Annals of Warsaw University of Life Sciences - SGGW
Forestry and Wood Technology № 83, 2013: 322-328
(Ann. WULS - SGGW, For. and Wood Technol. 83, 2013)

Dynamics of cutting power during sawing with circular saw blades as an effect of wood properties changes in the cross section

KAZIMIERZ A. ORLOWSKI[1], TOMASZ OCHRYMIUK[2]
[1] Department of Manufacturing Engineering and Automation, Faculty of Mechanical Engineering, The Gdansk University of Technology, Gdansk, Poland
[2] Department of Transonic Flows and Numerical Methods, The Szewalski Institute of Fluid-Flow Machinery, Polish Academy of Sciences, Gdansk, Poland

Abstract: *Dynamics of cutting power during sawing with circular saw blades as an effect of wood properties changes in the cross section.* In the paper the effect of the method calculation upon the cutting power is presented. In computations were used models in which fracture toughness was incorporated. The comparison concerned models as follows: FM-CM – classic model in which the sum of all uncut chip thicknesses of the simultaneously teeth engaged represented the mean uncut chip thickness, FM-FDM – full dynamical model in which besides variable uncut chip thickness additionally variable values of fracture toughness and shear yield stresses according to the tooth position in relation to the grains were taken into account, and FM-SDM – semi dynamical model in which in which uncut chip thickness is variable, but fracture toughness and shear yield stresses are constant and equal to the mean values. The largest values of the cutting power have been obtained while the FM-SDM model applied.

Keywords: circular sawing machine, cutting power, fracture mechanics, macro-mechanic model of sawing

INTRODUCTION

In the classical approach, energetic effects (cutting forces and cutting power – more interesting from energetic point of view) of wood sawing process are generally calculated on the basis of the specific cutting resistance k_c (cutting force per unit area of cut) [13, 14, 15]. The latter has been confirmed in the latest review paper by Naylor and Hackney [12], in which sawing became the focus of interest. During the 21st IWMS the methods of cutting power determination during sawing with circular saw blades became the focus of interest in some works: Sitkei [19] studied similarities of the energy requirement of saws (frame saws, bandsaws and circular saws), Cristóvão et al. [6] compared the industrial results of cutting power measurements with the original Axelsson's model [3] outcomes. The latter model has been converted by Porankiewicz et al. [18] into the multi-factor and non-linear dependencies between main (tangential) F_c and normal (radial) F_N cutting forces and eight machining parameters for sawing simulation of wood of *Pinus sylvestris* L.. In the models for a circular sawing machine kinematics described in works by Orlowski et al. [16], similarly to metal milling [8], the sum of all uncut chip thicknesses of the simultaneously teeth engaged represented the mean uncut chip thickness. However, in reality the instantaneous uncut chip thickness at a certain location of the cutting tooth changes its value (Fig. 1). Hence, Orlowski and Ochrymiuk [17] have converted the model described in the paper [16] into a new model in which besides variable uncut chip thicknesses additionally variable values of fracture toughness and shear yield stresses according to the tooth position in relation to the grains were taken into account. Thus, for this reason that kind of the model could be called as FM-FDM (fracture mechanics incorporated - full dynamical model). In this paper results of cutting power with the use of: FM-CM – classic model [15, 16], FM-FDM [17], and FM-SDM (fracture mechanics incorporated – semi dynamical model in which uncut chip thickness is variable, nevertheless, fracture toughness and shear yield stresses are constant and equal to the mean values as in the FM-CM).

THEORETICAL BACKGROUND

In the case of circular sawing, identically as in analytical models for milling [1, 5], the instantaneous uncut chip thickness $h_j(\varphi)$ at a certain location of the cutting edge can be approximated as follows:

$$h_j(\varphi) = f_z \sin\varphi_j \tag{1}$$

where: f_z is feed per tooth, φ_j is the angular position of the j-th tooth (immersion angle), and its value changes as follows:

$$\varphi_j = \varphi + (j-1)\varphi_P \qquad j = 1,\dots,z \tag{2}$$

φ_P is the pitch angle defined as $\varphi_P = \frac{2\pi}{z}$, and z is number of teeth.

