ISSN impresa 0717-3644
ISSN online 0718-221X
Maderas. Ciencia y tecnología 20(1): 25 - 34, 2018
DOI: 10.4067/S0718-221X2018005001301

IMPACT OF FEED RATE, MILLING DEPTH AND TOOL RAKE ANGLE IN PERIPHERAL MILLING OF OAK WOOD ON THE CUTTING FORCE

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ABSTRACT

The paper presents the results of investigations performed in the peripheral milling of oak wood (*Quercus robur*), where the impact of cutting regime elements and tool geometry on the cutting force is analyzed. A large-scale experiment was conducted to implement the obtained results in developing a reliable analytical and simulation model for analyzing and predicting the cutting forces, depending on the feed rate, the milling depth and the tool rake angle. The generated mathematical model is adequate and describes accurately enough the dependence of the cutting forces upon the selected impact factors in the adopted test conditions. The evaluation of the model parameters significance indicates a significant impact of feed rate and milling depth, whereas tool rake angle does not show any significant impact in this case. The developed mathematical model can be employed in manufacturing conditions as an indicator of wood and wood-based materials machinability.

Keywords: Cutting forces, cutting regime, machinability, peripheral milling, tool rake angle.

INTRODUCTION

Investigations of wood machinability are gaining in importance considering rapid development of new materials and their machining technologies. Machinability is defined as the capacity of the material to be machined by cutting using common economical manufacturing techniques and technologies (machines, tools, methods) (Stanić 1989). This definition applies to all materials and so does to wood as well. It is evaluated by a set of criteria or functions: tool life, cutting forces, quality of machined surface, accuracy and quality characteristics, chip shape (Kalajdžić 2008). In general, good machinability implies good machined surface quality, long tool life, low values of the required cutting force and lower machining costs. However, factors improving surface quality often diminish other machinability indicators (heat treatment, versatile chemical treatments and the like). That is why it is a real challenge to devise a method for enhancing machinability without product surface quality loss.

The papers dealing with the theory of wood processing considered different factors such as regime of cutting (Axelsson *et al.* 1993, Wen-Hsiang 2000, Aguilera and Zamora 2009, Aguilera and Muñoz 2011, Aguilera *et al.* 2013), various machining conditions, including feeding direction and grain direction (Goli and Uzielli 2004), cutter material, effect of shear cutter, effect of cutting angle (Belleville *et al.* 2016), properties of wood (Thoma *et al.* 2015) and their impact on change in the cutting forces, machining accuracy and quality of machined surface.The major goal of mentioned investigations was to improve understanding of the interaction between the tools and the workpieces so as to achieve more efficient cutting process management. Knowledge of interaction between the tools and the wood as well as the control of the cutting process are unavoidable factors affecting productive and economical manufacturing in wood processing (Eyma *et al.* 2004).

The literature with the focus on mechanical wood processing presents different models (methods) for predicting cutting forces. By applying data on the properties of wood and wood-based materials being machined, and scheduled regimes of cutting, these models are able to predict the material behavior in the machining process, the machining outcome, and primarily the quality of machined surface. Most often, those are the methods of coefficients generated based on carried out experiments

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Received: 23.06.2016 Accepted: 18.09.2017

(Orlicz 1982, Axelsson *et al.* 1993, Goglia 1994, Porankiewicz *et al.* 2011, Naylor *et al.* 2012, Kršljak 2013, Porankiewicz and Goli 2014, Mandić *et al.* 2015). This paper presents the evaluation of the cutting force based on a mathematical model, whose parameters were determined using experimental results obtained under controlled laboratory conditions. The verified mathematical model could be used for predicting wood behavior in different cutting regimes under real conditions. Combination of data obtained from the model and monitoring and analyzing the engaged cutting power would facilitate the control of the machining process and reduce the number of machined pieces with impermissible deviations of dimensions and surface quality.

