WOOD RESEARCH
59 (5): 2014
827-834

# AN INNOVATIVE APPROACH TO PREDICTION ENERGETIC EFFECTS OF WOOD CUTTING PROCESS WITH CIRCULAR-SAW BLADES

Zdeněk Kopecký, Luďka Hlásková
Mendel University in Brno, Faculty of Forestry and Wood Technology
Brno, Czech Republic

Kazimierz Orlowski
Gdansk University of Technology
Gdansk, Poland

(Received July 2013)

## ABSTRACT

In the classical approach, energetic effects (cutting forces and cutting power) 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 more or less important factors. The aim of the paper is to present a new calculating model using the application of modern fracture mechanics and to compare cutting parameters of native beech, Bendywood and Belmadur. Cutting and feed forces are determined by the application of the Ernst-Merchant theory in the conditions of circular-saw blade cutting. It includes the prediction 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.

KEYWORDS: Cutting resistance, circular-saw blade, fracture mechanics, shear yield stress, fracture toughness, native beech, Belmadur, Bendywood.

## INTRODUCTION

In the wood processing industry, starting with primary production up to the machining of the final product, 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. It is relatively difficult to determine individual components of cutting resistance which depend on many other factors. The demanding nature of the search for the optimum results is significantly influenced by wood properties, by its anisotropy and variations of physical and mechanical properties in relation to the direction of grains. 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, Manžos 1974, Orlicz 1988, Naylor et al. 2012). Cutting and feed forces are determined by the application of the Ernst-Merchant theory in the conditions of circular-saw blade cutting. The chip formation process is the main factor for the determination process of cutting and feed forces. The model is based on the determination of the internal work for shearing and the subsequent chip cut-off, and further on the energy necessary to overcome the friction between the workpiece and the tool blade, and last but least, on the specific work for forming a new workpiece surface (Atkins 2003, 2009).

The cutting kinematics (Fig. 1) makes it clear that the saw blade teeth move in the constant cutting velocity vc along a circular trajectory. When cutting, this rotating movement compounds with the linear work piece movement $v_f$, i.e. tooth cutting edge moves along a cycloid. 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° ($\varphi_3 = 0 - 90°$), as it was assumed for the sash gang saw and the band sawing machines.

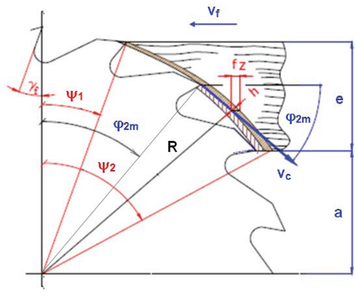


*Fig. 1: Saw blade cutting kinematics (Orlowski et al. 2013).*

The rotation movement of the cutting tool and the steady feed result in the change in the chip thickness. The model of the main edge of the tooth is longitudinally transversal towards the grain direction (‖ - ⊥) $\varphi_1 = 90°$, $\varphi_2 = 0 - 90°$, $\varphi_3 = 0 - 90°$.

The calculations use the mean chip thickness $h_m$, which is determined at the point of the central angle of cutting of grains $\varphi_{2m}$. The geometry (Fig. 1) shows that the angle of grain cutting is changing. At the point of a tooth entry into workpiece, it equals the value of angle $\psi_1$, at the point of blade teeth run-out of contact, it increases substantially and equals to the exit angle $\psi_2$. The mean angle of cutting the grains is then determined as the average value of both angles.

$$\psi_1 = arccos\left(\frac{a+e}{R}\right),\ \psi_2 = arccos\left(\frac{a}{R}\right),\ \varphi_{2m} = \frac{\psi_1 + \psi_2}{2} \qquad (°) \tag{1}$$

At the moment when a tooth starts cutting, the chip thickness has a minimum value $h_{min}$. Maximum chip thickness $h_{max}$ is created when tooth leaves the workpiece. As mentioned above, the calculation models use the mean chip thickness $h_m$.

$$h_m = f_z \cdot sin\varphi_{2m} \tag{2}$$

The determination of energetic ratios in traditional calculation models is based on the effects of cutting force $F_c$ on saw blade teeth where a chip of the width $b$ and thickness $h$ is produced. The intensity of cutting force (per one tooth) is then given by the product of the specific cutting resistance of the separated material $k_c$ and chip cross-sectional area

$$F_c^{1z} = k_c \cdot b \cdot h \qquad \text{(N)} \qquad (3)$$

For the circular saw blade cutting force can also be expressed as a function of feed and cutting velocity.

