamically balanced driving system and elliptical teeth trajectory movement (WASIELEWSKI and ORLOWSKI 2002). The tests were carried out at the laboratory of the Gdańsk University of Technology (GUT). Every investigated sample was cut with feed speed set up at two levels, around 0.3 and 1.1 m/min. The exact values of the feed speed and corresponding feeds per tooth were determined on the basis of actual recorded courses of cutting power, following the works by CHUCHALA and ORLOWSKI (2016) and SINN *et al*. (2020). The use of electric power (active and passive) during idling and cutting cycles was continuously monitored and recorded with the power converter PP54 (LUMEL S.A., Zielona Góra, Poland). The average cutting power P_c while frame sawing was calculated as the difference between the mean total power P_T and the mean idle power P_i following to CHUCHALA and ORLOWSKI (2016) and SINN *et al*. (2020), and expressed in equation (1):

$$P_c = P_T - P_i \tag{1}$$

The average idle power P_i of the frame sawing process was determined each time before starting the regular cutting cycle. The average cutting power in a working stroke P_{cw} was calculated as in equation (2), following the works (ORLOWSKI and PALUBICKI 2009, CHUCHALA and ORLOWSKI 2016; SINN *et al*. 2020):

$$P_{cw} = 2 \cdot P_c \tag{2}$$

A specific list of frame saw settings and parameters of the applied tool is shown in Table 1.

Tab. 1 Machine tool and tools settings for frame sawing and linear cutting processes.

Parameter		Symbol	Value	Unit
frame saw setting				
number of strokes of saw frame per min		n_F	685	spm
saw frame stroke		H_F	162	mm
number of saws in the gang		m	5	–
average cutting speed		v_c	3.69	$m \cdot s^{-1}$
feed speed	slow	v_{f1}	0.92	$m \cdot min^{-1}$
	fast	v_{f2}	1.35	$m \cdot min^{-1}$
feed per tooth	slow	$f_{z1} = h_1$	0.11	mm
	fast	$f_{z2} = h_2$	0.16	mm
frame blade parameters				
the sharp saw blades with stellate tipped teeth		–	–	–
overall set (kerf width)		S_t	2	mm
saw blade thickness		s	0.9	mm
free length of the saw blade		L_0	318	mm
blade width		b	30	mm
tooth pitch		t_p	13	mm
tool side rake angle		γ_f	9	°
tool side clearance		α_f	14	°
tension stresses of saws in the gang		σ_N	300	MPa
linear cutting settings				
average cutting speed		v_c	0.05	$m \cdot s^{-1}$
uncut chip thickness	small	h_1	0.10	mm
	mid	h_2	0.15	mm
	large	h_3	0.20	mm
linear cutting blade parameters				
sharp knife blade made of High-Speed Steel (HSS)		–	–	–
tool side rake angle (tool-in machine system)		γ_f	15	°
tool wedge angle		β_f	55	°

Orthogonal cutting tests

The analyzed linear cutting process was conducted using the microtome instrument (Figure 1b) which is located at the University of Natural Resources and Life Sciences, Vienna (BOKU) laboratory. The investigated linear cutting process was performed in perpendicular direction to wood fiber (direction 90°–90° according to KIVIMAA (1952)) (Figure 1a). The same direction in relation to wood fibers was performed while sawing using the frame saw. The uncut chip thickness h was set at three levels 0.1, 0.15 and 0.2 mm. For each level of tested h, five repetitions were conducted. The linear cutting tests were conducted with sharp knife blades made of High-Speed Steel (HSS) by Leitz GmbH & Co. KG., Germany. The other detailed parameters of cutting process are shown in Table 1. The cutting forces in cutting speed v_c direction were recorded during this process.

