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COMPARISON OF MEASURED AND CALCULATED VALUES OF CUTTING FORCES IN OAK WOOD PERIPHERAL MILLING

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ABSTRACT

The aim of investigations was to determine whether the tested models for calculating forces in wood cutting, set up under strictly controlled laboratory conditions, can yield sufficiently accurate results for predicting wood behavior in real cutting conditions. Tests were carried out on oak wood (*Quercus robur*). On the basis of measured values for the required cutting power, cutting forces were calculated and used for comparison by applying the method of coefficient (Kršljak's model) and Axelsson's model. The analysis indicated that there is not a result, but there is similarity in the curve shape, i.e. changes in measured values are followed by corresponding changes in calculated values. It can be inferred that analyzed models are not suitable for the cutting forces quantification, but could serve for comparing different cutting modes. More accurate modeling of the cutting process requires, besides physical, wood mechanical properties as well.

KEY WORDS: Oak, peripheral milling, cutting power, cutting forces, wood properties.

INTRODUCTION

In the times of rapid development of new materials there is a growing need for better understanding of the interaction between work pieces and tools. Considering this fact, the analysis of material machinability represents one of the major interests of contemporary manufacturing. Since the cutting force is one of the basic criteria for machinability evaluation, no wonder that accurate prediction of the cutting force values is a necessity in manufacturing conditions. In the literature dealing with wood mechanical processing there is a volume of papers researching the cutting force issues (Axelsson et al. 1991, Cooz and Meyer 2006, Orlowski and Palubicki 2009, Marchal et al. 2009, Taşcioğlu et al. 2010, Naylor et al. 2013, Guo et al. 2014). Also, the literature offers an account of various methods (models) for the evaluation of the cutting forces, set up based on extensive experiments, for more important wood species and major types of machining by cutting. Using data on wood/wood-based materials that are machined and a chosen cutting mode, models predict the material behavior in the machining process, the result of machining, and primarily the quality of the machined surface. The methods of coefficients are the simplest methods (Orlicz 1982, Zubčević 1988, Goglia 1994, Kršljak 2013). The authors of these models start from the reference unit cutting resistance (K_{ref}) for a particular wood species measured under accurately defined and controlled (standard) conditions. The specific resistance for specific material and specific cutting conditions (K) is obtained when reference unit cutting resistances (K_{ref}) are multiplied by corresponding correction coefficients (C_i) calculated in advance and that can be found in the respective tables:

$$K = K_{ref} \cdot C_1 \cdot C_2 \cdot C_3 \cdot \ldots \cdot C_n \quad (N \cdot mm^{-2}) \tag{1}$$

The magnitude of the main cutting resistance is obtained when the calculated coefficient K is multiplied by the cross-sectional surface of a separate particle/chip for a corresponding type of cutting As:

$$F = K \cdot A_s \quad (N) \tag{2}$$

The model is a simple tool to use because calculations of the cutting force require data on the measured unit cutting resistance, conditions of carried out cutting, minimum number of relatively readily available data on the material, tools and cutting conditions and respective tables. However, these models have certain weaknesses. When comparing measured and thus calculated cutting forces values, significant differences occur in some cases. This phenomenon can be explained by the fact that wood physical and mechanical properties are insufficiently and inadequately included in the models, i.e. these properties are most commonly represented only via correction coefficients for wood species C_{vr}, which need not be always sufficient. For example, two pieces manufactured from the same wood species (with the same C_{vr}) may have different physical and mechanical properties, and therefore may behave differently in the cutting process. Another reason is that the correction coefficients, provided by the tables, are not the result of multifactorial experiments, so that the model does not include interdependencies commonly existing between some factors. There is a range of other potential reasons, and it can be concluded that the control model for the cutting process control should include impact of other wood properties such as anatomical, physical and mechanical: mode of wood cutting (longitudinal, transverse, tangential, or combined), wood density and moisture content, bending strength, tensile strength and the like (Eyma 2004).