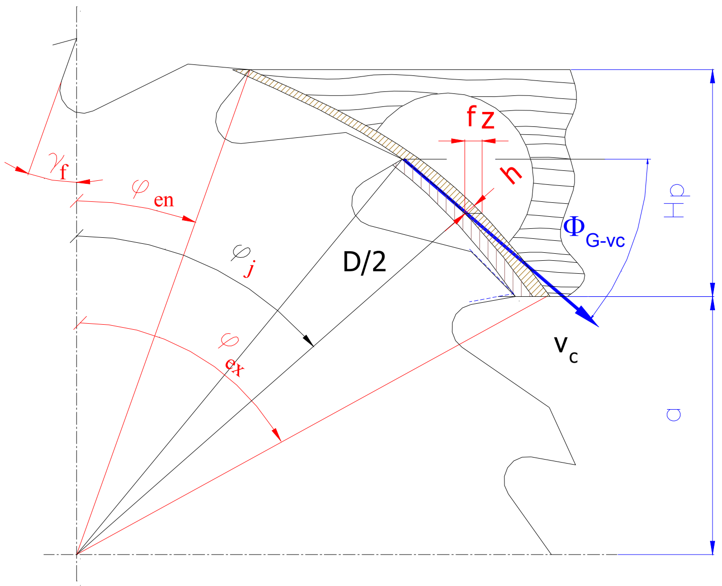

Figure 1. Sawing kinematics on circular sawing machine: H_p workpiece height (depth of cut), a position of the workpiece, φ_j angular tooth position, $\Phi_{G\text{–}vc}$ an angle between grains and the cutting speed direction [17]

If $\varphi_{en} \le \varphi_j \le \varphi_{ex}$, then it has a value, otherwise it is null. φ_{en} is an angle of teeth entrance which is given by $\varphi_{en} = \arccos\frac{2(H_p + a)}{D}$ (when the tool tooth gets into the workpiece for machining), and φ_{ex} is an exit angle (the tooth of the saw blade gets out of the workpiece) which can be determined as $\varphi_{ex} = \arccos\frac{2a}{D}$, D is a diameter of the circular saw blade. In the case of cutting with circular saw blades the cutting power a new developed macro-mechanic model, which is based on the model proposed initially in work [16], can be expressed as:

$$P_{cj}(\varphi) = v_c S_t \left[\frac{\tau_{\gamma\parallel\perp\_j}(\varphi)\cdot\gamma_j(\varphi)}{Q_{shear\_j}(\varphi)} h_j(\varphi) + \frac{R_{\parallel\perp\_j}(\varphi)}{Q_{shear\_j}(\varphi)} \right] \tag{3}$$

where: v_c is cutting speed, S_t is the kerf (overall set), $\tau_{\gamma\parallel\perp\_j}(\varphi)$ is the shear yield stress, $\gamma_j(\varphi)$ is the shear strain along the shear plane [2, 16, 17], $\Phi_c(\varphi_j)$ is the shear angle which defines the orientation of the shear plane with respect to cut surface [2, 16, 17], $R_{\parallel\perp\_j}(\varphi)$ is specific work of surface separation/formation (fracture toughness) [2, 16, 17], and $Q_{shear\_j}(\varphi)$ is the friction correction [2, 16, 17]. The shear angle $\Phi_c(\varphi_j)$ is material dependent [2] and can be computed numerically [2, 15, 16, 17].

Taking into account the position of the cutting edge in relation to the grains, for indirect positions of the cutting edge fracture toughness $R_{\|\perp\_j}(\varphi)$ and the shear yield stress $\tau_{\gamma\|\perp\_j}(\varphi)$ may be calculated from formulae:

$$R_{\|\perp\_j}(\varphi) = R_{\|}\cos^2\varphi_j + R_{\perp}\sin^2\varphi_j \qquad \tau_{\gamma\|\perp\_j}(\varphi) = \tau_{\gamma\|}\cos^2\varphi_j + \tau_{\gamma\perp}\sin^2\varphi_j \tag{4}$$

In case of FM-FDM and FM-SDM models, maximum, average or RMS values of power can be determined after one full revolution of the tool, i.e. φ: 0–360° is simulated [5]. Thus, the total cutting power can then be computed as:

$$P_c(\varphi) = \sum_{j=1}^{j=z} P_{cj}(\varphi) \tag{5}$$

The obtained values from the Eq. 5 should be augmented by the chip acceleration power P_{ac} variation as a function of mass flow and tool velocity [6, 15, 16].

