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Energetic effects predictions by using new fracture mechanics approach

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Abstract: *Energetic effects predictions by using new fracture mechanics approach.* This paper presents a new calculating model which might be applied for estimation of energetic effects (cutting forces and cutting power) of wood sawing with circular saw blades. Modern fracture mechanics is further used in this new method for determination of the specific work of surface formation (fracture toughness) and the shear yield strength. In order to verify the validity and function of the new calculation model, the samples of native, samples of ammonia refined wood material Lignamon and chemically treated beech (DMDHEU) Belmadur were used in the experiment.

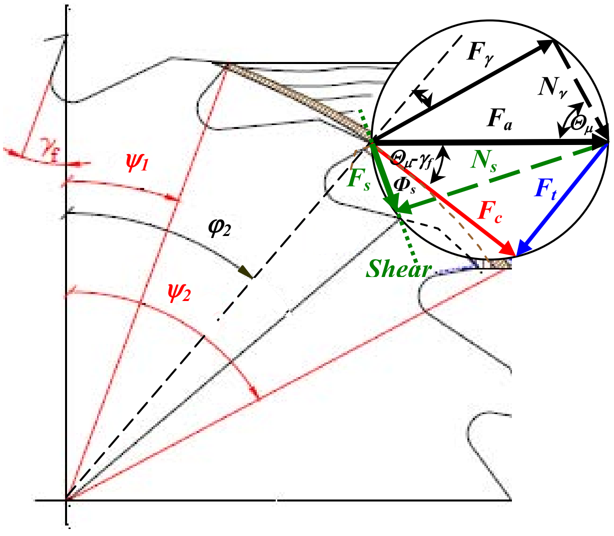
Keywords: cutting resistance, circular-saw blade, fracture mechanics, beech, Lignamon, Belmadur

INTRODUCTION

In the wood processing industry, the circular-saw blade cutting is the most frequent way to machine materials on the basis of wood, plastic, as well as composite materials. Despite the relatively extensive theoretical and practical knowledge of wood machining, no process is currently known which would help to accurately determine the magnitude of cutting resistance and cutting force. Cutting resistance is influenced by wood properties, by its anisotropy and variations of physical and mechanical properties in relation to the direction of grains. It is relatively difficult to determine individual components of cutting resistance. Nowadays, different modifications of two basic methods are used for theoretical purposes and in practice – the technological and physical method, and analytical method (Lisičan 1996), (Naylor et al. 2012).

THEORETICAL BACKGROUND

The article presents a new calculating model using the application of modern fracture mechanics. Cutting and feed forces are determined by the application of the Ernst-Merchant theory (Atkins 2003) in the conditions of circular-saw blade cutting.



Forces:
F_a = *active force*
F_c = *cutting force*
F_t = *thrust (passive) force*
F_s = *shear force*
N_s = *normal force to shear plane*
F_γ = *friction force on rake*
N_γ = *normal force to rake*
Angles:
Θ_μ ... *friction angle*
γ_f ... *rake angle*
Φ_s ... *shear angle*

Fig. 1 Breakdown of forces with the use of the Ernst-Merchant diagram

According to the latest theoretical findings with the use of fracture mechanics methods (Atkins 2003, 2009) and (Orlowski 2010, Orlowski et al. 2012), a mathematical model of power when cutting by saw blades can be expressed in the following form

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

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 (no effect on cutting resistance), 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:

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

Under the theory which uses fracture mechanics, the cutting force, related to one blade tooth, is expressed by the slope of the line in the form *y=(k)·x+(q)* (Orlowski and Palubicki 2009, Orlowski 2010)

$$F_c^{1z} = \left(\frac{\tau_\gamma \cdot b \cdot \gamma}{Q_{shear}} \right) \cdot h_m + \left(\frac{R \cdot b}{Q_{shear}} \right) \quad [\mathrm{N}] \qquad (3)$$

where: τ_γ is shear yield stress (Pa), R is specific work of a surface separation (fracture toughness) ($\mathrm{J{\cdot}m^{-2}}$), b is the width of a saw kerf, Q_{shear} is a friction correction coefficient (-), γ shearing strain along the shear plane (-).

Shearing strain along the shear plane is possible to obtain from the formula

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

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, and which is calculated with the use of the Ernst-Merchant diagram (Fig. 2).

