INFLUENCE OF VARYING ENERGY CONSUMPTION WITH DIFFERENT GRAIN ORIENTATION

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Abstract

Due to the energy consumption during machining, it is important to know cutting resistance, which is a very significant property of the material machined. In the conventional methods, energetic effects (cutting forces, cutting power and cutting resistance) of wood sawing process are generally calculated on the basis of the specific cutting resistance, which is in the case of wood cutting the function of many factors. This paper presents new calculating model using the application of fracture mechanics. New model is based on the application of the Ernst-Merchant theory in the conditions of circular-saw blade cutting. It includes the prediction of the shear plane angle, fracture toughness, shear yield stress, coefficient of friction and shear strain along the shear plane. It provides a possibility of modelling energetic effects of the sawing process even for small values of the chip thickness.

Key words: *Angelim Vermelho, fracture mechanics, circular saw blade, fracture toughness, shear yield stress, cutting resistance*

INTRODUCTION

Wood, whether in native or modified form, has to be machined to the final shape to fulfill its intended purpose. In wood processing industry, the circular-saw blade cutting is the most frequent way to machine materials on the basis of wood. It is assumed that new wood-based materials will be machined on existing woodworking machines and therefore it is necessary to know its behavior during cutting.

Due to the energy consumption during machining, it is important to know cutting resistance, which is a very significant property of the material machined (Böllinghaus et al 2009). This paper presents a new calculating model which is based on application of fracture mechanics. This model uses to determination cutting, feed, shear and friction forces the application of the Ernst-Merchant theory in the conditions of circular-saw blade cutting and might be applied for estimation of energetic effects (Atkins 2003, 2009).

MATERIAL AND METHODS

The cutting process was performed with a circular saw blade, which is produced by Flury Systems AG. This standard circular-saw blade of 350 mm diameter with straight teeth is

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designed for longitudinal cutting of wood. The construction parameters of the blade are shown in Tab. 1. The cutting was performed under the optimum operation speed $n = 3800\ min^{-1}$. Feed velocity varied within the range of $v_f = 2 – 22\ m \cdot min^{-1}$ with measuring step $2\ m \cdot min^{-1}$. This corresponded with the changing feed per tooth f_z and mean chip thickness h_m.
The series of cutting tests to empirically determine the cutting force was carried out on a test rig for research *via* cutting with circular saw blades at the laboratory of the Department of Wood Processing of the Faculty of Forestry and Wood Technology of Mendel University in Brno (Kopecký and Rousek 2012). This device simulates the conditions of circular-saw blade cutting in the real operation. The parameters of the cutting process were recorded by sensors installed in the measuring stand. The signals were transferred in the data switchboard Spider 8 and in the software Conmes Spider and subsequently processed into tables and graphs.
The samples of *Angelim Vermelho* (ρ = 950 kg.m^{-3}) were used in the experiment. The scantlings were dried (relative moisture content 7 %) and unified in the same thickness (e = 22 mm). In order to verify the validity and function of the new calculation model, different directions of the cutting in relation to the grain and on the cutting edge position were used (perpendicular cutting, axial-perpendicular cutting).

Table 1 Parameters of saw blade K3

Parameters of saw blade K3 – Flury systems 350	
Saw blade diameter **D**	350 mm
Number of teeth **z**	28
Clamping hole diameter **d**	30 mm
Blade body width **s**	2,5 mm
Tooth width (cutting joint) $\mathbf{s_t}$	3,5 mm
Tooth height **h**	10,5 mm
Tooth pitch $\mathbf{t_p}$	39,27 mm
Clearance angle $\boldsymbol{\alpha_f}$	15°
Cutting edge angle $\boldsymbol{\beta_f}$	55°
Rake angle $\boldsymbol{\gamma_f}$	20°