MATERIALS AND METHODS

Predictions of cutting powers have been made for the case of sawing on the circular sawing machine (HVS R200, f. HewSaw), which is used in Polish sawmills. The basic sawing machine data and cutting parameters for which computations were done are shown in Table 1. Computations were carried out in each case for one saw blade with both a new analytical models (FM-FDM and FM-SDM, described in this paper, at the feed speed v_f = 70 m·min^{-1} usually applied at the sawmill), and additionally with the model presented by Orlowski et al. [15, 16].

Table 1. Tool and machine tool data [17]

H_P [mm]	n_{sb} [mm]	S_t [mm]	v_c [ms^{-1}]
80	6	3.6	63.95
γ_f [°]	z [–]	v_f [m·min^{-1}] ([ms^{-1}])	f_z [mm]
25	30	60–200 (1 – 3.33)	0.57–1.91
h [mm]	v_f [m·min^{-1}] ([ms^{-1}]) applied	f_z [mm] applied	h [mm] applied
0.273–0.913	70 (1.17)	0.67	0.32
P_{EM} [kW]	P_i [kW]	P_{cA} (P^1_{cA}) [kW]	φ_P [°]
90	14	64.6 (10.77)	12
Legend: P_{EM} – electric motor power, P_i – idling power, P_{cA}, (P^1_{cA}) – available cutting power in the cutting zone (available cutting power per one saw blade), n_{sb} – number of saw blades			

Table 2. Raw material data [15]

Region	ρ	$R_\perp$	$\tau_{\gamma\perp}$	MOR*
	kgm^{-3}	Jm^{-2}	kPa	MPa
C	478	1267.17	17986	35,2
ρ – density, MOR – modulus of rupture in bending (* values were taken from Krzosek [10])				

The raw material was pine wood (*Pinus sylvestris* L.) of depth of cut equal to H_p, at moisture content MC 8.5–12%, derived from the Little Poland Natural Forest Region (C, [17]). The value of friction coefficient μ = 0.6 for dry pine wood was taken according to Glass and Zelinka [7]. In case of circular sawing in which indirect positions of the cutting edge are present, R and τ_y have to be calculated from formulae (4). According to Aydin et al. [4] it was assumed that fracture toughness for pine for longitudinal (axial) cutting $R_{\parallel} = 0.05R_{\perp}$. Moreover, an assumption was made that in the case of pine wood for axial cutting the shear yield stress $\tau_{y\parallel}$ is equal to 0.125·MOR (modulus of rupture in bending [9, 11]). The set of the raw material initial data is presented in tab. 2.

RESULTS

In Figure 2, the values of the shear yield stresses $\tau_{\gamma\parallel\perp\_j}(\varphi)$ (Fig. 2a) and fracture toughness $R_{\parallel\perp\_j}(\varphi)$ (Fig. 2b) for indirect positions of the cutting edge of Polish pine wood from the Little Poland Natural Forest Region provenance are presented. It could be emphasised that for the cutting edge position φ = 90º, while there are conditions of perpendicular cutting, in case of the shear yield stresses the largest differences caused by raw material provenance were observed [17]. On the other hand, for fracture toughness mentioned differences were not so meaningful [17].