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

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

The Atkinson model, which includes the fracture toughness *R* (equation 1), can help to derive a relationship for the calculation of specific cutting resistance k_c.

$$k_c = \frac{1}{Q_{shear}}\left(\tau_\gamma \cdot \gamma + \frac{R}{h}\right) \quad \text{[Pa]} \qquad (6)$$

The formula for the calculation of specific cutting resistance shows that the specific cutting resistance will increase sharply with a small feed per tooth (with small chip thickness *h*). The friction correction coefficient Q_{shear} 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).

$$Q_{shear} = 1 - \frac{\sin \Theta_\mu \cdot \sin \Phi_s}{\cos\left(\Theta_\mu - \gamma_f\right) \cdot \cos\left(\Phi_s - \gamma_f\right)} \quad \text{[-]} \qquad (7)$$

Furthermore, it is difficult to assume that under 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° ($\varphi_3 = 0 - 90°$). 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 (Orlicz 1988). For example, regarding cutting on circular sawing machines (a case of axial-perpendicular cutting) these material features are as follows:

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

$$\tau_{\gamma\parallel\perp} = \tau_{\gamma\parallel} \cos^2 \varphi_2 + \tau_{\gamma\perp} \sin^2 \varphi_2 \qquad (9)$$

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

MATHERIALS AND METHODS

The cutting process was performed with a circular saw blade (provisional code K3), which is produced by Flury Systems AG (Fig. 2). This standard circulare saw blade of 350 mm diameter with straight teeth is designed for longitudinal cutting of wood. It has adjusted tension by rolling. Four radial dilatation slots are laser-burnt in the cutting part of the blade, in order to compensate the waviness due to the increasing temperature.

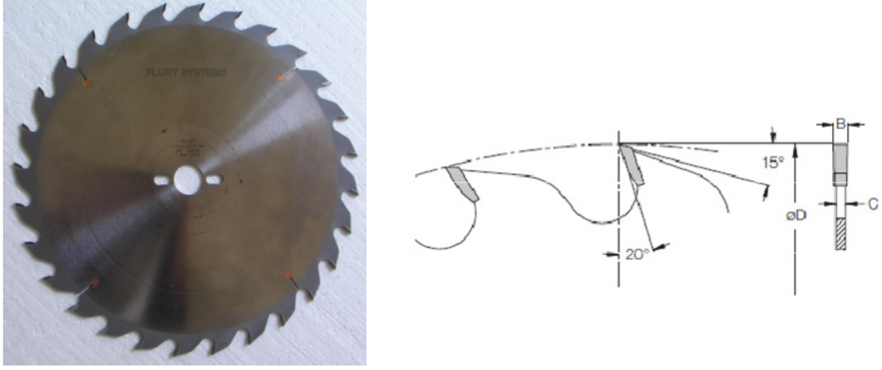


Fig. 2 Circular saw blade Flury systems 350 – K3

The cutting was performed under the optimum operation speed $n = 3800\ min^{-1}$ under cutting velocity $v_c = 70\ m \cdot s^{-1}$. Workpiece 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 experiment was performed on a testing device used for research of circular-saw blade cutting. This device simulates the conditions of circular-saw blade cutting in the real operation as precisely as possible. The parameters of the cutting process (cutting force F_c, feed force F_f, cutting velocity v_c, workpiece feed velocity v_f) were recorded by sensors installed in the measuring stand. The signals from the sensors were transferred in the data switchboard Spider 8 and in the software Conmes Spider and subsequently processed into tables and graphs.

In order to verify the validity and function of the new calculation model, the samples of native, samples of ammonia refined wood material Lignamon and chemically treated beech (DMDHEU) Belmadur were used in the experiment. The samples were dried (relative moisture content 8,5%) and unified in the same thickness $e = 21\ mm$ on a thickness woodworking machine.

RESULTS AND DISCUSSION

The validity verification of the new calculation model was performed by an experiment. Fig. 3 shows the relation of cutting force and size of mean chip thickness. Almost linear increase of cutting force occurred along with the growing chip thickness, which confirms the theoretical assumptions, see equation 3.

In the previous experiment we found out that the intensity of cutting force, when cutting Belmadur, is lower by 35% in comparison with native beech. This hypothesis was verified by repeated measurement. The cutting process of treated beech with ammonia isn´t see any difference in comparison with native beech. Cutting force is almost equivalent. This material retains most of the good properties of the original wood. It can therefore be easily machined with standard woodworking machines. The mechanical properties of lignamon are better than those of ordinary wood. These mechanical properties affect resulting cutting resistance which is higher than cutting of native beech.

In contrast to native beech, chemically impregnated and compressed beech Belmadur is greater hardness, but, on the other hand, it is fragile material. Shear stress and tensile strength are reduced, which substantially reduces cutting force and resistance in the cutting process.