Somewhat more complex models for predicting the cutting forces are the models that include wood properties as well (Axelsson 1993, Naylor et al. 2012, Porankiewicz et al. 2011, Mandić et al. 2015). Empirical equation of the Axelsson model involves the following impact factors: wood density, wood moisture content, temperature of wood, the angle between the cutting speed vector and the wood grain orientation, cutting speed and mean chip thickness. Author has tested the obtained model by applying it to his results and found that the coefficient of determination for correlation between measurement results and calculated values amounted to $R^2 = 0.81$ in the entire domain of the model validity. When authors created the Naylor model (Naylor et al. 2012), variables involved not only wood density and moisture content but also milling depth, as well as wood mechanical properties: bending strength and shear strength, modulus of elasticity and modulus of shear, and toughness. Testing was carried out for four different moisture contents and on eight different wood species. Considering that the samples were machined longitudinally and transversally against wood grain orientation, in the paper two separate equations were set up for the cutting force in longitudinal and transverse milling against wood grain orientation. The disadvantage of the mentioned model are cutting conditions that differed greatly compared to those in practice. The tool was moving in a straight line, at a very low speed, not higher than at 0.1 m.s^{-1}. The Porankiewicz model is created and verified using the results of investigations performed on a specially built laboratory machine (Porankiewicz et al. 2011). The model involves physical and mechanical properties of samples, tool characteristics and cutting mode characteristics. The paper gives equations for peripheral and normal cutting force as a function of the angle between cutting direction and grain orientation, radius of cutter blade roundness/bluntness, the size of the cutter blade rake angle, mean chip thicknesses, cutting speeds, wood density at 8% moisture content, wood moisture content and temperature of wood.

MATERIALS AND METHODS

Tests were conducted on oak wood (*Quercus robur*) at the Center for Wood Processing Machines and Tools, Faculty of Forestry, Belgrade, using a table-mounted milling cutter MiniMax CU410K equipped with a Maggi Engineering feeding device Vario Feed (speed 3-24 m·min^{-1}). Density and moisture content of procured planks were tested and thereafter used to make samples for testing density and moisture content, complying with current standards ISO 3131 – 1975 (E) and ISO 3130 – 1975 (E). The dimensions of samples intended for cutting power measurements in peripheral milling, as a function of different cutting conditions, were 1000 x 30 x 200 mm (Fig. 1). Prior to the initiation of measurements, samples were conditioned at the temperature of 20±20°C and relative air humidity of 65±5%. The tool used consisted of three milling cutters with four blades equipped with plates made of hard metal, diameter D = 125 mm, width B = 40 mm with different cutter angles. For milling cutter 1, the cutting angle was 74° (clearance angle α = 15°, sharpening angle β = 59° and rake angle γ = 160°), for milling cutter 2, the cutting angle was 70° (clearance angle α = 15°, sharpening angle β = 55° and rake angle γ = 20°), and for milling cutter 3, the cutting angle was 65° (clearance angle α = 15°, sharpening angle β = 50° and rake angle γ 25°). Appearance of the construction of one such milling cutter is represented in Fig. 1.

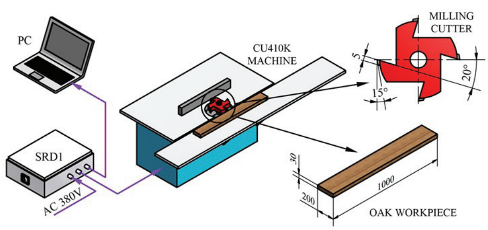

Fig. 1: Representation of experimental setup.

Peripheral milling was performed parallel with wood grains, open, and up milling. Cutting powers required for milling were measured indirectly by measuring power input of the machine driving the electric motor using measurement-acquisition device SRD1 (Fig. 1) equipped with the Power Expert software that allows for the analysis, processing and storage of the results and their subsequent presentation (Mandić and Danon 2010, Mandić et al. 2015b).

RESULTS AND DISCUSSION

Statistical analysis of measured values for elementary physical properties of tested oak wood samples is shown in Tab. 1. Mean value of measured samples' oven dry densities was 725 kg·m^{-3} and standard deviation was ±23 kg·m^{-3}. Mean measured moisture content was 7.28 % and standard deviation 0.30 %, which confirms uniform distribution of moisture content in tested samples. The table also gives calculated values of densities for 8 % wood moisture content that are used in one of the considered models.

Tab. 1: Statistical analysis of physical properties.

Physical property	Measure unit	Mean value	Standard deviation	Maximum value	Minimum value
Measured density	(kg·m^{-3})	745	24	780	690
Measured moisture content	(%)	7.28	0.30	7.96	6.67
Oven dry density	(kg·m^{-3})	725	23	760	670
Density at 8% moisture content	(kg·m^{-3})	749	24	785	692

Mean values of measured cutting powers, for different cutting modes in peripheral milling, i.e. for different mean depths of cut are shown in Fig. 2.

