Annals of Warsaw University of Life Sciences - SGGW
Forestry and Wood Technology No 90, 2015: 73-78
(Ann. WULS - SGGW, For. and Wood Technol., 90, 2015)

Fracture toughness and shear stresses determining od chemically modified beech

LUĎKA HLÁSKOVÁ, ZDENĚK KOPECKÝ
Mendel University in Brno, Faculty of Forestry and Wood Technology

Abstract: *Fracture toughness and shear stresses determining od chemically modified beech.* Due to the energy consumption during machining, it is important to know cutting resistance, which is very significant property of the machined material. On the other hand it is difficult to estimate its accurate value – in the case of wood cutting, cutting resistance is the function of many factors. This paper presents a new calculating model which might be applied for estimation of energetic effects and which uses the application of fracture mechanics. New model uses to determination of cutting force, feed force, shear force and friction force the application of the Ernst-Merchant diagram in the conditions of circular-saw blade cutting.

Keywords: fracture toughness, shear yield stress, cutting resistance, circular-saw blade

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***). Nowadays, different modifications of two basic methods are used for theoretical purposes and in practice – the technological and physical method, and the analytical method (***Lisičan 1996***). 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 designed for longitudinal cutting of wood. 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.

In order to verify the validity and function of the new calculation model, the samples of native beech and samples of ammonia refined wood material Lignamon ($\rho_1 = 1066\ kg{\cdot}m^3$,

ρ_2 = *1107 kg·m*^{3}, ρ_3 = *1185 kg·m*^{3}) were used in the experiment. The samples were dried (relative moisture content *9%*) and unified in the same thickness *e = 21 mm* on a thicknesser.

According to the latest theoretical findings with the use of fracture mechanics methods (***Atkins 2003, 2009***) and (***Orłowski 2010, Orłowski et al. 2012***), a mathematical model of the cutting power can be expressed as:

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

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, 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 (***Orłowski 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)* (***Orłowski and Pałubicki 2009, Orłowski 2010***)

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

where: τ_γ is shear yield stress (Pa), *R* is specific work of a surface separation (fracture toughness) (J·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

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

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, can be calculated for larger values of chip thickness h_m with the Merchant's equation (because for large uncut chip values Φ_s is constant) (***Atkins 2003***)

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

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} 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. (***Orłowski and Pałubicki 2009, Orłowski 2010***).

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

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

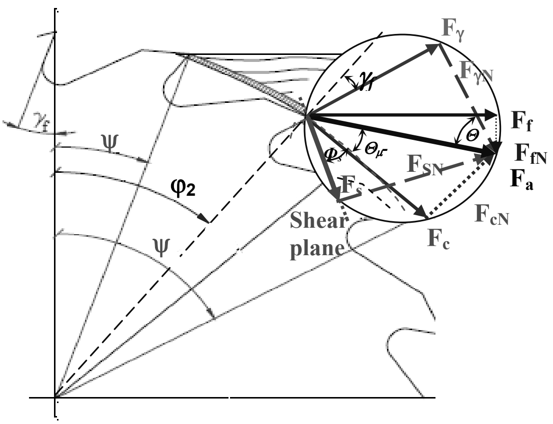

Fig. 1 Simplified cutting process model with Ernst and Merchant' s force circle

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 $R_{\|\perp}$ and the shear yield stress $\tau_{\gamma\|\perp}$ 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:

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

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

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

RESULTS AND DISCUSSION

Data which were obtained through the experiment are very important for the determination of the main model parameters shear yield stress $\tau_{\gamma\|\perp}$ and fracture toughness $R_{\|\perp}$ (***Atkins 2005***).

Fig. 2 shows the relation of cutting force and size of mean chip thickness. Almost linear increase in the cutting force occurred along with the growing chip thickness, which confirms the theoretical assumptions.

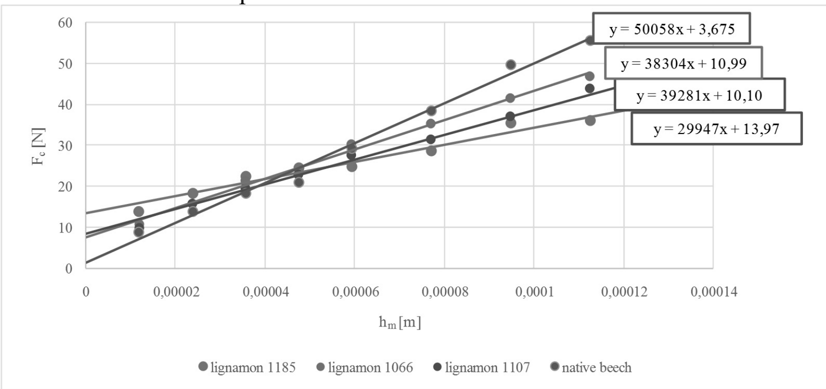

Fig. 2 Cutting force as a function of mean chip thickness

Samples of native beech compared to Lignamon show slightly increased values of cutting resistance (force) at lower feed speed, however, at greater feed speeds, cutting resistance does not increase as steeply as for native beech, see Fig. 2. Regression line slope of Lignamon exhibits accordance to the conventional methods. This is valid particularly for samples having density of 1066 and 1107 kg.m^{-3}. For sample with the highest density (1185 kg.m^{-3}), regression line slope is not as steep as in the previous samples. The difference of regression line slope was caused by the different orientation of the sample during cutting - either the sample was oriented so that the direction of compression was the same as the cutting direction or not.

