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On some approaches to cutting power estimation while wood sawing

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Abstract: *On some approaches to cutting power estimation while wood sawing.* In the classical approach, energetic effects of wood sawing process (cutting forces and cutting power) are generally calculated on the basis of the specific cutting resistance. Another tool for determination of cutting power in case of wood sawing is the "Horsepower calculator", the on-line software. On the other hand, cutting forces (power) could be considered from a point of view of modern fracture mechanics. Forecasting of the shear plane angle for the cutting models, which include fracture toughness in addition to plasticity and friction, broaden possibilities of energetic effects modelling of the sawing process even for small values of the uncut chip. The latter model is useful for estimation of energetic effects of sawing of every kinematics. In this paper methods which might be applied for estimation of cutting power while sawing with circular saw blades are presented and compared.

Keywords: wood sawing, circular sawing machine, cutting power, fracture mechanics

INTRODUCTION

Theoretical and experimental determination of values of forces acting in the cutting process belongs to the basic and simultaneously the most developed field of mechanics of this process. Data of cutting force values and their action directions are used in the designing process of machine tools and their tooling, and also for the needs of the automatic control of manufacturing processes [1]. An engineer has to make a decision, willy-nilly, which a method of the cutting power determination should be chosen. In this paper we are going to present methods which might be applied for estimation of cutting power while sawing with circular saw blades.

THEORETICAL BACKGROUND

Kinematics of sawing on circular sawing machines (Fig. 1) differs from kinematics of cutting on sash gang saws and bandsawing machines, since the cutting speed direction in regard to the wood grain direction changes its position.

In the Manžos's method [2, 3], which could be classified as a classical approach, cutting power P_c [W] is given by:

$$P_c = \frac{v_f \cdot S_t \cdot H_P}{60} k_c \tag{1}$$

where: v_f – feed speed [m·min^{-1}], S_t – kerf (overall set) [mm], H_p – workpiece height (depth of cut) [mm]

$$k_c = k_\Phi k_H k_{vc} k_\delta \tag{2}$$

where: k_Φ – pine specific cutting resistance [N·mm^{-2}], which takes into account the position of the cutting edge in relation to the grains; k_H – depth of cut (workpiece thickness) coefficient;

k_{vc} – cutting speed coefficient, k_δ – coefficient of the angle δ_f, called often as a cutting angle [2], which is defined as a sum of a clearance angle α_f and a tool side wedge angle β_f.

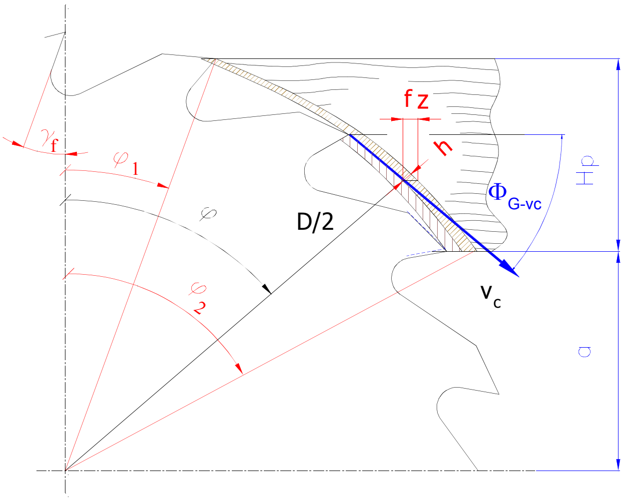

Fig. 1. Sawing kinematics on circular sawing machine: f_z – feed per tooth, D – circular saw blade diameter, h – uncut chip thickness, H_p – workpiece height (depth of cut), a – position of the workpiece, φ – angular tooth position, $\Phi_{G\text{-}vc}$ – an angle between grains and the cutting speed direction

The pine specific cutting resistance k_Φ can be calculated as follows:

$$k_\Phi = 29.562\left(\frac{h}{\sin\varphi}\right)^{-0.4052} \tag{3}$$

The above equation has been worked out on the basis of the graphic representation of empirical relations published by Manžos [2].
Another tool for determination of cutting power in case of sawing on circular sawing machines is the “Horsepower calculator” [4], the on-line software in which the user can choose between imperial and metric units, the cutting power P_c [W], for a set of wood species, can be calculated as:

$$P_c = \frac{v_f \cdot H_P \cdot S_t \cdot SG}{379.786} \times 10^3 \tag{4}$$

where: SG – wood specific gravity, which is density of wood relative to the density of water, it should be emphasised that other values are in the same units of measurements as previously, H_p and S_t in [mm].
On the other hand, cutting forces (power) could be considered from a point of view of modern fracture mechanics [5, 6]. In case of cutting with circular saw blades uncut chip thickness $\bar{h}$ (an average value e.g.) instead of feed per tooth f_z should be taken into account, hence, the cutting power may be expressed as:

$$\overline{P}_{cw} = F_c v_c + P_{ac} = \left[z_a \cdot \frac{\tau_\gamma S_t \gamma}{Q_{shear}} v_c \bar{h} + z_a \cdot \frac{RS_t}{Q_{shear}} v_c \right] + P_{ac} \tag{5}$$

where: $z_a = \left(\frac{\varphi_2 - \varphi_1}{\varphi_t} \right)$ is a number of teeth being in the contact with the kerf (average), φ_1 is an angle of teeth entrance which is given by $\varphi_1 = \arccos \frac{2(H_p + a)}{D_{cs}}$, φ_2 is an exit angle which can be determined as $\varphi_2 = \arccos \frac{2a}{D_{cs}}$, D_{cs} is a diameter of circular saw blade, an average uncut chip thickness is given by $\bar{h} = f_z \sin \bar{\varphi}$, and an average angle of tooth contact with a workpiece $\bar{\varphi}$ is calculated from $\bar{\varphi} = \frac{\varphi_1 + \varphi_2}{2}$, τ_γ is the shear yield stress, R is specific work of surface separation/formation (fracture toughness). The chip acceleration power P_{ac} variation as a function of mass flow and tool velocity [6]. The shear strain along the shear plane γ and the friction correction Q_{shear}, which is a function the shear angle Φ_c (defines the orientation of the shear plane with respect to cut surface), can be calculated with formulae given in the work [6]. However, the shear angle Φ_c (material dependent) can be obtained numerically [7].

Furthermore, it is difficult to assume that in this kind of sawing kinematics there is a case of perpendicular cutting, because the angle between the grains and the cutting speed direction differs from 90°, as it was assumed for the sash gang saw and the band sawing machines [6]. Hence, taking into account the position of the cutting edge in relation to the grains, for indirect positions of the cutting edge fracture toughness R and the shear yield stress τ_γ may be calculated from formulae known form strength of materials [3]. For example for cutting on circular sawing machines (a case of axial-perpendicular cutting) these material features are as follows:

$$R_{\parallel\perp} = R_{\parallel} \cos^2 \Phi_{G-vc} + R_{\perp} \sin^2 \Phi_{G-vc} \tag{6}$$

and

$$\tau_{\gamma\parallel\perp} = \tau_{\gamma\parallel} \cos^2 \Phi_{G-vc} + \tau_{\gamma\perp} \sin^2 \Phi_{G-vc} \tag{7}$$

where: $\Phi_{G\text{-}vc}$ is an angle between grains and the cutting speed direction (Fig. 1).

MATERIAL 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 parameter for which computations were done are as follows: H_p = 80 mm, S_t = 3.6 mm, γ_f = 22°, teeth (stellite tipped) number z = 24, v_c = 61.14 m·s^{-1}, circular saw blade diameter D = 300 mm, feed speed v_f ≤150 m·min^{-1}(≤2.5 m·s^{-1}), f_z ≤1.56 mm, $\bar{h}$ ≤0.747 mm, and power of installed electric motors P_{EM} = 2×90 kW. The raw material was pine wood (*Pinus sylvestris* L.) of depth of cut equal to H_p derived from the Little Poland Natural Forest Region in Poland. The average density of samples was ρ = 478 kgm^{-3}, (specific gravity SG = 478) at moisture content MC 8.5–12%.The cutting power was determined with three methods described in the previous chapter.

In the approach in which energetic effects have been considered from a point of view of modern fracture mechanics the indispensable raw material data for computation such as: fracture toughness $R_\perp$ = 1267.17 Jm^{-2} and the shear yield stress $\tau_{\gamma\perp}$ = 17986 kPa was applied. The latter was determined according to the methodology described in the works [5]. The value of friction coefficient $\mu = 0.6$ for dry pine wood was taken from the work by Beer [8]. In the case of circular sawing in which indirect positions of the cutting edge are present, R and τ_{γ} have to be calculated from formulae (6) and (7). According to Aydin et al. [9] it was assumed that fracture toughness for pine for longitudinal (axial) cutting $R_{\parallel} = 0.05R_{\perp}$. Moreover, an assumption was made that in case of pine wood for axial cutting the shear yield stress $\tau_{\gamma\parallel}$ is equal to $0.125 \cdot$MOR (modulus of rupture in bending [10]). The average value of MOR for pine wood derived from the Little Poland Natural Forest Region (PL), was equal to MOR = 35.2 MPa [11, 12].

RESULTS AND DISCUSSION

Predictions of three methods: the Manžos method (the classical approach, Pc_Man), the "Horsepower calculator" (Pc_www) and the cutting model that includes work of separation in addition to plasticity and friction (Pc_Frac) in the case of sawing dry pine wood on examined circular sawing machine are shown in Fig. 2.