MATERIALS AND METHODS

Investigations deployed oak wood (*Quercus robur)*, it has a strong history as some of the most valuable and highest quality domestic hardwoods. The most widely utilization oak has found in the production of costly solid wood furniture. Samples were of uniform properties, of radial direction and without visible irregularities in wood grain. Physical and mechanical properties were tested in accordance with various standards, i.e., standards for density (SRPS ISO 13061-2, 2015), bending strength (SRPS ISO 13061-3, 2015), Brinell hardness, perpendicular to the wood grains, in radial direction (EN 1534, 2010) and for modulus of elasticity (SRPS ISO 13061-3, 2015). Mean values for samples' measured physical and mechanical properties are presented in Table 1 and lie within standard deviation of ±5%.

Table 1. Average values of measured samples' physical and mechanical properties.

Property	Mean	Minimum	Maximum	Std.Dev.	Coef.Var.
Density (kg/m^3)*	790	770	800	20	2,19
Ovendry density (kg/m^3)	760	740	770	20	2,28
Moisture Content (%)	7,97	7,80	8,10	0,15	1,92
Hardness (MPa)	45,18	43,12	47,18	2,03	4,49
Bending strength (MPa)	125,14	119,70	130,33	5,32	4,25
Modulus of elasticity (MPa)	11274,40	10949,32	11471,77	283,68	2,52

*The moisture content, of samples varied (from 7,80% to 8,10%, with an average of 7,97%), so the values of the wood density computationally were normalized to a humidity of 8%.

Oak samples has been conditioned before testing in laboratory environment conditions: relative humidity of 45 ±5% and room temperature of 20 ±3°C. These conditions brought samples to an equilibrium moisture content of 8 ±1%, which is standard recommendation for values of moisture content for furniture in Serbian climates conditions.

Mathematical model for predicting the cutting force

Investigations of any process or system require the selection of an adequate model and testing of its accuracy and adequacy against the real process. This paper employed a common model form of regression analysis for prediction of the cutting forces in peripheral cutting, depending on certain impact factors. The paper analyzes the impact of feed rate $f_1 = v_F$, milling depth $f_2 = c_D$ and cutting edge rake angle $f_3 = \gamma$ upon components of cutting force (F_x and F_y). The degree function of machinability (Mason *et al.* 2003), applied of F_x example was calculated according to equation (1).

$$F_x = C \cdot {v_F}^{p_1} \cdot {c_D}^{p_2} \cdot \gamma^{p_3} \quad (1)$$

The adopted experimental design is a three-factorial plan of the first order with the total number of experiments $N = 2^k + n_0 = 2^3 + 4 = 12$. Each experiment was replicated at least eight times. The experiment was carried out at constant cutting speed v_C= 38,3 *m/s* (*D* = 125 mm, *n* = 5860 RPM), for three different feed rates v_F= 4, 8 and 16 m·min^{-1}, three milling depths c_D = 2, 3 and 4,5 mm and three different rake angles γ = 16°, 20° and 25°. The limits of factor interval variation were chosen to satisfy the condition $f^2_{i\ sr} = f_{i\ min} \cdot f_{i\ max}$ for i = 1, 2, 3.

Program for the machining process simulation in peripheral milling

Based on developed mathematical model for prediction of the cutting force, a universal flowchart of the sequence of steps in a procedure was created to simulate the peripheral milling process, as presented by the example of the component F_x (Figure 1).

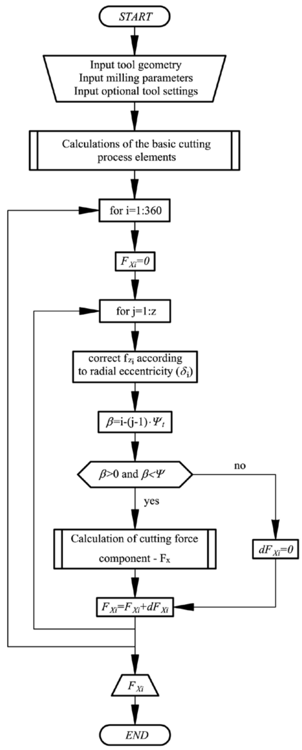

Figure 1. Flowchart for determining current values of the milling force components (F_{xi} - current value of the milling force, f_{Zi} -feed per tooth, δ_i -tooth radial run-out/ radial eccentricity dF_x - current elementary value of the milling force component, ψ_t - cutter pitch angle, ψ - engagement angle, β - current engagement angle).