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, Orłowski and Pałubicki 2009, Orłowski 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 the application of fracture toughness

	ρ (kg·m^{-3})	μ (-)	Θ (°)	Φ_c (°)	γ (-)	Q_{shear} (-)	$\tau_{\gamma\parallel\perp}$ (MPa)	$R_{\parallel\perp}$ (Jm^{-2})
Beech	691	0,014	0,83	54,58	1,53	0,98	44,83	1020,83
Lignamon 1	1066	0,06	3,54	56,77	1,54	1,07	89,05	3052,77
Lignamon 2	1107	0,09	5,66	57,83	1,55	1,11	78,32	2805,55
Lignamon 3	1185	0,09	4,97	52,512	1,53	0,92	68,68	2902,77

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

Fig. 3 shows modelling of the functional relationship of the specific cutting resistance and chip thickness. 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 (***Atkins 2003, 2009***).

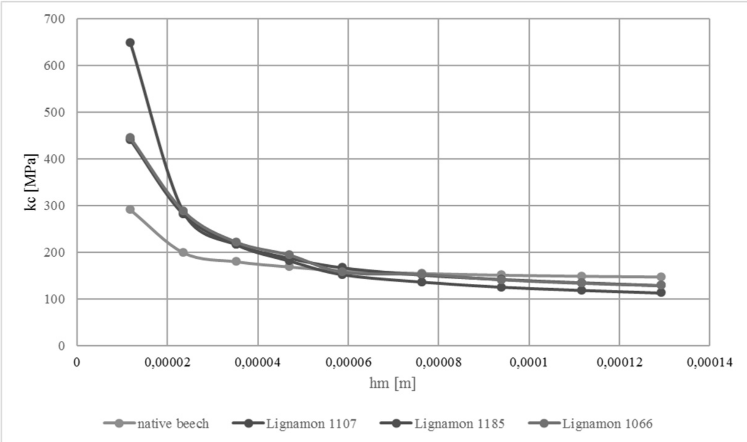

Fig. 3 Cutting resistance as a function of mean chip thickness

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 material Lignamon by a circular-saw blade. Knowing these two parameters, it is possible to make prognosis for the necessary cutting power and cutting resistance. These determined values of sawn beech wood and modified beech 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.

This model, which is based on fracture mechanics, is useful for technologists who work in the field of wood processing and also designers who design new saw blades.

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: 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: 849-860.
3. ATKINS A.G. 2009: The science and engineering of cutting. The mechanics and proces sof separating, scratching, and puncturing biomaterials, metals and non metals. Butterworth-Heineman is an imprint of Elsevier, Oxford,2009, 413 p.
4. BÖLLINGHAUS T. et al. 2009: Manufacturing engineering. Springer Handbook of Mechanical Engineering, K.-H. Grote and E. K. Antonsson (eds.), Springer, Würzburg, pp. 609-656.
5. KOPECKÝ Z., ROUSEK M. 2012: Impact of dominant vibrations on noise level of dimension circular sawblades. *Wood Research.* 2012. sv. 57, č. 1, s. 151-160. ISSN 1336-4561.
6. LISIČAN J. et al. 1996: Theory and wood technology. Zvolen: Matcentrum. 626 p.
7. ORLICZ T 1988: Obróbka drewna narzędziami tnącymi. (In Polish: Wood machining with cutting tools) Skrypty SGGW-AR w Warszawie, Wydawnictwo SGGW-AR, Warszawa.

8. ORŁOWSKI K., PAŁUBICKI 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, Vol. 63, iss. 2: 181–185. ISSN 0018-3830
9. ORŁOWSKI 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.
10. ORŁOWSKI K., OCHRYMIUK T., ATKINS T., CHUCHAŁA D. 2012: Application of Fracture Mechanics for Energetic Effects Predictions While Wood Sawing. Wood Science and Technology. (a paper accepted for publication)

Streszczenie: *Odporność na pękanie i naprężenia ścinające chemicznie zmodyfikowanego drewna bukowego.* Z punktu widzenia zużycia energii podczas obróbki, ważne jest poznanie jednostkowego oporu skrawania, który jest bardzo istotną własnością materiału obrabianego. Z drugiej strony trudno jest określić jego dokładną wartość - w przypadku skrawania drewna, opory skrawania są funkcją wielu czynników. W artykule przedstawiono nowy model predykcji oparty na mechanice pękania, który może być wykorzystany do oceny efektów energetycznych procesu skrawania drewna. Nowy model może być wykorzystany do określania siły skrawania, siły posuwu, siły ścinającej i siły tarcia z wykorzystaniem diagramu Ernst-Merchanta w warunkach procesu cięcia piłami tarczowymi.

Author's address:

Ing. Luďka Hlásková, doc. Ing. Zdeněk Kopecký, CSc.:
Mendel University,
Faculty of Forestry and Wood Technology
Zemědělská 3,
613 00 Brno,
Czech Republic