Methodology for determination of the fracture toughness from machinability tests

The both recorded values, cutting power and cutting forces, correspondingly while frame sawing and linear cutting processes were conducted can be described by ATKINS (2003, 2005, 2009) model proposed. This model was adopted for determined fracture toughness of wood based on sawing process by ORLOWSKI and ATKINS (2007) and based on linear cutting by BEER *et al*. (2005). Equation (3) shows model described cutting power for frame sawing process:

$$P_{cw} = \frac{m \cdot H_p \cdot \tau_\gamma \cdot \gamma \cdot S_t}{Q \cdot t_p} h \cdot v_c + \frac{m \cdot H_p \cdot R \cdot S_t}{Q \cdot t_p} \cdot v_c \tag{3}$$

where: R – is the fracture toughness in J·m^{-2}, τ_γ – is the shear yield stress (in the cutting zone) in MPa, m – is the number of saw blades in the gang, H_P – is workpiece height (cutting depth) in mm, h – is the uncut chip thickness (corresponding to the feed per teeth f_z for frame sawing) in mm, t_p – is the tooth pitch in mm, S_t – is the overall set (kerf width) in mm, v_c – cutting speed in m·s^{-1}, γ – is the shear strain along the shear plane and can be calculated according to equation (4), assuming that Φ_c corresponds to the shear angle:

$$\gamma = \frac{\cos\gamma_f}{\cos(\Phi_c - \gamma_f) \cdot \sin\Phi_c} \tag{4}$$

where: γ_f – tool side rake angle (tool-in machine system).

The coefficient of friction correction Q represents an effect of friction between tool rake face and separated material, it can be calculated using equation (5):

$$Q = 1 - \frac{\sin\beta_\mu \cdot \sin\Phi_c}{\cos(\beta_\mu - \gamma_f) \cdot \cos(\Phi_c - \gamma_f)} \tag{5}$$

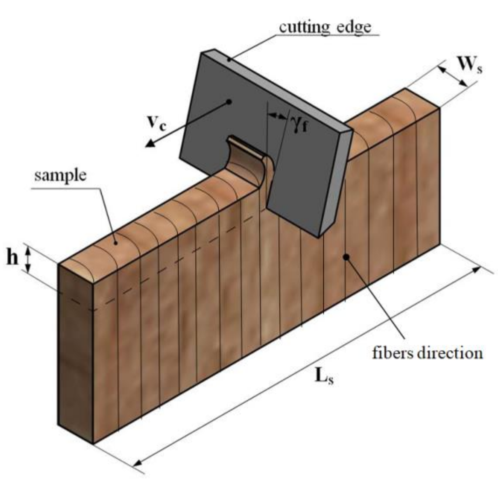
where: $\beta_\mu = \tan^{-1}\mu$ is a friction angle (rad) directly related to the coefficient of friction μ.

Equation (6) shows the model described cutting force F_c for analysed linear cutting process:

$$F_c = \frac{\tau_\gamma \cdot \gamma \cdot S_t}{Q} h + \frac{R \cdot W_s}{Q} \tag{6}$$

where: W_s – is the width of sample (analogue to the kerf width in frame sawing) in mm.

a)



b)

Fig. 1 Orthogonal linear cutting process: a) schema of cutting process, b) microtome instrument while cutting.

Both equations (3) and (6) can be expressed as a linear regression functions:

$$P_{cw}(h) = c_1 \cdot h + c_0 \tag{7}$$

$$F_c(h) = c_1 \cdot h + c_0 \tag{8}$$

In those cases, c_1 and c_0 correspond to the slope and intercept, respectively. An independent variable of the regression is the uncut chip thickness h. This makes it possible to determine the values of the fracture toughness $R_\perp$ by matching the regression equation (8) with the experimental data from the cutting tests. The equations (9) and (10) express mathematical procedure for calculation values of fracture toughness $R_\perp$ based on frame sawing tests and linear cutting tests, respectively:

$$R_\perp = \frac{c_0 \cdot t_p \cdot Q}{m \cdot H_p \cdot S_t \cdot v_c} \tag{9}$$

$$R_\perp = \frac{c_0 \cdot Q}{W_s} \tag{10}$$

RESULTS AND DISCUSSION

Obtained experimental results from the series of sawing and linear cutting performed on the pine wood samples in 90° – 90° direction to the wood grain (KIVIMMA 1952) are summarized in Figures 2 and 3. Figure 2 presents two test point groups that correspond to the mean value and standard deviations of measured cutting powers at two levels of feed speed v_f (Table 1). Applied values of feeding are represented by the basic geometrical parameter of the cutting process, i.e. uncut chip thickness h. The exact values of the uncut chip thickness determined individually for each processed sample based on recorded experimental data were clustered around values of $h_1 = 0.11$ mm and $h_2 = 0.16$ mm. The data fitting curve (linear regression), as well as regression equation with coefficient c_1 and intercept c_0, is provided.