According to the developed procedure for a given tool geometry, i.e. cutter diameter (D), number of cutter teeth (z), rake angle (γ) and clearance angle (α) and machining process parameters, simulation is done of one complete cutter revolution in increment of i=1°. Depending on input parameters, calculations are made of the cutter pitch angle (ψ_t) according to equation (2), engagement angle (ψ) according to equation (3), number of teeth in engagement (i_z) according to equation (4), cutting speed (v_C) according to equation (5), feed per revolution (f_R) according to equation (6) and feed per tooth (f_z) according to equation (7).

Cutter pitch angle: $$\psi_t = \frac{360°}{z} \quad [°] \tag{2}$$

Engagement angle: $$\psi = \arcsin\left(2\sqrt{\frac{c_D}{D} - \frac{c_D^{\ 2}}{D^2}}\right) \quad [°] \tag{3}$$

Number of teeth:
$$i_z = \text{roundup}\left(\frac{\psi}{\psi_t}\right) \quad (4)$$

Cutting speed:
$$v_C = \frac{\pi \cdot D \cdot n}{1000} \quad [\text{m/s}] \quad (5)$$

Feed per revolution:
$$f_R = \frac{1000 \cdot v_F}{n} \quad [\text{mm/rev}] \quad (6)$$

Feed per tooth:
$$f_z = \frac{f_R}{z} \quad [\text{mm}] \quad (7)$$

Within the framework of the machining process, for each value of the angle increment (i), based on each cutter tooth engagement angle (ψ), it is checked if the considered tooth is in engagement and if it is, the value of the current milling thickness (a_i) and current elementary value of the milling force component (dF_x) are calculated according to the created model. Finally, summation of all elementary values of the milling force components is done for each individual tooth.

Milling and experimental scheme

In order to create the model for predicting the milling forces, firstly, the values of the milling force were experimentally measured for selected machining conditions and tool geometry (cutter rake angle, depth of cut and feed rate). At least 6 times (two measurements on three or four samples) measurement was repeated for each combination of parameters. For a zero point of experiment (point with average values of parameters) measurement was repeated 16 times (two measurements on eight samples). Meaning, making total of 79 measurements for the whole experiment.

Experimental investigations were performed using a table milling unit of the universal combined machine "Minimax CU410K" at the Center for Machines and Tools, Faculty of Forestry, University of Belgrade. On the milling unit, a fixture was mounted for positioning a two-component dynamometer with strain gauges and wood sample (workpiece). Samples were obtained from boards of uniform properties, of radial direction and without visible irregularities in wood grain. Final dimensions of samples (30x30x110 mm) were obtained using a circular saw. The values of measured cutting forces change during peripheral milling depending on the current chip thickness and tooth position in engagement, Figure 2a. Signals from the dynamometer are transmitted to the Hottinger measuring bridge – HBM-KWS3082A, and from there to the acquisition card cDAQ-9174 (National Instruments), and then to the PC, where LabView software is used to create a file of records of the components of milling forces F_x (component in the feed rate direction) and F_y (component normal to the machined surface) as a function of time (Figure 2b).

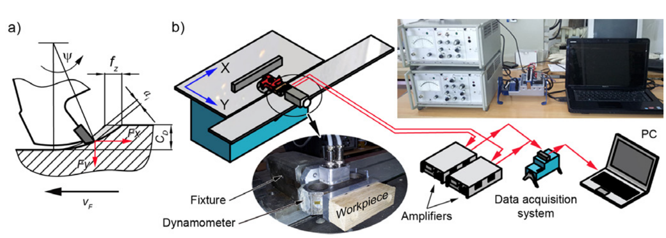

Figure 2. a) Scheme of forces in peripheral up - milling (v_F-feed rate, c_D-cutting depth, f_Z-feed per tooth, a_i-current milling thickness, ψ- engagement angle, F_x and F_y-components of milling forces), b) Scheme of equipment setup for experimental determination of forces in peripheral milling.

Figure 3 shows values of the milling forces measured with respect to time (applying software package Matlab). Time records of two perpendicular components of the milling force and the fact that it is orthogonal cutting provide for determining the intensity of the resultant cutting force according to the formula $F_r = \sqrt{F_x^2 + F_y^2}$ (Figure 3).

