Sawing Processes as a Way of Determining Fracture Toughness and Shear Yield Stresses of Wood

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A new computational model, based on fracture mechanics, was used to determine cutting forces. Unlike traditional computing methods, which depend on many coefficients reflecting the machining of solid wood, the new model uses two main parameters: fracture toughness and shear yield stresses. The aim of this study was to apply this new method to determine these parameters for the tooth cutting edge principal positions and longitudinal and perpendicular cutting speed directions. Samples of beech wood (*Fagus sylvatica* L.) were sawn. The measurements of energetic effects (cutting power and cutting force) while sawing wood were carried out on two laboratory stands: the sash gang saw and the circular sawing machine. The basic relationships between different sawing methods, such as cutting on a frame sawing machine (sash gang saw) and a circular sawing machine, and the fracture toughness and shear yield stresses were recognizable. The data obtained could be applied to the computation of the energetic effects on other wood cutting methods.

Keywords: Cutting resistance; Wood sawing process; Fracture mechanics; Shear yield stress; Fracture toughness

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INTRODUCTION

A number of scientific studies, both theoretical and experimental, have been performed to better understand and predict cutting forces, including those by Naylor and Hackney (2013) and Chuchala *et al*. (2014). Markopoulos (2013) stated that today, most of the research dealing with machining modelling is performed to gain predictive ability. Important machining parameters, such as cutting forces, can be calculated before any cutting is actually performed on a machine tool. In the classical approach (Böllinghaus *et al*. 2009) to the machining process, the energetic effects (cutting forces and cutting power) on metal cutting are based on the specific cutting resistance k_c (cutting force per unit area of cut). Moreover, the specific cutting resistance k_c is also extensively applied in wood sawing processes (Fischer 2004; Orlowski 2007; Scholz *et al*. 2009; Orlowski *et al*. 2010). On the other hand, Orlowski *et al.* (2013) demonstrated that cutting power could be considered from a modern fracture mechanics point of view (Atkins 2003, 2009). Elements from this study were taken into account in the calculation models of cutting forces developed by Laternser *et al*. (2003), Stanzl-Tschegg and Navi (2009), Merhar and Bučar (2012), and Hellström *et al*. (2013).

Even though the analyses of energetic effects using cutting models (including the work of separation, plasticity, and friction) corroborated their versatility and revealed the usefulness for every known type of sawing kinematics (Orlowski *et al.* 2013), there is a general lack of timber data, such as the fracture toughness (specific work of separation) and shear yield stresses in a shear zone. Moreover, the properties of wood, its anisotropy, and disparities in its physical and mechanical properties depend significantly on the direction of the cutting in relation to the grain and on the cutting edge position (Fig. 1).

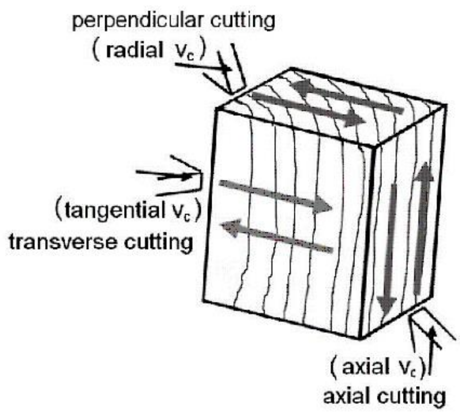

Fig. 1. Tooth cutting edge principal positions and cutting speed directions (adapted by authors (Orlowski *et al.* 2013) from Laternser *et al.* 2003)

Nevertheless, the cutting process is a good way to determine the fracture toughness and shear yield stresses of the material being cut (Atkins 2005; Orlowski and Palubicki 2009; Patel *et al.* 2009; Wang *et al.* 2013). Hence, sawing on the sash gang saw, according to the method presented by Orlowski and Palubicki (2009), can be applied to determine the toughness and strength for perpendicular cutting. If a circular saw blade is applied during the cutting process, a similar methodology can be implemented to determine the fracture toughness and shear strength (Kopecky *et al.* 2014); however, it concerns an indirect position of the cutting edges in relation to the wood grain for a distinct direction of cutting speed. The objective of this study was to provide some possible new measurement methods for determining raw material data such as the fracture toughness and shear yield stresses. Combining the two approaches mentioned earlier, which are based on sawing processes, could allow researchers to determine these properties for both the perpendicular and axial cutting directions.

Sash Gang Saw Cutting Force Model

According to Orlowski *et al.* (2013), the mechanical process of material separation from the sawn workpiece (*i.e.*, chip formation) can be described as an orthogonal process (two-dimensional deformation). The forces acting on the tooth can be represented in the classical approach by Ernst and Merchant's force circle, shown in Fig. 2.