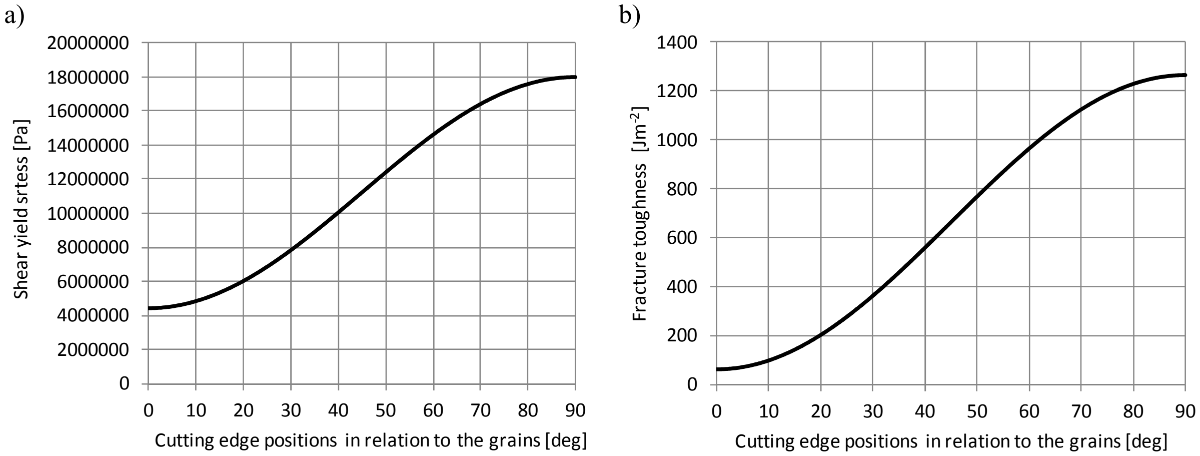

Figure 2. The effect of the cutting edge positions in relation to the grains of Polish pine wood from the Little Poland Natural Forest Region on shear yield stresses (a) and fracture toughness (b)

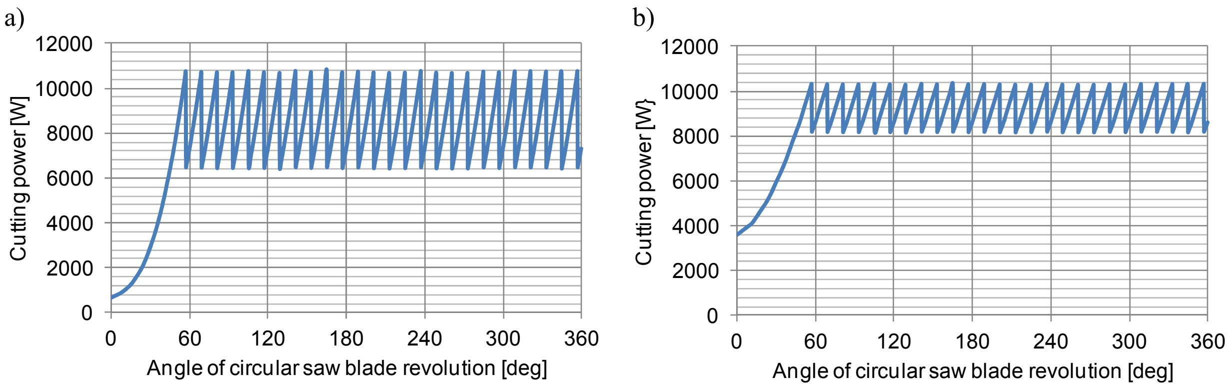

Figure 3. Comparison of predictions of cutting powers obtained with the use of new developed cutting models that include work of separation in addition to plasticity and friction for the circular sawing machine with one circular saw blade in the case of dry pine sawing from the Little Poland Natural Forest Region, where: a – FM-FDM [17], b – FM-SDM

Results of predictions of cutting powers obtained with the use of new developed cutting models that include work of separation in addition to plasticity and friction in the case of sawing of pine (the Little Poland Natural Forest Region provenance) with one circular saw blade, at the feed speed v_f = 70 m·min^{-1} usually applied at the sawmill, for one full revolution of the tool (the first one), are shown in Fig. 3, respectively FM-FDM (Fig. 3a) and FM-SDM (Fig. 3b). The larges dynamical changes of cutting power are observed for sawing process of pine wood while FM-FDM is applied, but the smaler alteretions are for the FM-SDM model used. For a stable condition of cuting power changes RMS values were computed, and they are equal to: for FM-FDM P_c(RMS_C) = 8799 W and for FM-SDM P_c(RMS_D) = 9153 W.