$$F_c = k_c \cdot b \cdot e \cdot \frac{v_f}{v_c} \qquad \text{(N)} \qquad (4)$$

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 power when cutting by saw blades can be expressed in the following form

$$\overline{P}_{cw} = F_c \cdot v_c + P_{ac} = \left[ z_a \cdot \frac{\tau_\gamma \cdot b \cdot \gamma}{Q_{shear}} \cdot h_m \cdot v_c + z_a \cdot \frac{R \cdot b}{Q_{shear}} \cdot v_c \right] + \dot{m} \cdot v_c^2 \ \text{(W)} \qquad (5)$$

The first equation member expresses the power necessary for shearing 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. 2013). The following is applied for the mass flow of chips:

$$\dot{m} = \frac{b \cdot l \cdot v_f \cdot \rho}{2} \qquad (\text{kg}\cdot\text{s}^{-1}) \qquad (6)$$

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 $y=(k)\cdot x+(q)$ (Orlowski and Palubicki 2009, Orlowski 2010).

$$F_c^{1z} = \left( \frac{\tau_\gamma \cdot b \cdot \gamma}{Q_{shear}} \right) \cdot h_m + \left( \frac{R \cdot b}{Q_{shear}} \right) \qquad \text{(N)} \qquad (7)$$

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

Shearing strain along the shear plane is possible to obtain from the formula (Atkins 2003)

$$\gamma = \frac{\cos \gamma_f}{\cos(\Phi_s - \gamma_f) \cdot \sin \Phi_s} \qquad (-) \qquad (8)$$

where: $\gamma_f$ - tooth rake angle,
$\Phi_s$ - 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).

It should be emphasised that Eq. (9) could be applied only for larger values of uncut chip thicknesses (Atkins 2003, 2009).

$$\Phi_s = \left(\frac{\pi}{4}\right) - \left(\frac{1}{2}\right) \cdot \left(\Theta_\mu - \gamma_f\right) \qquad (°) \qquad (9)$$

where: $\Theta_\mu$ friction angle obtained from $\tan^{-1}\mu = \Theta\mu$ ($\mu$ is friction coefficient)
$\pi$ *(rad)* … 180°

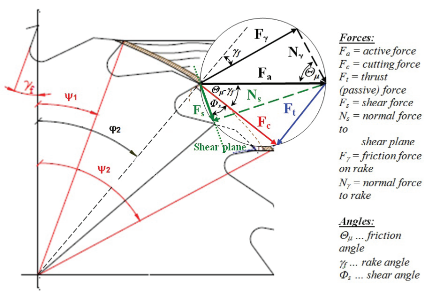


*Fig. 2: System of forces with the use of the Ernst-Merchant diagram.*

The Atkins's model, which includes the fracture toughness R (Eq. 5), can help to derive a relationship for the calculation of specific cutting resistance $k_c$.

$$k_c = \frac{1}{Q_{shear}} \left(\tau_\gamma \cdot \gamma + \frac{R}{h}\right) \qquad (Pa) \qquad (10)$$

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 (Atkins 2003, 2009). When shear angle $\Phi_s$ equals zero (the tool cuts off no chips), the friction correction coefficient $Q_{shear}$ equals one. (Orlowski and Palubicki 2009, Orlowski 2010).

$$Q_{shear} = 1 - \frac{\sin\Theta_\mu \cdot \sin\Phi_s}{\cos\left(\Theta_\mu - \gamma_f\right) \cdot \cos\left(\Phi_s - \gamma_f\right)} \qquad (-) \qquad (11)$$

## MATERIAL AND METHODS

The experiment was realized on a testing device used for research of circular-saw blade cutting (Kopecký and Rousek 2012). 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.

The cutting process was performed with a prototype blade (provisional code K9) produced by Pilana Hulín, which had been designed for carpentry. This circular saw blade had a regular tooth pitch of 10°, was equipped with cemented carbide teeth, and had also properly adjusted tension by rolling. Anti-noise slots finished with 6-*mm* holes are burnt in the blade body.

Furthermore, six radial dilatation slots are laser-burnt in the cutting part of the blade, in order to compensate the waviness due to the increasing temperature. The construction parameters of the blade are shown in Tab. 1.

The cutting was performed under the optimum operation rotational speed $n = 4200\ min^{-1}$ (Veselý et al. 2010, 2012), i.e. under cutting velocity $v_c = 77\ m \cdot s^{-1}$. Workpiece feed velocity varied within the range of $v_f = 2.5 – 22\ m \cdot min^{-1}$ with measuring step $2\ m \cdot min^{-1}$. This corresponded with the changing feed per tooth $f_z$ and mean chip thickness $h_m$.