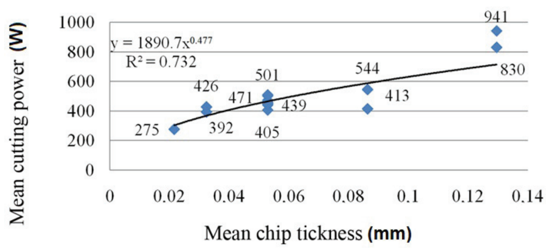

Fig. 2: The dependence of the measured cutting power and mean chip thickness in peripheral milling.

Measured cutting powers range widely, from 274 to 942 W, depending on cutting conditions and physical properties of wood being machined. Dependency was established between achieved cutting powers and mean chip thickness as the most influential machining parameters, the determination degree being very high (R^2 = 0.73):

$$P = 1890.7 \cdot e_m^{0,477} \quad \text{(W)} \tag{3}$$

where: P - cutting power (W),
e_m - mean chip thickness (mm).

Mean values of measured powers were used to calculate mean values of the main cutting resistance by applying the formula as follows:

$$F_m = \frac{P_m}{v_r} \quad \text{(N)} \tag{4}$$

where: F_m - mean value of the main cutting force for one cutter revolution,
P_m - mean cutting power (W),
v_r - cutting speed (m·s^{-1}).

Calculated value of the mean force Fm, based on Eq. 4, represents mean force for one cutter revolution, which means that it also includes idle feed between the blades (Fig. 3).

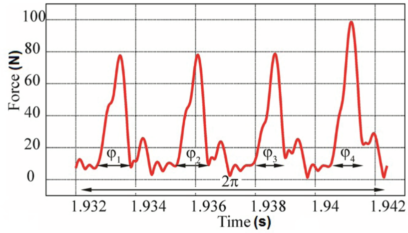

Fig. 3: Change of the main cutting force for one cutter revolution.

Considering that the values of specific force Fm obtained via measured power represent mean specific cutting force for one cutter revolution, involving idle feed as well, correction is needed so as to obtain mean specific force for cutter Fb engagement, and it is done as follows:

$$F_b = \frac{F_m \cdot O_{gl}}{\sum_1^4 l_{r1}} = \frac{F_m \cdot 2 \cdot \pi \cdot R}{z \cdot \varphi_0 \cdot R} = \frac{F_m \cdot \pi}{2 \cdot \varphi_0} \quad (N) \tag{5}$$

where: O_{gl} - circumference of the milling cutter (m),
l_{r1} - engagement length of a single blade and work piece (m),
z - number of milling cutter blades,
R - milling cutter radius (m),
φ_0 - mean angle of blade engagement and work piece (work),
a - depth of cut (milling) (m).

Values of force per revolution and per a single cutter tooth were calculated for constant main cutting speed (n = 5860 RPM) and for the following values of angle and engagement length of blade and work piece:

$$\varphi_0 = \arccos\left(\frac{R-a}{R}\right) = \arccos\left(\frac{0.0625-a}{0.0625}\right)$$
$$\varphi_{0(a=2)} = 0.254 \text{ rad}; \; l_{r1} = \varphi_0 \cdot R = 0.254 \cdot 0,0625 = 0.0158 \text{ m};$$
$$\varphi_{0(a=3)} = 0.311 \text{ rad}; \; l_{r1} = \varphi_0 \cdot R = 0.311 \cdot 0,0625 = 0.0194 \text{ m};$$
$$\varphi_{0(a=4,5)} = 0.382 \text{ rad}; \; l_{r1} = \varphi_0 \cdot R = 0.382 \cdot 0,0625 = 0.0239 \text{ m}. \tag{6}$$

Fig. 4 displays the dependence of calculated mean cutting forces per cutter blade of mean chip thickness in peripheral milling.

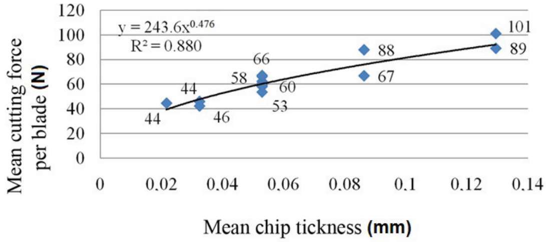

Fig. 4: The dependence of mean cutting forces per cutter blade and mean chip thickness in peripheral milling.