In Figure 4, the effect of the calculation method on the cutting power value for the circular sawing machine with one circular saw blade in the case of dry pine sawing is shown. While the classic approach is used, it meant that the sum of all uncut chip thicknesses of the simultaneously teeth engaged represented the mean uncut chip thickness, the computed value of the cutting power has the lowest value.

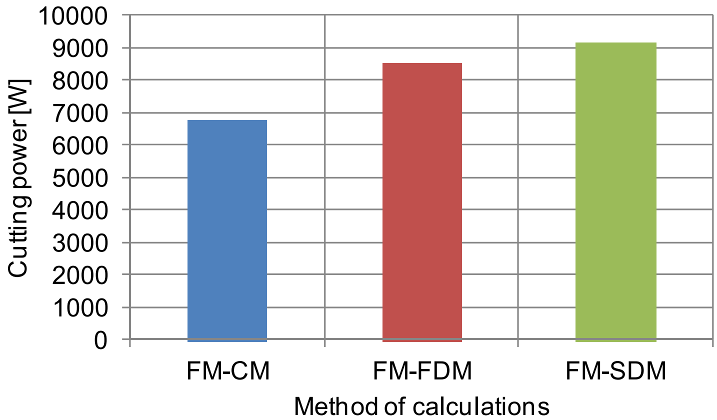

Figure 4. The effect of the calculation method on the cutting power value for the circular sawing machine with one circular saw blade in the case of dry pine sawing from the Little Poland Natural Forest Region (for FM-FDM and FM-SDM values of RMS are presented)

CONCLUSIONS

The conducted analyses of energetic effects using the developed macro-mechanic cutting models (FM-FDM and FM-SDM) that include work of separation in addition to plasticity and friction corroborated their versatility and revealed the usefulness for predictions not only average values of cutting power but also mainly its dynamical changes.

The conducted analyses have demonstrated that in each case values of RMS of cutting powers obtained with new developed dynamical models are larger than values computed with the use of the mean uncut chip thicknesses and mean values of raw material data such as R and τ in the model. Furthermore, the largest values have been obtained while the FM-SDM model applied.

Acknowlegements: The financial assistance of Ministry of Science and Higher Education, Poland, Grant N N 508 629840 is kindly acknowledged. The authors would like also to acknowledge firms the firm PPH GASSTECH Sp. z o.o. for circular saw blades data, and the Olczyk Sawmill (Poland) for data on the sawing process.

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Streszczenie: *Dynamika mocy skrawania podczas przecinania piłami tarczowymi jako efekt zmian właściwości drewna w przekroju poprzecznym*. W niniejszym artykule przedstawiono wpływ metody obliczeń na wartość mocy skrawania. Każdy z zastosowanych modeli obliczeniowych zawierał elementy współczesnej mechaniki pękania. W porównaniach uwzględniano następujące modele obliczeniowe: FM-CM – model klasyczny, w którym suma wszystkich grubości warstwy skrawanej ostrzy będących w kontakcie z przedmiotem obrabianym odpowiadała wartości średniej grubości niezeskrawanego wióra, FM-DDM – pełny model dynamiczny, w którym uwzględniano dla ostrza zmiany właściwości mechanicznych materiału obrabianego, a także zmiany grubości warstwy skrawanej, oraz FM-SMD – pół (quasi) dynamiczny model, w którym uwzględniano jedynie zmiany grubości warstwy skrawanej, zaś właściwości materiału przyjęto jak w modelu klasycznym. Największe wartości mocy skrawania w rozpatrywanym przypadku otrzymano dla metody FM-SMD, pomimo, iż zmiany dynamiczne mocy skrawania były mniejsze niż dla modelu FM-FDM.

Corresponding author:

Prof., Dr. Sc., Eng. Kazimierz A. Orlowski,
Department of Manufacturing Engineering and Automation,
Faculty of Mechanical Engineering,
The Gdansk University of Technology
11/12 Narutowicza,
80-233 Gdańsk, Poland
email: korlowsk@pg.gda.pl
phone: +48 583472101