*Tab. 1: Parameters of saw blade K9 (Veselý et al. 2010).*

| **Parameters of saw blade K9, prototype with slots** | |
|---|---|
| Saw blade diameter **D** | 350 mm |
| Number of teeth **z** | 36 |
| Clamping hole diameter **d** | 30 mm |
| Blade body width **s** | 2.4 mm |
| Tooth width (cutting joint) $s_t$ | 4.5 mm |
| Tooth height **h** | 15 mm |
| Tooth pitch $t_p$ | 30.5 mm |
| Clearance angle $\alpha_f$ | 15° |
| Cutting edge angle $\beta_f$ | 65° |
| Rake angle $\gamma_f$ | 10° |
| Set of cutting edges $\lambda_s$ | 10° |

In order to verify the validity and function of the new calculation model, the samples of native beech (specific density $\rho = 691\ kg \cdot m^{-3}$), Bendywood ($\rho = 739\ kg \cdot m^{-3}$) - hydrothermally treated and compressed beech (http://www.ohybacidrevo.cz/vlastnosti/ohybaci-drevo-bendywood) and Belmadur ($\rho = 707\ kg \cdot m^{-3}$) - chemically treated beech by DMDHEU (dimethyloldihydroxyethylenurea) (http://www.unece.org/fileadmin/DAM/timber/docs/tc-sessions/tc-65/md/presentations/17Militz.pdf) were used in the experiment (three samples of each material). The length of the scantlings was 700 mm and the width of the scantlings was 120 mm. Samples were dried (relative moisture content 8 %) 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. Data which were obtained by experiment are very important for determination of main model parameters ($\tau_\gamma$ and R) (Atkins 2005). Knowing these parameters, it is possible to make prognosis for the cutting power and cutting resistance (Eqs. 5 and 10).

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 Eq. 7.

The cutting process of compressed plasticized beech Bendywood is easier in comparison with native beech; the cutting force is lower by approx. 15 %. Bendywood is known as material with higher density and very good bending properties – up to 1:10. The characteristic features of the inner structure include micro-cracks on the walls of libriform fibres and chemical changes in lignin-carbohydrates matrix, together forming a certain viscoplastic joint. A slight waviness of fibres, which was created as a reflection to longitudinal compression load, has a positive effect on forces for bending and subsequent chip cut-off in the cutting process.

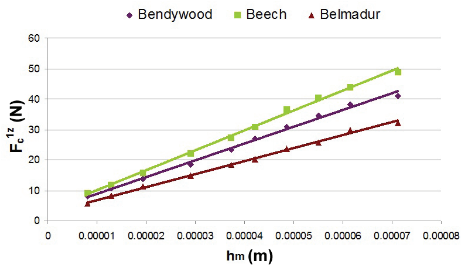


*Fig. 3: Cutting force (per tooth) as a function of mean chip thickness.*

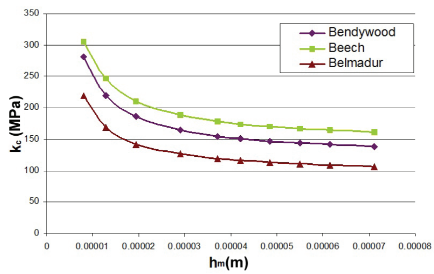


*Fig. 4: Relationship of specific cutting resistance and mean chip thickness.*

The intensity of cutting force, when cutting Belmadur, is lower by 35 % in comparison with native beech. In contrast to native beech, chemically impregnated and compressed beech Belmadur is of 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.

The determination of the main parameters of the model is based on the regression analysis. The fracture toughness $R_{\parallel\perp}$ (for $\varphi_2$ = 29.3°, Fig. 1) was determined from the line Y-intercept 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. 2):

*Tab. 2: Results obtained by the application of fracture toughness.*

| | ρ (kg·m$^{-3}$) | $\tau_{\gamma\parallel\perp}$ (MPa) | $R_{\parallel\perp}$ (Jm$^{-2}$) | M | $\Theta_\mu$ | $Q_{shear}$ |
|---|---|---|---|---|---|---|
| Beech | 691 | 42.99 | 757.89 | 0.83 | 39.72 | 0.45 |
| Bendywood | 739 | 36.56 | 742.26 | 0.84 | 39.87 | 0.45 |
| Belmadur | 707 | 28.75 | 581.96 | 0.81 | 38.93 | 0.47 |

The Ernst-Merchant theory (Eq. 9) alowed to calculate the orientation of the shear plane in respect to the worked surface $\Phi_s$ = 29.52° for native beech, $\Phi_s$ = 29.77° for Bendywood and $\Phi_s$ = 30.46° for Belmadur (in each case for larger values of chip thickness. The shearing strain along the shear plane $\gamma$ = 2.03 for native beech, $\gamma$ = 2.01 for Bendywood and $\gamma$ = 1.98 for Belmadur under the longitudinal transverse cutting model. These values are the input data for determination of the specific cutting resistance for the longitudinal transverse model of saw blade cutting.