The calculated mean forces fall within the 44 – 102 N range, depending on cutting conditions and physical properties of wood being cut. Dependency was established between calculated forces and mean chip thickness with a high determination degree (R^2 = 0.88).

$$F_b = 243.6 \cdot e_m^{0,4761} \quad (7)$$

where: F_b - mean cutting force per tooth/blade of the milling cutter (N),
e_m - mean chip thickness (mm).

The paper analyzes two models such as: the method of coefficients (Kršljak, 2013) as a representative of the method of coefficients and the Axelsson model (Axelsson 1993) as the simplest and least demanding model based on wood properties and cutting conditions. Tests of other mentioned and available models could not be performed due to lack of data on wood properties.

Method of coefficients

Specific cutting resistance, as above mentioned, is affected by numerous factors such as: wood species and structure, wood moisture content, elements of blade geometry, blade penetration angle against wood grain orientation, chip dimensions, cutting conditions etc. In his book, Kršljak (2013) analyzed each of those factors and their impact is represented by corresponding equations, while specific data for the coefficients are given in tabular form. The formula for calculating wood specific resistance, according to Kršljak, has the following form:

$$K = K_{el} \cdot C_{vr} \cdot C_u \cdot C_\delta \cdot C_\varphi \cdot C_e \cdot C_v \cdot C_\rho \quad (8)$$

where: K - wood specific resistance for specific cutting conditions,
K_{el} - wood specific resistance for e = 1 mm where e is (mean) chip thickness,
C_{vr} - correction factor for wood species,
C_u - correction factor for wood moisture content,
C_δ - correction factor for wood species,
C_φ - correction factor for penetration angle into the wood,
C_e - correction factor for chip thickness,
C_v - correction factor for cutting speed,
C_ρ - correction factor for the dullness of a cutting edge.

The first step is to determine the value of wood specific resistance Kel corresponding to a 1 mm^2 chip area, i.e. chip thickness of e=1 mm. For the needs of further calculations, the value of Ke1= 14 $N{\cdot}mm^{-2}$ for wood specific resistance was adopted that holds for longitudinal oak wood cutting. For the impact factors of wood moisture content, the adopted value is C_u = 1.1 that applies to wood moisture contents between 5 % and 8 %. Considering that cutting is performed longitudinally against wood grain orientation and that tests employed milling cutters with different rake angles, i.e. cutting angles, the following values were adopted for C_δ. For the cutting angle of 74° and rake angle of 16°, the value is 2, for the cutting angle of 70° and rake angle of 20°, the value is 1.7, and for the cutting angle of 65° and rake angle of 25°, the tabular value is 1.5. The impact of blade penetration angle into the wood φ_s, for all cutting modes, is taken via correction coefficient C_φ. Since the machining mode is longitudinal milling, the angle between the tool blade motion direction and wood grain orientation is varying and ranges from 0 to φ_0 that depends on the layer thickness, under removal, i.e. depth of cut. For the given case, the literature recommends to calculate φ_s in the following manner:

$$\varphi_m = \varphi_s + \frac{\varphi_o}{2} = \varphi_s + \frac{\arccos(1 - \frac{a}{R})}{2} \tag{9}$$

where: φ_m - mean angle between tool blade motion direction and wood grain orientation,
φ_s - angle of wood grain orientation against machined surface,
φ_0 - engagement angle of the cutter edge ,
a - milling depth, mm,
R - cutter radius, mm.

Our investigations deployed three milling cutters of identical radii and cutting was replicated at three different milling depths. Samples were cut from radial planks, and it was adopted that $\varphi_s = 0$ and that φ_{m1} = 5.1° (for a = 2 mm), φ_{m2} = 6.3° (for a = 3 mm), φ_{m3} = 7.7° (for a = 4.5 mm). Based on values of the angles (formula 6) and tabular values, it is possible to calculate the impact of blade penetration angle against wood grain orientation C_φ according to the following dependency derived from data given in (Kršljak 2013):

$$C_\varphi = 0.7 + 0.0178 \cdot \varphi_m \tag{10}$$

For the angle of 5.1°, correction factor C_φ amounts to 0.79; for the angle of 6.3°, correction factor C_φ is 0.81 and for the angle of 7.7°, correction factor C_φ equals 0.83.