The linear regression for three test point groups is presented in Figure 3. These point groups correspond to the mean value and standard deviations of measured cutting forces at three levels of uncut chip thickness: $h_1 = 0.1$ mm, $h_2 = 0.15$ mm and $h_3 = 0.2$ mm. Figure 3, similarly like in Figure 2, includes regression equation with coefficient c_1 and intercept c_0, which is the basis for determination of fracture toughness value according to equations (9) and (10). The both presented linear regressions are characterized by high values of determination coefficient, about $r^2 = 0.95$. The determined average values of fracture toughness $R_\perp$ for Scots pine are shown in Table 2, together with their standard deviations.

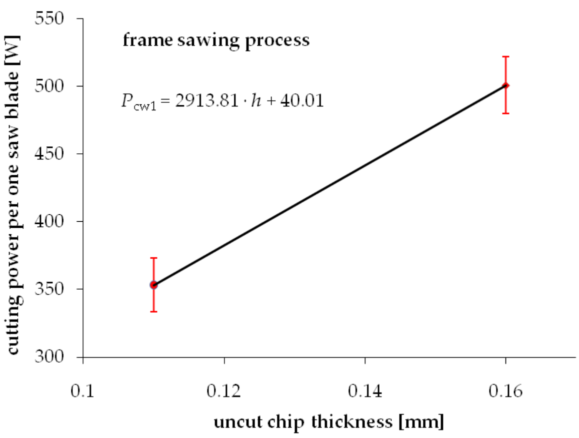


Fig. 2 Cutting power per one saw blade versus uncut chip thickness when sawing on frame saw pine wood.

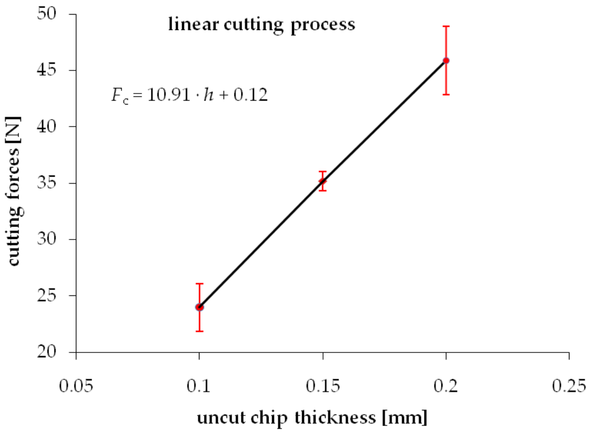
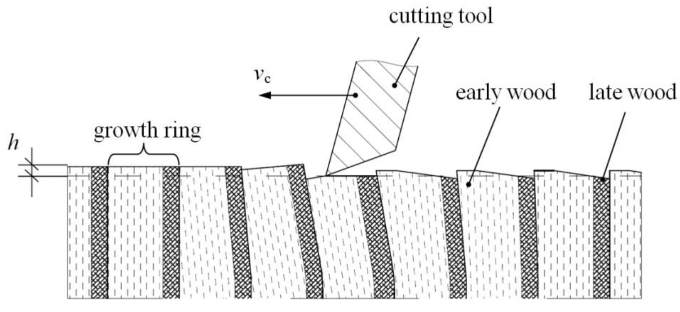


Fig. 3 Cutting force versus uncut chip thickness when orthogonal linear cutting pine wood.