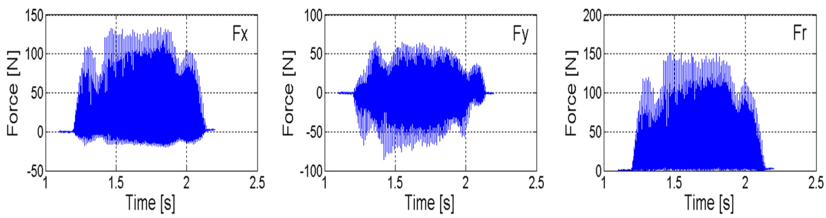

Figure 3. Diagrams of the milling forces records.

The experiment was used to create models for predicting mean values of the components and the resultant milling force that were embedded in a developed software solution for time change simulation of the components and the resultant cutting force in the peripheral milling process. Further below, an example provided is a description of creating a model and a representation of simulation solely for the cutting force in the feed rate direction.

RESULTS AND DISCUSSION

Log transformations must be applied to convert the mathematical model of the cutting force component F_x into linear form $ln\ F_x = \ln C + p_1 \ln v_F + p_2 \ln C_D + p_3 \ln \gamma$, so as to determine numerical values of constant C and exponents p_1, p_2 and p_3 in the model. Experimental results obtained in this research were employed to determine constants of the force C and the exponents p_1, p_2 and p_3, i.e. machinability parameters in the assumed mathematical model.

Table 2 shows the plan of matrices with numerical values of the experiment factor, mean values for experimental results of the component F_x (obtained based on 5 replicates minimum), model results and measurement errors.

Table 2. Plan of matrices for experimental measurements of mean value of the cutting force component F_x (v_F - feed rate, c_D - cutting depth, γ-rake angle).

No	Plan of matrices			Measurement results		Model results		Error	
	v_F (m/min)	c_D (mm)	γ (°)	F_x (N)	$y = \ln F_x$	F_x (N)	$y = \ln F_x$	$(y_u - \hat{y}_u)^2$	$(y_{0u} - \bar{y}_0)^2$
1	16	4,5	25	25,89	3,2538	28,53	3,3510	0,009448	
2	16	2	25	14,55	2,6775	16,96	2,8306	0,023456	
3	4	4,5	25	18,29	2,9063	18,10	2,8959	0,000108	
4	4	2	16	8,99	2,1966	10,68	2,3688	0,029643	
5	8	3	20	19,56	2,9734	17,46	2,8599	0,012892	0,012892
6	4	4,5	16	16,63	2,8110	17,98	2,8892	0,006113	
7	8	3	20	18,32	2,9077	17,46	2,8599	0,002290	0,002290
8	16	4,5	16	29,12	3,3714	28,34	3,3443	0,000735	
9	4	2	25	11,91	2,4776	10,76	2,3755	0,010422	
10	8	3	20	19,02	2,9455	17,46	2,8599	0,007325	0,007325
11	8	3	20	17,97	2,8887	17,46	2,8599	0,000828	0,000828
12	16	2	16	18,34	2,9093	16,84	2,8239	0,007286	
							$\sum$	0,110545	0,023335

Regression dependency of the cutting force component F_x in peripheral milling upon the feed rate, milling depth and cutting edge rake angle is shown by the model (Equation 8):

$$F_x = 4,16 \cdot v_F^{0,328} \cdot c_D^{0,642} \cdot \gamma^{0,015} \quad (8)$$

Linear mathematical model adequacy is tested according to Fisher's F-criterion. An adequate model must fulfill the condition $F_c < F_t$, i.e. $F_c = 2,24 < F_t = 9,01$ shows that the condition is fulfilled, meaning that the mathematical model describes with adequate accuracy the dependency of the cutting force upon mentioned impact factors in adopted testing conditions.

Evaluation of the model parameters' significance, also performed according to the F-criterion ($F_{ci} > F_t$), indicated that the condition is satisfied for impact parameters such as feed rate *u* ($F_{c1} = 53,19 > F_t = 10,13$) and milling depth *a* ($F_{c2} = 69,58 > F_t = 10,13$), which means that these parameters are significant. However, the condition is not satisfied for the cutting edge rake angle γ ($F_{c3} = 0,01 < F_t = 10,13$), that is, in this case rake has not shown any significant impact. However, the condition is not satisfied for the cutting edge rake angle γ, that is, in this case rake has not shown any significant impact.