Chip elements also have high impact on wood specific resistance. According to the results shown in (Kršljak 2013), based on tabular values, an equation is set up for calculating the impact of chip thickness Ce on wood coefficient of resistance in cutting (coefficient of determination amounts to R^2 =0.99):

$$C_e = 0.9814 \cdot e_m^{-0.3338} \tag{11}$$

Mean chip thicknesses were calculated using the following formula:

$$e_m = s_z \cdot \sqrt{\frac{a}{D}} = \frac{u \cdot 1000}{n \cdot z} \cdot \sqrt{\frac{a}{D}} \tag{12}$$

where: e_m - mean chip thickness in peripheral milling,
s_z - feed size for a single blade (mm),
a - milling depth (mm),
D - milling cutter diameter (mm),
u - feed speed ($m \cdot min^{-1}$),
n - number of cutter revolutions ($o \cdot min^{-1}$),
z - number of tool blades.

Tab. 2 gives correction coefficients for the observed cutting conditions.

Tab. 2: Correction coefficients for chip thickness C_e.

u ($m \cdot min^{-1}$)	a (mm)	e_m (mm)	C_e -
4	2	0.0216	3.53
4	3	0.0264	3.30
4	4.5	0.0324	3.08
8	2	0.0432	2.80
8	3	0.0529	2.62
8	4.5	0.0648	2.45
16	2	0.0863	2.22
16	3	0.1057	2.08
16	4.5	0.1295	1.94

*Given coefficients were calculated for the following initial data: n = 5 860 $o.min^{-1}$ and D = 125 min.

Cutting speed has a significant impact on the magnitude of wood specific resistance, primarily for higher cutting speeds. In our investigations, cutting speed was constant and amounted to 38.2 $m.s^{-1}$ so that the coefficient of impact for all performed measurements is the same and amounts to C_v = 1.28 (Kršljak 2013). Prior to experiment initiation, tools were sharpened, so that it is adopted that the impact of the dullness of a blade on the size of wood coefficient of resistance is minimum, i.e. C_ρ=1.

Tab. 3 presents the adopted values of coefficients and calculated specific resistances and cutting forces.

Tab. 3: Calculated wood specific resistance and cutting forces – Kršljak model .

K_{e1}	C_u	C_e	C_v	C_ρ	C_φ	Calculated specific resistance of wood K	Calculated cutting force F
($N.mm^{-2}$)	-	-	-	-	-	$N \cdot mm^{-2}$	N
14	1.10	3.57	1.28	1.00	2.00	140.63	91.06
14	1.10	3.57	1.28	1.00	2.00	140.63	91.06
14	1.10	3.12	1.28	1.00	2.00	122.83	119.31
14	1.10	3.12	1.28	1.00	2.00	122.83	119.31
14	1.10	3.12	1.28	1.00	2.00	122.83	119.31
14	1.10	2.25	1.28	1.00	2.00	88.53	229.32
14	1.10	2.25	1.28	1.00	2.00	88.53	229.32
14	1.10	1.96	1.28	1.00	2.00	77.32	300.44
14	1.10	2.65	1.28	1.00	1.70	88.64	140.60
14	1.10	2.65	1.28	1.00	1.70	88.64	140.60
14	1.10	2.65	1.28	1.00	1.70	88.64	140.60
14	1.10	2.65	1.28	1.00	1.70	88.64	140.60
14	1.10	2.65	1.28	1.00	1.70	88.64	140.60
14	1.10	2.65	1.28	1.00	1.70	88.64	140.60
14	1.10	2.65	1.28	1.00	1.70	88.64	140.60
14	1.10	2.65	1.28	1.00	1.70	88.64	140.60

14	1.10	3.12	1.28	1.00	1.50	92.12	89.48
14	1.10	3.12	1.28	1.00	1.50	92.12	89.48
14	1.10	2.25	1.28	1.00	1.50	66.40	171.99
14	1.10	2.25	1.28	1.00	1.50	66.40	171.99
14	1.10	1.96	1.28	1.00	1.50	57.99	225.33
14	1.10	1.96	1.28	1.00	1.50	57.99	225.33

Calculated values range from 89.48 N to 225.33 N. It is evident from the table that specific resistance is most strongly affected by the change in mean chip thickness and blade penetration angle into the wood. Other factors are constant. Similar results were obtained by using other similar models (Goglia 1994, Zubčević 1988).