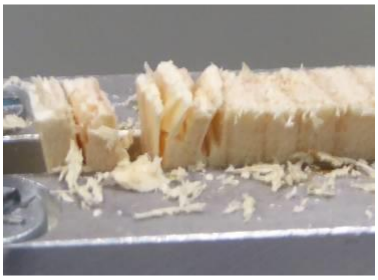
Tab. 2 Fracture toughness $R_{\perp}$ of Scots pine (mean value and its standard deviations) determined from two different cutting tests.

name of cutting process	fracture toughness, $R_{\perp}$		
	mean value	standard deviations	unit
frame sawing	747.93	±327.2	$J \cdot m^{-2}$
orthogonal linear cutting	273.13	±75.24	$J \cdot m^{-2}$

Differences in the determined average fracture toughness $R_{\perp}$ values from two different machining tests are noticeable. Despite large standard deviations for both values, these differences are significant. This case is very puzzling because the material properties of the same wood sample in the same direction in relation to the fibres should be the same or at least very similar. The reason for this phenomenon might be the flexible bending of wood fibres during linear cutting. The cutting process was carried out in the 90°– 90° direction, which meant that the cutting force was also the bending force of the fibres. Applied a small values of the uncut chip thickness, the fibres under the pressure of the cutting edge were partially tilt (bend) before the shearing process occured (Figure 4).



a)



b)

Fig. 4 Bending of the pine wood fibers while orthogonal linear cutting in the 90° – 90° direction in relation to the fibers: a) scheme of cutting process with bending of wood fibers, b) example of a sample with bent and destroyed fibers.

Mentioned tilt of wood fibers might change the cross-section of the cutting layer and consequently reduce the cutting forces. As a result, the reduced values of the cutting forces cause the experimentally determined linear regression (Figure 3) to cross the axis of ordinates lower than it should and the determined values of fracture toughness might be underestimated. The early wood has lower mechanical properties (GONÇALEZ *et al*. 2018, BENDTSEN and SENFT 1986) and is therefore more susceptible to such deflections and its percentage share in annual growth may have a significant effect on this occurrence.

The phenomenon of the fiber tilt does not occur during frame sawing. Fibers loaded by cutting force, which also gives bending torque, do not tilt because they are supported by unloaded material on both sides of the cut kerf. The frame sawing process is called quasi-orthogonal cutting process because during this process the main cutting edge works mostly. However, minor cutting edges also take part in cutting process, but to a smaller share (ORLOWSKI 2007). The minor cutting forces do not significantly affect cutting process, but material located on both sides of kerf stabilizes process, which is most notifiable while sawing in 90° – 90° direction in related to the wood fibers.

The analysed cutting processes also differ very significantly in their cutting speeds. The cutting speed for the frame sawing process (v_c = 3.69 m·s^{-1}) is 74 times higher than for the linear cutting process (v_c = 0.05 m·s^{-1}) (Table 1). Nevertheless, both KIVIMAA (1950, 1952) and MCKENZIE (1961) have shown in their works that cutting speed does not significantly affect the values of cutting forces (cutting power).

CONCLUSIONS

The conducted research and obtained results allow the following conclusions to be drawn:

1. The value of the fracture toughness for pine wood based resulting from the orthogonal linear cutting tests in 90° – 90° direction related to fibers, are more than 2.5 times lower than values based on frame sawing tests.
2. While the orthogonal linear cutting of soft wood (e.g. pine wood) in 90° – 90° direction to fibers can cause fiber bending and result in disruption of the cross-sectional dimension of the cutting layer, what directly affects values of cutting forces.
3. In order to analyze the phenomenon of wood fiber bending in more detail during the orthogonal linear cutting of softwood, it would be necessary to conduct research using a high frame rate camera and Digital Image Correlation system (DIC).

REFERENCES

ATANASOV, V., KOVATCHEV, G. 2019. Determination of the cutting power during milling of wood-based materials. In Acta Facultatis Xylologiae Zvolen, 61(1): 93−101. https://doi.org/10.17423/afx.2019.61.1.09

ATKINS, A.G. 2003. Modelling metal cutting using modern ductile fracture mechanics: quantitative explanations for some longstanding problems. In International Journal of Mechanical Sciences, 45: 373–396.