Based on the values and signs of exponents in the setup mathematical model (Equation 8), it can be inferred that in terms of intensity the milling depth has more significant impact on the resultant cutting force compared to the feed rate, and that both parameters impact the cutting force directly proportionally, which is in agreement with the literature sources (Krilek *et al.* 2014, Barcik *et al.* 2008).

When milling depth is increased in the range of c_D=2÷4,5 mm the force component F_x is increased by 1,59 - 1,75 times (v_F = 16m/min, γ = 16° ÷25°), i.e. by 1,53 - 1,84 times (v_F = 4m/min, γ = 16° ÷ 25°). An increase of feed rate from 4 m/min to 16 m/min in all depths of cutting leads to the increase of the cutting force, as a consequence of a larger amount of removed chip. The force component F_x increase ranges from 1,22 to 1,41 (c_D = 2÷4,5 mm, γ = 25°), i.e. 1.75÷2 times (c_D = 2÷4,5 mm, γ=16°), which can be explained by the chip compression process in the cutting zone.

Rake angle γ affects chip compression and its optimum value is related to material hardness and plasticity. Under considered machining conditions, as the rake is increased from 16°÷25°, the force component F_x is decreased by as much as 32%, which is more prominent in smaller depths of cut and feed rates. This complies with the theory that the cutting force decreases as the value of rake angle increases (Günay *et al.* 2005, Yanda *et al.* 2010, Krilek *et al.* 2014) and vice versa. Geometrically viewed, rake angle does not have any direct impact on the surface roughness. However, indirectly, as the rake angle is increased, chip evacuation is facilitated, whereby elastic deformations of machined surface are decreased thus reducing surface roughness but causing destruction of the cutting edge, on the other hand. Investigations carried out indicate that this phenomenon shown on the oak wood is not manifested for the considered range of the rake angle 16°÷25° and for the considered machining conditions.

Among other things, a small range of rake angle varying was chosen, following manufacturer's recommendations, and all this with the aim to bring experimental conditions to real ones as close as possible, which has contributed to non-significance of rake angle impact on the cutting force.

Using software package Matlab, according to the flowchart presented in Figure 1, an application was created for the machining process simulation. Application is divided into several units related to entering data on tool geometry and machining process parameters. By activating the command for the machining process simulation, a diagram of the milling force component is drawn for one complete tool revolution and mean value of the milling force component is shown in a corresponding field on the screen, Figure 4.

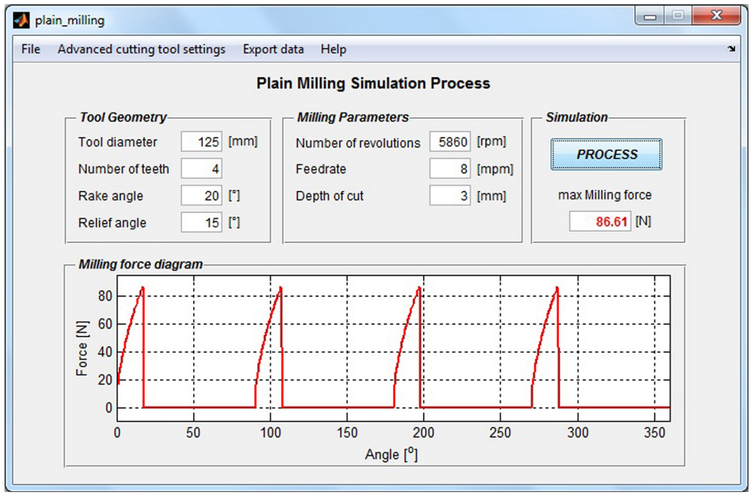

Figure 4. Representation of the application for the milling process simulation.

Elementary alignment of the application implies that milling cutter tooth radial run-out equals zero, and therefore the value of the milling force component for each tooth is equal in intensity.