According to the latest theoretical findings with the use of fracture mechanics methods (Atkins 2003, 2009) and (Orlowski 2010, Orlowski et al. 2013), a mathematical model of the cutting power may be expressed in the case of cutting with circular saw blades as:

$$\overline{P}_{cw} = F_c \cdot v_c + P_{ac} = \left[z_a \cdot \frac{\tau_\gamma \cdot b \cdot \gamma}{Q_{shear}} \cdot h_m \cdot v_c + z_a \cdot \frac{R \cdot b}{Q_{shear}} \cdot v_c \right] + \dot{m} \cdot v_c^2 \ [\mathrm{W}] \quad (1)$$

The first equation member expresses the power necessary for bending and subsequent removal of the chip, the second member expresses the power for overcoming friction between the workpiece and the tool edge, including the formation of a new surface, and the third member expresses the power necessary for the chip acceleration and its sweep out of the point of cutting. However, the third member does not express force ratios at the chip separation, but expresses kinetic energy for carrying chips (sawing) out of the cut by the saw blade. This means that it only affects the total consumed saw power (Orlowski et. al 2012). The following is applied for the mass flow of chips:

$$\dot{m} = \frac{b \cdot l \cdot v_f \cdot \rho}{2} \quad [\ \mathrm{kg \cdot s^{-1}}\ ] \qquad (2)$$

The Atkins (2003) established the cutting force equation, which is based on Ernst-Merchant theory (by considering surface energy, plastic deformation work and friction work). Atkins model can help to derive a relationship for the calculation of specific cutting resistance k_c. The formula for the calculation of specific cutting resistance shows that the specific cutting resistance will increase sharply with a small chip thickness h_m.

$$k_c = \frac{1}{Q_{shear}} \left(\tau_\gamma \cdot \gamma + \frac{R}{h_m} \right) \qquad \text{[Pa]} \qquad (3)$$

where: Q_{shear} is a friction correction coefficient (-), τ_γ is shear yield stress (Pa), R is specific work of a surface separation (fracture toughness) (J·m^{-2}), γ shearing strain along the shear plane (-), h_m is chip thickness (mm).

The determination of shear strain along the shear plane defined by the shear angle Φ_s allows the formula as follows:

$$\gamma = \frac{\cos \gamma_f}{\cos(\Phi_s - \gamma_f) \cdot \sin \Phi_s} \qquad [\,-\,] \qquad (4)$$

where: γ_f is tooth rake angle, Φ_s is shear angle, which expresses the orientation of the shear plane in relation to the worked surface.
For the necessary aim of this study, Φ_s can be calculated for larger values of chip thickness h_m with the Merchant's equation (it is the most frequent formula) (Atkins 2003)

$$\Phi_s = \left(\frac{\pi}{4}\right) - \left(\frac{1}{2}\right) \cdot (\Theta_\mu - \gamma_f) \qquad [\,^\circ\,] \qquad (5)$$

where: Θ_μ friction angle obtained from $tan^{-1}\mu = \Theta_\mu$ (μ is friction coefficient), π *[rad]* 180°

The friction correction coefficient Q_{shear} is not only a function of friction coefficient μ but depends substantially on the orientation of the shear plane towards the worked surface. When shear angle Φ_s equals zero (the tool cuts off no chips), the friction correction coefficient Q_{shear} equals one (Orlowski and Palubicki 2009, Orlowski 2010).

$$Q_{shear} = 1 - \frac{\sin \Theta_\mu \cdot \sin \Phi_s}{\cos(\Theta_\mu - \gamma_f) \cdot \cos(\Phi_s - \gamma_f)} \qquad [\,-\,] \qquad (6)$$