ATKINS, A.G**.** 2005. Toughness and cutting: a new way of simultaneously determining ductile fracture toughness and strength. In Engineering Fracture Mechanics, 72: 849–860.

ATKINS, A.G. 2009. The science and engineering of cutting. The mechanics and process of separating, scratching and puncturing biomaterials, metals and non-metals. Oxford: Butterworth-Heinemann is an imprint of Elsevier, 2009, 413 p.
BEER, P., SINN, G., GINDL, M., TSCHEGG, S. 2005. Work of fracture and of chips formation during linear cutting of particle-board. In Journal of Materials Processing Technology, 159: 224–228.
BENDTSEN B.A., SENFT J. 1986. Mechanical and anatomical properties in individual growth rings of plantation-grown eastern cottonwood and loblolly pine. In Wood and Fiber Science. 18(1): 23–38.
CHUCHALA, D., OCHRYMIUK, T., ORLOWSKI, K.A., LACKOWSKI, M., TAUBE, P. 2020. Predicting cutting power for band sawing process of pine and beech wood dried with the use of four different methods. In BioResources, 15(1): 1844–1860. https://doi.org/10.15376/biores.15.1.1844-1860.
CHUCHAŁA, D., ORŁOWSKI, K. 2016. Shear yield stresses and fracture toughness of Scots pine (*Pinus sylvestris* L.) according to the raw material provenance. In Trieskove a beztrieskove obrabanie dreva, X, 49–55.
GONÇALEZ, J.C., SANTOS, N., DA SILVA, F.G.JR., SOUZA, R.S., DE PAULA, M.H. 2018. Growth ring width of *Pinus Caribaea* and its relationship with wood properties. In Scientia Forestalis/Forest Sciences, 46(120): 670–678. https:/doi.org/10.18671/scifor.v46n120.15.
HLÁSKOVÁ, L., ORLOWSKI, K.A., KOPECKÝ, Z., SVITÁK, M., OCHRYMIUK, T. 2018. Fracture toughness and shear yield strength determination for two selected species of central European Provenance. In BioResources, 13(3): 6171–6186. https://doi.org/10.15376/biores.13.3.6171-6186.
HLÁSKOVÁ, L., KOPECKÝ, Z., SOLAŘ, A., POTOČKA, Z. 2019. Cutting test as a source of fracture toughness and shear yield strength for axial-perpendicular model of wood cutting. In Wood and Fiber Science, 51(1): 1–11. https://doi.org/10.22382/wfs-2019-006.
HLÁSKOVÁ, L., KOPECKÝ, Z., NOVÁK, V. 2020. Influence of wood modification on cutting force, specific cutting resistance and fracture parameters during the sawing process using circular sawing machine. In European Journal of Wood and Products, (e-print). https://doi.org/10.1007/s00107-020-01581-2.
KIVIMAA, E. 1950. Cutting force in woodworking. State Institute for Technical Research, Helsinki.
KIVIMAA, E. 1952. Die Schnittkraft in der Holzbearbeitung. (The cutting force in wood processing). In Holz Roh- Werkst, 10(3): 94–108.
KOPECKÝ, Z., HLÁSKOVÁ, L., ORLOWSKI, K.A. 2014. An innovative approach to prediction energetic effects of wood cutting process with circular-saw blades. In Wood Research, 59(5): 827–834.
MCKENZIE, W.M. 1961. Fundamental analysis of the wood-cutting process. PhD thesis, University of Michigan, Department of Wood Technology, MI, USA.
NASIR, V., COOL, J. 2019. Optimal power consumption and surface quality in the circular sawing process of Douglas-fir wood. In European Journal of Wood and Wood Products, 77: 609–617. https://doi.org/10.1007/s00107-019-01412-z.
NASIR, V., COOL, J. 2020. A review on wood machining: characterization, optimization, and monitoring of the sawing process. In Wood Material Science & Engineering, 15(1): 1–16. https://doi.org/10.1080/17480272.2018.1465465.
NASIR, V., COOL, J. 2021. Cutting power and surface quality in sawing kiln-dried, green, and frozen hem-fir wood. Wood Science and Technology. https://doi.org/10.1007/s00226-020-01259-1
ORLOWSKI, K.A., ATKINS, A. 2007. Determination of the cutting power of the sawing process using both preliminary sawing data and modern fracture mechanics. In Proceedings of the Third International Symposium on Wood Machining. Fracture Mechanics and Micromechanics of Wood and Wood Composites with regard to Wood Machining, 21–23 May, Lausanne, Switzerland. Eds. Navi, P., Guidoum, A. Presses Polytechniques et Universitaires Romandes, Lausanne, 2007, 171–174.
ORŁOWSKI, K. 2007. Experimental studies on specific cutting resistance while cutting with narrow-kerf saws. In Advances in Manufacturing Science and Technology, 31(1): 49–63.
ORŁOWSKI, K.A., PAŁUBICKI B. 2009. Recent progress in research on the cutting process of wood. A review COST Action E35 2004–2008: Wood machining – micromechanics and fracture. In Holzforschung, 63:181–185.