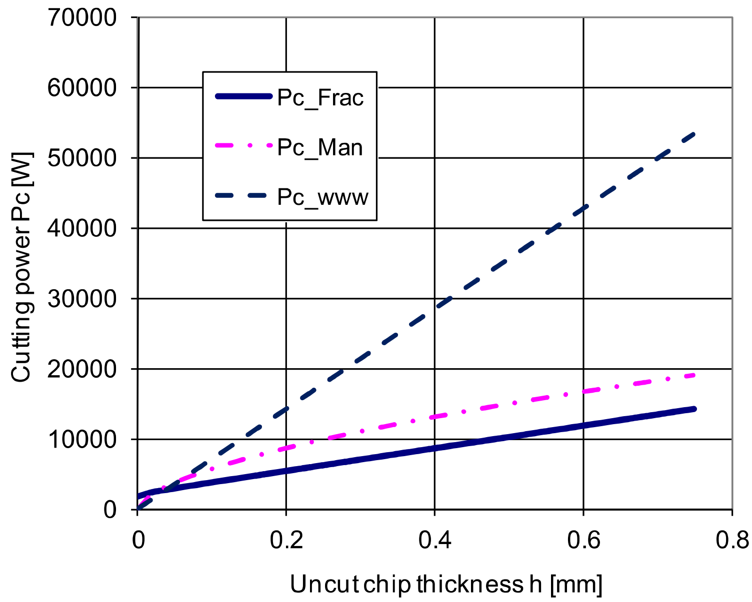

Fig. 2. Comparison of predictions of cutting powers obtained with the use of: the classical Manžos method (Pc_man), the web_source – the "Horsepower calculator" (Pc_www) and the cutting model that include work of separation in addition to plasticity and friction for the circular sawing machine in the case of dry pine sawing with one saw blade

This comparison revealed that there is a small difference between results of methods Pc_Frac and Pc_Man because in Manžos's method the material data concerns the Russian pine (from the territory of the Union of Soviet Socialist Republics). Furthermore, the latter method does not take the geographical location of the forest in which the trees were harvested, which strongly affects wood physical properties and timber grade [11, 12]. The results obtained with the "Horsepower calculator" significantly depart from cutting power values computed with both methods Pc_Frac and Pc_Man. Thus, this kind of approach could be applied in very rough estimations of cutting power, the more so because correlation coefficients between cutting forces and *SG* is rather average [13].

At small depths of the cut the 'size effect' might be noticed for the cutting power prediction method which bases on the fracture mechanics (Pc_FRAC) [14, 15] and also in the case of circular sawing for Manžos's method (see also Eq. 3) [2]. However, in the case of the "Horsepower calculator" the scale effect is not imperceptible. This phenomenon has its roots in empirical formulae which are used because the calculated power is just directly proportional to the material removal rate (the product of the first three factors, see Eq. 4) and the specific gravity *SG* is constant.

CONCLUSIONS

Based on the results of this study the following conclusions can be drawn:

- Cutting power values, in case of sawing of dry pine wood on examined circular sawing machine, obtained with the Manžos method (the classical approach, Pc_Man) and the cutting model that includes work of separation in addition to plasticity and friction (Pc_Frac) have been more or less the same. Nevertheless, the latter method allow the user to estimate the cutting power for the sawing process more precisely because the wood derivation could be taken into account.
- The results obtained with the "Horsepower calculator" significantly depart from cutting power values computed with other examined methods. Thus, this kind of approach could be applied in very rough estimations of cutting power, the more so because correlation coefficients between cutting forces and *SG* is rather average.

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Streszczenie: *O pewnych podejściach do szacowania mocy skrawania podczas przecinania drewna piłami.* W niniejszym artykule przedstawiono i porównano metody, które mogą być stosowane do szacowania mocy skrawania przy przecinaniu drewna na pilarkach tarczowych. Przy klasycznym podejściu efekty energetyczne procesu przecinania drewna piłami są obliczane na bazie właściwego powierzchniowego oporu skrawania. W internecie dostępne są narzędzia do określania mocy skrawania w postaci oprogramowania dostępnego on-line, przykładowo „Horsepower calculator". Oprócz tego, siły skrawania (moce skrawania) mogą być rozpatrywane z punktu widzenia współczesnej mechaniki pękania, dzięki czemu możliwe jest przewidywanie kąta ścinania. Model, który uwzględnia wiązkość materiału, zjawiska plastyczności w strefie skrawania oraz tarcie, poszerza możliwości modelowania procesu skrawania. Wspomniany model obliczeniowy jest uniwersalny i przydatny do szacowania efektów energetycznych procesu przecinania dla każdej kinematyki.

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