The circular-saw blade cutting process is not an example of purely orthogonal cutting (angle between the direction of grains and cutting velocity vector may differ by up to 90° (φ_3= 0-90°). Taking into account the position of the cutting edge in relation to the grain, for indirect positions of the cutting edge, the fracture toughness $R_{\parallel\perp}$ and the shear yield stress $\tau_{\gamma\parallel\perp}$ may be calculated from formulae known from the strength of materials (Orlicz 1988). For example, for cutting on circular sawing machines (a case of axial-perpendicular cutting), these material features are as follows:

$$R_{\parallel\perp} = R_{\parallel} \cos^2 \varphi_2 + R_{\perp} \sin^2 \varphi_2 \qquad (7)$$

$$\tau_{\gamma\parallel\perp} = \tau_{\gamma\parallel} \cos^2 \varphi_2 + \tau_{\gamma\perp} \sin^2 \varphi_2 \qquad (8)$$

φ_2 angle between the cutting plane and the direction of grains (Fig. 1)

Forces:
F_a = activ force
F_c = cutting force
F_{cN} = normal to cutting force
F_f = feed force
F_{fN}= normal to feed force
F_s = shear force
F_{sN} = normal to shear plane
F_γ = friction force
$F_{\gamma N}$ = normal to friction force
Angles:
γ_f = rake angle
Θ_μ = friction angle
Φ_s = shear angle
φ_2 = angle between the cutting plane and the direction of grains

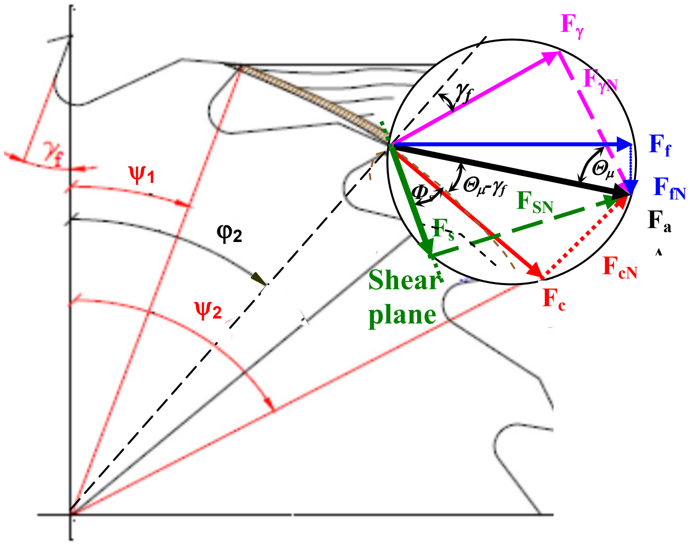

Fig. 1 Simplified cutting process model with Ernst and Merchant's force circle

RESULTS AND DISCUSSION

The obtained regression models of the cutting force per tooth, as a function of the uncut chip thicknesses, are presented in Fig. 2. The model is characterized by Pearson's R values of 0.9978 (perpendicular cutting) and 0.9926 (axial-perpendicular cutting). Almost linear increase of cutting force occurred along with the growing chip thickness, which confirms the theoretical assumptions

The average (medium) cutting force per tooth for axial-perpendicular cutting with the circular saw blade, for the kerf width (S_t) 3.5 mm, for a tooth position defined by the average angle of tooth contact with the workpiece $\bar{\varphi}$ = 39.04°, is described as,

$$F_c^1 = 386442 h_m + 4.2493 \text{ (N)} \qquad (9)$$

The cutting force per tooth for perpendicular cutting is as follows:

$$\bar{F}_c^1(\varphi_2 = 39.04°) = 296901 h_m + 4.6132 \text{ (N)} \qquad (10)$$

In the first step, characteristic data for other materials and cutting processes were estimated according to Atkins (2005). Application of the mechanics approach to the sawing processes of Angelim Vermelho on both directions yielded fracture toughnesses $R_\perp$, $R_{\|\perp}$(φ_2 = 39.04°) and shear yield stresses $\tau_{\gamma\perp}$, $\tau_{\gamma\|\perp}$(φ_2 = 39.04°). Additionally, calculations determining shear yield stresses τ_γ were conducted for uncut chip thicknesses $h_m > 0.12$ mm, when the cutting resistance is practically constant (Orlowski 2007). The orientation of the shear plane with regard to the cut surface could be calculated with Eq. 5. The computed data input, such as the shear strain along the shear plane γ (Eq. 4); the shear angle Φ_s (Eq. 5); the friction correction Q_{shear} (Eq. 6); and the friction angle Θ_μ, given by $\tan^{-1}\mu = \Theta_\mu$, are presented in Table 1. The application of experimental data in the proposed model brings significant data for the longitudinally transversal cutting model to the circular saw blade cutting process. These values are the input data when calculating the specific cutting resistance.