Axelsson's model

Axelsson (1993) has set up a model equation using a multifactorial experiment of woodcutting with a circular saw. The model encompasses impacts such as material properties, cutting conditions, sharpening angles and blade condition, environmental conditions, which has to contribute to obtaining more realistic results.

$$F_p = \left[\frac{-7.37+e_m\times(0.38\cdot\rho_8-224.5\cdot\gamma)+15.61\cdot\varphi_s-2.6\cdot\varphi_s^3+1.31\cdot\rho+0.2\cdot v_r+u\cdot(0.3\cdot\varphi_s-0.01\cdot t)}{4.25}\right] \tag{13}$$

where: F_p - specific main cutting force ($N\cdot mm^{-1}$),
e_m – mean chip thickness (mm),
ρ_8 – wood density at 8% moisture content ($kg\cdot m^{-3}$),
γ –rake angle (rad),
φ_s – the angle between cutting direction and wood grain orientation (work),
ρ – radius of cutter blade roundness (μm),
u – moisture content (%),
v_r – cutting speed ($m\cdot s^{-1}$),
t – temperature (^0C).

Tab. 4 gives input data for the Axelsson model such as: mean chip thickness, wood density at 8% moisture content, cutter blade rake angle, cutting speed, wood moisture content, environment temperature and radius of the cutter tip roundness. The same table contains calculated cutting forces.

Tab. 4: Calculated wood cutting forces –Axelsson model.

NO	e_m	$\rho_{8\%}$	γ	φ_s	ρ	u	v	t	F_p*	F**
	(mm)	($g\cdot cm^{-3}$)	(°)	(rad)	μm)	(%)	($m\cdot s^{-1}$)	(°C)	($N\cdot mm^{-1}$)	(N)
1	0.0216	0.778	16	0.12683	2	6.86	38.20	20	1.20	36
2	0.0216	0.756	16	0.12683	2	7.05	38.20	20	1.16	34.8
3	0.0324	0.738	16	0.19089	2	6.79	38.20	20	1.67	50.1
4	0.0324	0.741	16	0.19089	2	7.83	38.20	20	1.68	50.4
5	0.0324	0.773	16	0.19089	2	7.55	38.20	20	1.77	53.1
6	0.0863	0.776	16	0.12683	2	7.06	38.20	20	4.73	141.9
7	0.0863	0.692	16	0.12683	2	7.70	38.20	20	4.08	122.4
8	0.1295	0.737	16	0.19089	2	6.86	38.20	20	6.64	199.2

9	0.0529	0.724	20	0.15555	2	7.31	38.20	20	2.46	73.8
10	0.0529	0.735	20	0.15555	2	7.22	38.20	20	2.51	75.3
11	0.0529	0.753	20	0.15555	2	7.51	38.20	20	2.60	78
12	0.0529	0.735	20	0.15555	2	7.14	38.20	20	2.52	75.6
13	0.0529	0.744	20	0.15555	2	7.31	38.20	20	2.56	76.8
14	0.0529	0.774	20	0.15555	2	7.39	38.20	20	2.70	81
15	0.0529	0.777	20	0.15555	2	6.94	38.20	20	2.71	81.3
16	0.0529	0.755	20	0.15555	2	7.25	38.20	20	2.61	78.3
17	0.0324	0.785	25	0.19089	2	7.25	38.20	20	1.54	46.2
18	0.0324	0.783	25	0.19089	2	7.48	38.20	20	1.54	46.2
19	0.0863	0.744	25	0.12683	2	7.41	38.20	20	3.77	113.1
20	0.0863	0.753	25	0.12683	2	7.46	38.20	20	3.84	115.2
21	0.1295	0.718	25	0.19089	2	6.67	38.20	20	5.35	160.5
22	0.1295	0.734	25	0.19089	2	7.31	38.20	20	5.53	165.9

*Force was calculated using Eq. 13.

**Force was calculated for work piece width of 30 mm.

It is obvious from Tab. 4 that three input quantities have a constant value for all observed cases. These are cutting force, rounded blades and environment temperature at the time of tests, whereas other quantities changed depending on physical properties of the samples, i.e. cutting mode, which resulted in a fairly wide range of calculated values for cutting forces. Comparison between results presented in Tabs. 3 and 4 shows that differences between forces calculated using these two models are relatively high and differ considerably from measured ones, with the comment to follow below.

Fig. 5 displays in parallel the values of measured and calculated values of mean cutting forces for all measurements carried out.

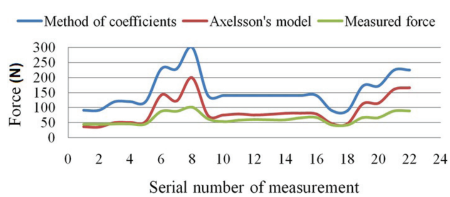

Fig. 5: Measured and calculated mean cutting forces in peripheral milling of oak.