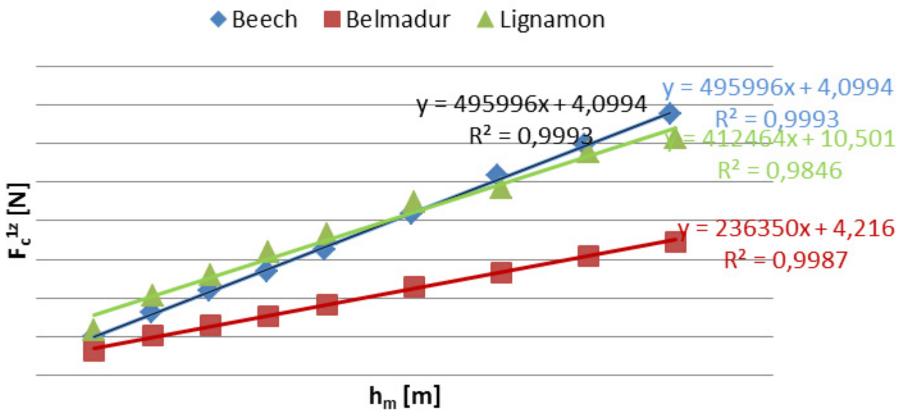


Fig. 3 Cutting force (per tooth) as a function of mean chip thickness

The determination of the main parameters of the model is based on the regression analysis. The fracture toughness $R_{\parallel\perp}$ (for $\varphi_2 = 39^\circ$, Fig. 1) was determined from the line sift and shear yield stress $\tau_{\gamma\parallel\perp}$ from its slope (Atkins 2005, Orlowski and Palubicki 2009, Orlowski 2010). The application of experimental data in the designed model brings significant data for the longitudinally transversal cutting model to the circular saw blade cutting process, see (Tab. 1):

Tab. 1 Results obtained by experiment

	ρ (kg·m^{-3})	**M**	**β_μ**	**Φ_c**	**Γ**	**Q_{shear}**	**$\tau_{\gamma\parallel\perp}$ (MPa)**	**$R_{\parallel\perp}$ (Jm^{-2})**
Beech	691	0,87	40.98	34,51	1,81	0,59	44,89	1137,333
Belmadur	707	0,81	38,78	35,61	1,78	0,60	22,257	1171,111
Lignamon	783	0,87	40,98	34,25	1,82	0,59	36,995	2919,444

These values are the input data when calculating the specific cutting resistance for the longitudinal transverse model of saw blade cutting.

Another Figure (Fig. 4) shows modelling of the functional relationship of the specific cutting resistance and chip thickness. The calculations were performed for the chip thickness of h = 0.012 – 0.13 [mm]. To sum up, the specific cutting resistance decreases with the increasing chip thickness. This phenomenon is known from metal machining. In contrast, under very small feeds per tooth when chip thickness comes closer to the existing cutting edge radius, the hyperbolic increase in the specific cutting resistance k_c occurs, also known as the so-called size effect, see equation 6 (Atkins 2003, 2009).

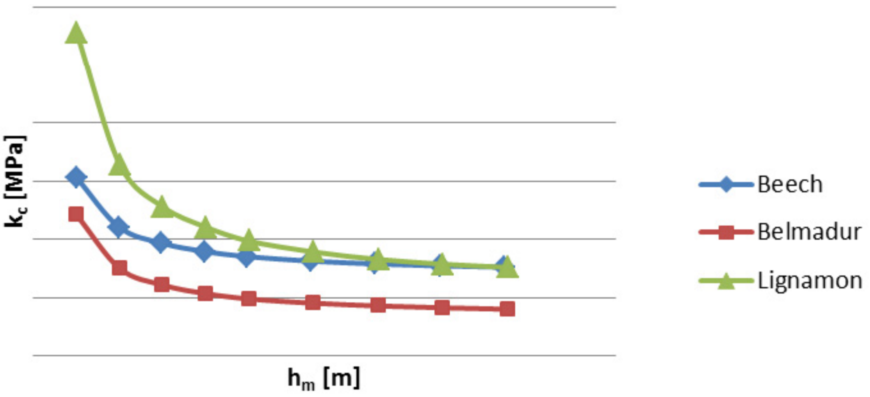


Fig. 4 Relationship of specific cutting resistance and mean chip thickness

CONCLUSIONS

On the basis of experimental measurement results we were able to determine the fracture toughness and shear yield stress for longitudinal transversal model of cutting beech and modified materials Lignamon and Belmadur by a saw blade. Knowing these two parameters, it is possible to make prognosis for the necessary cutting power, cutting resistance and forces affecting the workpiece and the tool. Not only is this model, which is based on fracture mechanics, useful to the technologists who work in the field of wood processing, but also to designers for designing new saw blades.

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Streszczenie: *Przewidywanie efektów energetycznych skrawania przy użyciu zasad mechaniki pękania*. Praca prezentuje model numeryczny który może zostać zastosowany do wyliczeń parametrów siłowych podczas piłowania drewna. Do opracowania modelu zastosowano nowoczesną metodę bazującą na mechanice pękania, pozwalającą na określenie pracy jednostkowej potrzebnej do formowania powierzchni i wytrzymałości na ścinanie. W celu weryfikacji modelu testowano proces cięcia drewna naturalnego, drewnopochodnego materiału Lignamon modyfikowanego amoniakiem oraz chemicznie zmodyfikowanego buka (DMDHEU) Belmadur.

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