Table 2: Results obtained by the application of fracture mechanics

	τ (MPa)	R (Jm^{-2})	Φ_s (°)	μ	γ	Θ_μ (°)	Q_{shear}
Perpendicular	59.07	1281.444	57.76	0.09	1.56	5.52	1.11
Axial-perpendicular	63.86	1180.361	52.63	0.09	1.53	5.13	0.913

The fracture toughness *R* (φ_2= 39.04°) was determined from the experimental ordinate intercept, where value of the intercept was 4.2493 (N) (Eq. 9) for axial-perpendicular cutting and *R* was determined from the value of experimental ordinate intercept 4.6132 (N) (Eq. 10) for circular saw blade. In both cases, the friction correction in these calculations was assumed to be Q_{shear} = 1, since the uncut chip thickness is equal to 0 and simultaneously Φ_s = 0 (Orlowski and Atkins 2007; Orlowski and Palubicki 2009; Orlowski 2010).

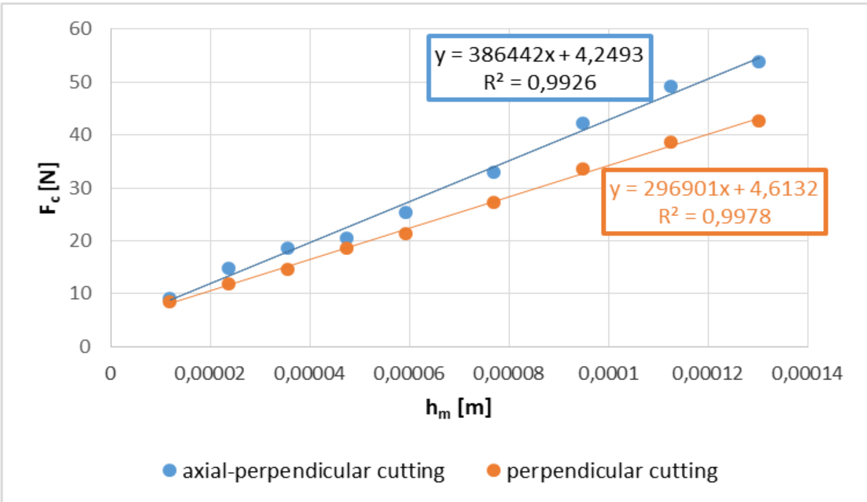

Fig. 2 Cutting force as a function of mean chip thickness

Samples of axial-perpendicular cutting show slightly increased values of cutting resistance (force) in whole range of feed speeds and cutting force increases steeply. Larger differences are obvious at greater feed speeds. Regression line slope of perpendicular cutting samples is not as steep as in the axial-perpendicular samples. Computed values of fracture toughness *R* exhibits similar values as in previous mesurements (Hlásková et al 2015).
The determined values of sawn wood properties could be useful in forecasting the energetic effects using cutting models that include the work of separation, plasticity, and friction for every known type of sawing kinematics.

CONCLUSIONS

The method for determining the cuting forces presented in this paper have shown the development of this issue. Neverthekless the convential approaches are still more popular methods. On the other hand, we can say, that application of the results obtained by experimental cutting allowed for the determination of the toughness and shear yield strength of sawn wood for both the perpendicular and axial cutting directions. It is obvious that the toughness and shear yield stresses of the cut wood depended on the cutting speed direction as related to the grain.

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