Fig. 5 indicates that the results do not coincide but that there is similarity in the shape of curves, i.e. changes in measured values are followed by corresponding changes in calculated values.

One possible way to establish the adequacy of some model is a comparison between the model and the calculated values obtained for the same input data. Statistical comparison between measured and calculated values is performed based on two parameters. The first is a ratio between mean values of the sets of measured and calculated values, i.e. systemic difference between measured and calculated values. The second is a ratio between variances of the sets of measured and calculated values (Tab. 5).

Tab. 5: Statistical analysis of calculated and measured cutting forces.

Force (N)	Valid N	Mean	Minimum	Maximum	Variance	Std.Dev.	Coef.Var.
Coefficient methods	22.00	154.46	89.54	300.39	3084.42	55.54	35.96
Axelsson model	22.00	88.87	34.80	199.20	2055.19	45.33	51.01
Measured values	22.00	62.89	42.08	101.03	319.39	17.87	28.42

Fig. 6 displays in parallel data on mean cutting force per a single blade and force calculated using the method of coefficients (Kršljak's model), i.e. the Axelsson's model.

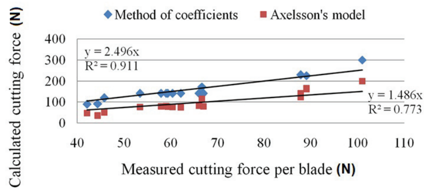

Fig. 6: The ratio between measured and calculated values of cutting force for both models.

The linear regression equation for the method of coefficients has the form:

$$F_{coeff} = 2.496 \cdot F_{measured} \quad (14)$$

On the basis of the given equation and obtained coefficient of determination ($R^2 = 0.91$), it can be concluded that there is a strong correlation between measured and calculated values, but they do not coincide. The latter is indicated by the coefficient of direction in the regression equation equals 2.496, the ratio between mean measured and calculated values equals 2.45, and the ratio of variations equals 3.10 (obtained on the basis of data shown in Tab. 5). The picture would be slightly different if considerations involve, instead of mean calculated forces, maximum measured forces (calculated with the condition that change of the main cutting force during blade - wood contact has approximately the shape of a triangle (Fig. 4), i.e. that $F_{max} = 2 \cdot F_m$. In that case, the linear regression equation would have the form:

$$F_{coeff} = 1.248 \cdot F_{measured} \quad (15)$$

and the coefficient of determination would remain the same. The ratio between measured and calculated values amounts to 1.23, and the ratio of variations is 1.55.

The linear regression equation for the Axelsson's model has the form:

$$F_{axelsson} = 1.487 \cdot F_{measured} \quad (16)$$

The coefficient of determination ($R^2 = 0.77$), in this case too, is very high and indicates a very strong correlation between variables. The problem points to a significant difference between measured and calculated values. The ratio between measured and calculated values amounts to 1.41, whereas the ratio between variations equals 2.54 (obtained on the basis of data shown in Tab. 5). There is higher coincidence for lower values of chip thickness, where values of cutting forces differ by about 20%, while higher values of chip thickness are almost two times higher than measured ones.

If the calculated values for two considered models are compared, the situation is as follows (Fig. 7).

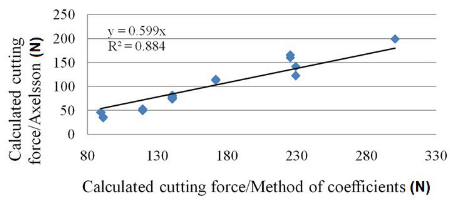

Fig. 7: The ratio between values of cutting force calculated by coefficient methods and Axelsson's models.

The linear regression equation has the form:

$$F_{axelsson} = 0.5995 \cdot F_{coeff.} \quad (17)$$

From the above equation and obtained coefficient of determination (R^2 = 0.88) it can be deduced that there is a strong correlation between calculated values but that they do not coincide. This is also proved by the coefficient of direction of the regression line (0.599). The ratio between measured and calculated values amounts to 1.73 and the ratio of variations is 1.22.

CONCLUSIONS

Comparative analysis of calculated and measured values established similar behavior, i.e. similar response to change in the cutting parameters, primarily mean chip thickness and mean angle between cutting direction and wood grain orientation.