ORLOWSKI, K.A., OCHRYMIUK, T., SANDAK, J., SANDAK, A. 2017. Estimation of fracture toughness and shear yield stress of orthotropic materials in cutting with rotating tools. In Engineering Fracture Mechanics, 178: 433–444. https://doi.org/10.1016/j.engfracmech.2017.02.023.
ORLOWSKI. K.A., OCHRYMIUK, T. 2017. A newly-developed model for predicting cutting power during wood sawing with circular saw blades. In Maderas Cienc. Tecnol. 19(2): 149–162. https://doi.org/10.4067/S0718 -221X2 01700 50000 13.
ORLOWSKI, K.A., OCHRYMIUK, T., HLASKOVA, L., CHUCHALA, D.; KOPECKY, Z. 2020. Revisiting the estimation of cutting power with different energetic methods while sawing soft and hard woods on the circular sawing machine: a Central European case. In Wood Science and Technology, 54(2): 457–477. https://doi.org/10.1007/s00226-020-01162-9.
OTTO, A., PARMIGIANI, J. 2015. Velocity, depth-of-cut, and physical effects on saw chain cutting. In BioResources, 10(4): 7273–7291. https://doi.org/10.15376/biores.10.4.7273-7291.
SINN, G., CHUCHAŁA, D., ORLOWSKI, K.A., TAUBE, P. 2020. Cutting model parameters from frame sawing of natural and impregnated Scots pine (*Pinus sylvestris* L.). In European Journal of Wood and Wood Products, 78(4): 777–784. https://doi.org/10.1007/s00107-020-01562-5.
WASIELEWSKI, R., ORLOWSKI, K. 2002. Hybrid dynamically balanced saw frame drive. In Holz Roh-Werkst 60(3): 202–206.

ACKNOWLEDGEMENTS

Financial support of NAWA (Polish National Agency for Academic Exchange) within the project PPN/BIL/2018/1/00100/U/00001 and BMBWF trough OEAD within the project PL 06/2019 is gratefully acknowledged.
The authors gratefully acknowledge the Ministry of Science and Higher Education, Poland, for support the maintenance of scientific and research equipment – PRW-15M frame saw, grant number 21/E-359/SPUB/SP/2019.

AUTHORS ADDRESSES

Kazimierz Orlowski (ORCID id: 0000-0003-1998-521X)
Daniel Chuchala (ORCID id: 0000-0001-6368-6810)
Aleksandra Konopka (ORCID id: 0000-0003-0733-249X)
Gdansk University of Technology
Faculty of Mechanical Engineering
Narutowicza 11/12
80-233 Gdansk
Poland

Gerhard Sinn (ORCID id: 0000-0002-8365-3650)
University of Natural Resources and Life Sciences
Institute of Physics and Materials Science
Peter-Jordan-Str. 82
1190 Vienna
Austria