Advanced cutting tool settings option enables additional definition of each tooth radial run-out that directly affects the value of feed per tooth for each tooth of the milling cutter. For the entered tool geometry and machining process parameters 4, experimental determination of the milling force component was carried out according to the experimental scheme from Figure 2b. Milling cutter tooth radial run-out amounted to - 0,02; 0,0; - 0,05; - 0,05 mm against nominal diameter respectively for each cutter tooth.

For the verification of the developed application, Figure 5 shows a diagram of values of the milling forces obtained by the experiment (solid line) and simulation (dashed line) separately for the cases with and without cutter tooth radial run-out, and all this for one complete tool revolution. Evidently, there is a better coincidence between experimental and model values of milling forces for the case when additional cutter tooth radial run-out is included in the application.

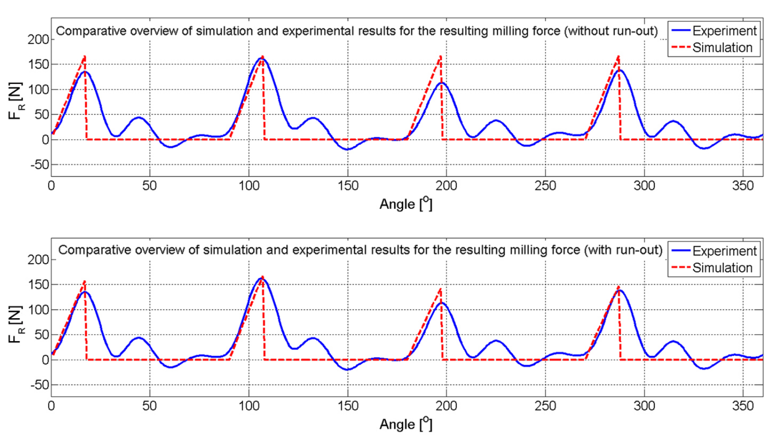

Figure 5. Comparative overview of simulation and experimental results for the resulting milling force $F_{R.}$

Apart from mentioned properties, the application can export simulation results in tabular form using the command Export data.

CONCLUSIONS

An adequate mathematical model has been created for prediction of cutting forces in oak wood milling under chosen machining conditions, as shown in the example of the cutting force component F_x. The model describes with adequate accuracy the dependency of the cutting force upon the feed rate, milling depth and cutting edge rake angle.

Evaluation of the model parameters' significance indicated that the cutting force is increased as feed rate and milling depth are increased, whereas cutting edge rake angle did not show significant impact in this case. The cause may lie in the fact that a small range of rake variation has been taken, in accordance with manufacturer's recommendations, and all this with the aim to bring experimental conditions to real manufacturing conditions as close as possible.

As for intensity, the milling depth has dominant impact on the resultant cutting force compared to feed rate.

Using software package Matlab and presented flowchart the application was created for simulation of the machining process that draws a diagram of change in the milling force for one complete tool revolution and performs computations of the milling force mean value.

The application has the capacity to additionally define radial run-out of each milling cutter tooth, which, as established, has direct impact on the intensity of the cutting force in peripheral milling.
Considering that the experimental conditions were very close to real manufacturing ones, these investigations could be of practical importance for determining optimal cutting regimes in terms of the machined surface quality and energy saving.

ACKNOWLEDGMENTS

This paper was realized as a part of the project "Studying climate change and its influence on the environment: impacts, adaptationand mitigation" (43007) financed by the Ministry of Education and Science of the Republic of Serbia within the framework of integrated and interdisciplinary research for the period 2011 - 2017.

REFERENCES

Aguilera A.; Barros, J.; Rolleri, A.; Cardenas, J.; Meausoone P.; Aguilar, C. 2013. Assessment of machining performance for solid wood moulding advances on trials running with sharp cutting edge. *Pro Ligno* 9(4): 398-407.

Aguilera, A.; Muñoz, H. 2011. Rugosidad superficial y potencia de corte en el cepillado de *Acacia melanoxylon* y *Sequoia sempervirens*. *Maderas-Cienc Tecnol* 13(1): 19-28.

Aguilera, A.; Zamora, R. 2009. Surface roughness in sapwood and heartwood of Blackwood (*Acacia melanoxylon* R. Br.) machined in 90-0 direction. *European Journal of Wood Products* 67: 297-301.