Another 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 = 0.008 – 0.072 m*.

To sum up, the specific cutting resistance decreases with the increasing chip thickness. This phenomenon is known from metal machining, and also was noticed in wood cutting even in case of cutting with circular saw blades (Manžos 1974, Orlowski 2010, Orlowski et al. 2013). 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 kc occurs, also known as the so-called size effect, see equation 10 (Atkins 2003, 2009).

## CONCLUSIONS

Despite the fact that the circular-saw blade cutting process is not an example of purely orthogonal cutting, the application of results obtained from the experimental measurement results allowed us to determine the fracture toughness and shear yield stress for longitudinal transversal model of cutting beech by a saw blade. Knowing these two parameters, it is possible to make prognosis for the necessary cutting power and forces affecting the workpiece and the tool. Not only is the model useful to the technologists who work in the field of wood processing, but also to designers for designing new saw blades.

## ACKNOWLEDGMENT

This paper was supported by the European Social Fund and the state budget of the Czech Republic, project "The Establishment of an International Research Team for the Development of New Wood-based Materials" reg. no. CZ.1.07/2.3.00/20.0269, further by project IGA 22/2013 – New approaches in determining of cutting resistance and project IGA 79/2013 – Combined Processes of Beech Wood Modification for Floorings – Influence on Properties, Durability and Health Aspects. The author thanks for a financial support to deal with the projects.

## REFERENCES

1. Atkins, A.G., 2003: Modelling metal cutting using modern ductile fracture mechanics: Quantitative explanations for some longstanding problems. International Journal of Mechanical Sciences 45(2): 373-396.
2. Atkins, A.G., 2005: Toughness and cutting: A new way of simultaneously determining ductile fracture toughness and strength. Engineering Fracture Mechanics 72(6): 849-860.
3. Atkins, A.G., 2009: The science and engineering of cutting. The mechanics and process of separating, scratching, and puncturing biomaterials, metals and non metals. Butterworth-Heineman is an imprint of Elsevier, Oxford, 2009, 413 pp.
4. Kopecký, Z., Rousek, M., 2012: Impact of dominant vibrations on noise level of dimension circular sawblades. Wood Research 57(1): 151-160.
5. Lisičan, J., 1996: Theory and wood technology. Zvolen: Matcentrum. 626 pp (in Slovak).
6. Manžos, F.M., 1974: Wood cutting machine tools. (Derevorežuŝčie Stanki). Izdatel'stvo "Lesnajâ promyšlennost'", Moskva (in Russian).
7. Naylor, A., Hackney, P., Perera, N., Clahr, E., 2012: A predictive model for the cutting force in wood machining developed using mechanical properties. Bio Resources 7(3): 2883-2894.

8. Orlicz, T., 1988: Wood machining with cutting tools. Warsaw University of Life Science (in Polish).
9. Orlowski, K., Palubicki, B., 2009: Recent progress in research on the cutting processes of wood. A review COST Action E35 2004–2008: Wood machining – micromechanics and fracture. Holzforschung 63(2): 181-185.
10. Orlowski, K., 2010: The fundamentals of narrow-kerf sawing: Mechanics and quality of cutting, Technical University in Zvolen. Pp 1-123, ISBN 978-80-228-2140-7.
11. Orlowski, K., Ochrymiuk, T., Atkins T., Chuchala D., 2013: Application of fracture mechanics for energetic effects predictions while wood sawing. Wood Science and Technology 47(5): 949-963. DOI: 10.1007/s00226-013-0551-x.
12. Veselý, P., Kopecký, Z., Svoreň, J., 2010: Effects of the construction of a circular sawblade on its critical speed and vibrations in the area of utilizable revolutions. In: Chip and Chipless Woodworking Processes 2010. TU in Zvolen. Pp 199-206.
13. Veselý, P., Kopecký, Z., Hejmal, Z., Pokorný, P., 2012: Diagnostics of circular sawblade vibration by displacement sensors. Drvna Industrija 63(2): 81-86.

Zdeněk Kopecký, Luďka Hlásková
Mendel University in Brno
Faculty of Forestry and Wood Technology
Zemědělská 3
613 00 Brno
Czech Republic
Corresponding author: kopecky@mendelu.cz

Kazimierz Orlowski
Gdansk University of Technology
G. Narutowicza 11/12
80-233 Gdansk
Poland