Between measured values of mean force in peripheral milling and those calculated by the method of coefficients (Kršljak's model) for the same input data there is a very strong correlation (coefficient of determination is 0.91), but there is no coincidence. The coefficient of direction in the regression equation amounts to 2.496, whereas calculated values are, on average, by 2.45 times higher than those measured.

The Axelsson's model proved to be somewhat better for the prediction of cutting forces in peripheral milling. The coefficient of determination (R^2 = 0.77) is very high in this case too and indicates a very strong correlation between measured and calculated values. However, the difference between measured and calculated values remains high. Coincidence is better for lower values of chip thickness, where values of cutting forces differ by about 20%, whereas for greater chip thickness the calculated values are almost by two times higher than those measured.

The final conclusion is that the given models are a simple tool to use and suitable for application if comparison is done between impact of some factors on the mechanics of cutting but they are not suitable for quantification of their impact, i.e. calculations of specific values of the cutting forces.

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REFERENCES

1. Axelsoon, B., Grundberg, S., Gronlud, J., 1991: The use of gray scale images when evaluating disturbances in cutting force due to changes in wood structure and tool shape, European Journal of Wood and Wood Products 49: 491-494.
2. Axelsson, B., Lundberg, Å., Grönlund, J., 1993: Studies of the main cutting force at and near a cutting edge, Eur. J. Wood Wood Prod. 51(1): 43-48.
3. Cooz, I., Meyer, R.W., 2006: Cutting forces for tension and normal wood of maple, Forest Prod. J. 56(4): 26-34.
4. Eyma, F., Méausoone, 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, Ann. 61: 55–64
5. Goglia, V., 1994: Tools and machines for wood processing I. University of Zagreb – Faculty of Forestry, Zagreb, Pp 40-78 (In Croatian).
6. Guo, X., Li, R., Cao, P., Ekevad, M., Cristóvão, L., Marklund, B., Grönlund A., 2015: Effect of average chip thickness and cutting speed on cutting forces and surface roughness during peripheral up milling of wood flour/polyvinyl chloride composite, Wood research 60 (1): 147-156.
7. ISO 3130:197: Wood – Determination of moisture content for physical and mechanical test.
8. ISO 3131:1975: Wood – Determination of density for physical and mechanical tests.
9. Kršljak, B., 2013: Tools and machines for wood processing I. University of Belgrade, Faculty of Forestry, Belgrade, Pp 5-36 (In Serbian).
10. Mandić, M., Danon, G., 2010: Measurements of cutting power in wood milling, Prerada drveta 29: 34-41 (In Serbian).
11. Mandić, M., Svrzić, S., Danon, G., 2015b: The comparative analysis of two methods for the power consumption measurement in circular saw cutting of laminated particle board, Wood research,) 60 (1): 125-136.
12. Mandić, M.; Porankiewicz, B.; Danon, G., 2015a: An attempt at modelling of cutting forces in oak peripheral milling, BioResources 10(3): 5489-5502.

13 Marchal, R., Mothe, F., Denaud, L., Thibaut, B. and Bleron, L., 2009: Cutting forces in wood machining-Basics and applications in industrial processes. Holzforschung 63(2): 157-167.

14. Naylor, A., Hackney, P., 2013: A review of wood machining literature with a special focus on sawing, BioResources 8 (2): 3122-3135.
15. Naylor, A., Hackney, P., Perera, N., Clahr, E., 2012: Mechanical cutting force model. A predictive model for the cutting force in wood machining developed using mechanical properties, BioResources 7 (3): 2833-2894.
16. Orlicz, T., 1982: Obróbka drewna narzędziami tnącymi. (Machining of wood with use of cutting tools). Study book SGGW-AR. Warsaw.
17. Orlowski, K., Palubicki, B., 2009: Recent progress in research on the cutting processes of wood, Holzforschung 63(2): 181-185.
18. Porankiewicz, B., Axelsson, B., Grönlund, A., Marklund, B, 2011: Main and normal cutting forces by machining wood of *Pinus Sylvestris*, BioResources 7(3): 2883-2894.
19. Taşcıoğlu, Y., Jackson, M. R., 2010: Material removal aspects and cutting power requirement of profile independent wood-moulding, Wood research 55 (4): 131-148.
20. Zubčević, R. 1988: Wood processing machines, Part 1, the theory of cutting. Univerzitet u Sarajevu – Mašinski fakultet, Sarajevo, Pp 4-7 (In Bosnian).

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