Axelsson, B.; Lundberg, S.; Grönlund, A. 1993. Studies of the main cutting force at and near a cutting edge. *Holz als Roh und Werkstoff* 52: 43-48.

Barcik, Š.; Pivuloskova, E.; Kminiak, R. 2008. Effect of technological parameters and wood properties on cutting power in plane milling of juvenilie poplar wood. *Drvna industrija* 59 (3): 107-112.

Belleville, B.; Ashley, P.; Ozarska, B. 2016. Wood planing properties of Australian plantation-grown eucalypts. *Maderas-Cienc Tecnol* 18(3):425-434.

EN 1534:2010. Wood flooring - Determination of resistance to indentation -Test method. EN 1534..

Eyma, F.; Méaysoone, P.; Martin, P. 2004. Study of the properties of thirteen tropical wood species to improve the prediction of cutting forces in mode B. *Annals of Forest Science* 61 (2004): 55-64.

Goglia, V. 1994. Tools and machines for wood processing I. University of Zagreb - Faculty of Forestry, Zagreb, Croatia (In Croatian).

Goli, G.; Uzielli, L. 2004. Mechanisms of wood surface formation and resulting final condition after planing. In S. E. Stanzl-Tschegg, M. Gindl, & G. Sinn (Eds.), Proceedings of the 2nd International Symposium on Wood Machining, BOKU, Vienna, Austria: 451-457.

Günay, M.; Korkut, I.; Aslan, E.; Şeker, U. 2005. Experimental investigation of the effect of cutting tool rake angle on main cutting force. *Journal of Materials Processing Technology* 166(1): 44-49.

Kalajdžić, M. 2008. Machine building. Faculty of Mechanical Engineering, Belgrade. (In Serbian).

Krilek, J.; Kováč, J.; Kučera, M. 2014. Wood Cross cutting Process Analysis for Circular Saws. *BioResources*9(1): 1417-1429.

Kršljak, B. 2013. Tools and machines for wood processing I. University of Belgrade, Faculty of Forestry, Belgrade. (In Serbian).

Mandić, M.; Porankiewicz, B.; Danon, G. 2015. An Attempt at Modelling of Cutting Forces in Oak Peripheral Milling. *BioResources* 10(3): 5489-5502.

Mason, R.; Gunst, R.; Hess, J. 2003. *Statistical Design and Analysis of Experiments: With Applications to Engineering and Science*. 2nd Edition, Wiley.

Naylor, A.; Hackney, P.; Perera, N.; Clahr, E. 2012. A predictive model for the cutting force in wood machining developed using mechanical properties. *BioResources* 7(3): 2883-2894.

Orlicz, T. 1982. *Obróbka drewna narzędziami tnącymi*. (*Machining of wood with use of cutting tools*), Study book SGGW-AR, Warsaw, Poland.

Porankiewicz, B.; Axelsson, B.; Grönlund, A.; Marklund, B. 2011. Main and normal cutting forces by machining of wood of *Pinus sylvestris*. *BioResources* 6(4): 3687-3713.

Porankiewicz, B.; Goli, G. 2014. Cutting forces by Oak and Douglas fir machining. *Maderas-Cienc Tecnol* 16(2): 199-216.

SRPS ISO13061-2:2015. Wood - Determination of density for physical and mechanical tests. SRPS ISO 13061-2

SRPS ISO 13061-3:2015. Wood - Determination of ultimate strength in static bending. SRPS ISO 13061-3.

Stanić, J. 1989. Theory of metal processing. Mechanical Engineering, University of Belgrade, Belgrade 218-259.

Thoma, H.; Peri, L.; Lato, E. 2015. Evaluation of wood surface roughness depending on species characteristics. *Maderas-Cienc Tecnol* 17(2): 285-292.

Wen-Hsiang, L. 2000. Modeling of Cutting Forces in End Milling Operations. *Tamkang Journal of Science and Engineering* 3(1): 15-22.

Yanda, H.; Ghani, J. A.; Hassan, C.; Haron, C. 2010. Effect of Rake Angle on Stress, Strain and Temperature on the Edge of Carbide Cutting Tool in Orthogonal Cutting Using FEM Simulation. *Journal of Engineering and Technological Sciences* 42(2): 179-194.