The cutting power for one saw blade during the cutting stroke of a sash gang saw, in which both chip momentum (Orlowski *et al.* 2013) and a ploughing effect caused by tooth cutting edge dullness (Wang *et al.* 2013) are disregarded, follows the equation,

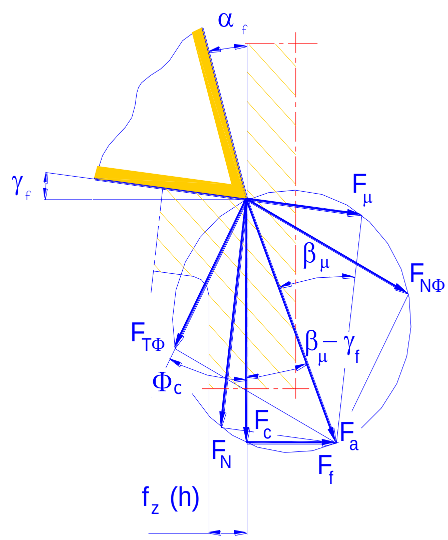

Fig. 2. Simplified cutting process model with Ernst and Merchant's force circle (Böllinghaus *et al.* 2009): F_a – active force, F_c – cutting force, F_f – thrust force (passive), F_μ – friction force on the rake face, F_N – normal force to the rake face, $F_{T\Phi}$ – the force required to shear the wood along the shear plane, $F_{N\Phi}$ – normal force on the shear plane, α_f – clearance angle, Φ_c – shear angle, γ_f – rake angle, and β_μ – friction angle (Orlowski *et al.* 2013)

$$\overline{P}_{cw} = F_c v_c = z_a \cdot \frac{\tau_{\gamma\perp} S_t \gamma}{Q_{shear}} v_c f_z + z_a \cdot \frac{R_\perp S_t}{Q_{shear}} v_c \tag{1}$$

where $z_a = \left(\frac{H_P}{P}\right)$ is the number of teeth in contact with the kerf (on average), H_p is the workpiece height (cutting depth); $\tau_{\gamma\perp}$ is the shear yield stress for the perpendicular cutting speed direction; and γ is the shear strain along the shear plane, given by,

$$\gamma = \frac{\cos\gamma_f}{\cos(\Phi_c - \gamma_f)\sin\Phi_c} \tag{2}$$

where f_z is the feed per tooth (uncut chip thickness h); S_t is a kerf (the width of the orthogonal cut); β_μ is the friction angle given by $\tan^{-1}\mu = \beta_\mu$; μ is the coefficient of friction; γ_f is the rake angle; Φ_c is the shear angle which defines the orientation of the shear plane with respect to the cut surface; $R_\perp$ is the specific work of surface separation/formation (fracture toughness); and Q_{shear} is the friction correction,

$$Q_{shear} = [1-(\sin\beta_\mu \sin\Phi_c / \cos(\beta_\mu - \gamma_f)\cos(\Phi_c - \gamma_f))] \tag{3}$$

The shear angle Φ_c, for the necessary aim of this study, can be calculated for larger values of feed per tooth f_z with the Merchant's equation (because for large uncut chip values Φ_c is constant) (Atkins 2003),

$$\Phi_c = (\pi/4) - (1/2)(\beta_\mu - \gamma_f) \tag{4}$$

The quantity Φ_c does not actually follow Eq. 4 and is dependent on the ratio of R to τ_γ (Atkins 2003). The values of Φ_c obtained from Eq. 3 are always greater than the experimental Φ_c (Atkins 2003); however, there is a lack of material-dependent data for sawing, except for some published results for Polish pine wood sawing (Orlowski and Ochrymiuk 2013; Orlowski *et al*. 2013).

Based on sawing results obtained on the sash gang saw (frame sawing machine) PRW-15M, it was possible to determine sawn material data, such as the specific work of surface formation (toughness) and the shear yield stresses, for the perpendicular cutting speed direction (Orlowski and Atkins 2007; Orlowski and Palubicki 2009). Since the kinematics of the cutting process during bandsawing has features of the perpendicular cutting, the same methodology of determining $R_\perp$ and $\tau_{\gamma\perp}$ could be possible during sawing processing on a band sawing machine, which is equipped with a similar measuring system, as described in the paper by Moradpour *et al*. (2013).

Circular Sawing Machine Cutting Force Model

The kinematics of sawing on circular sawing machines (Fig. 3) differs from the kinematics of cutting on sash gang saws and bandsawing machines.

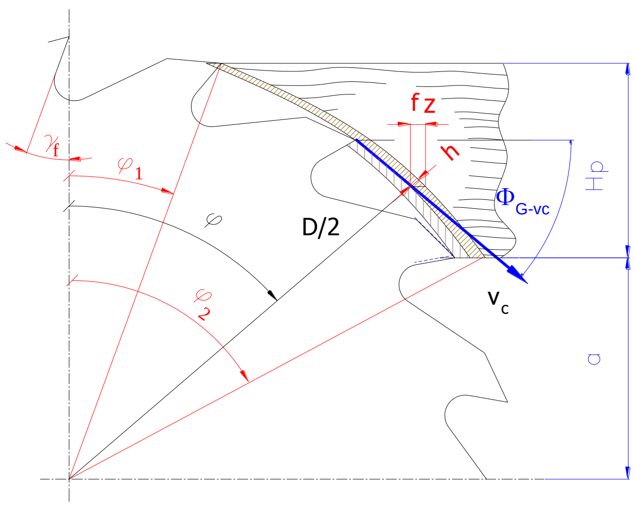

Fig. 3. Sawing kinematics on circular sawing machine: f_z – feed per tooth, D – circular saw blade diameter, h – uncut chip thickness, H_p – workpiece height (depth of cut), a – position of the workpiece, φ – angular tooth position, $\Phi_{G\text{-}vc}$ – an angle between grains and the cutting speed direction (Orlowski *et al*. 2013)

In the case of cutting with circular saw blades, uncut chip thickness $\bar{h}$ (an average value) should be taken into account instead of the feed per tooth f_z; hence, the cutting power may be expressed as (Orlowski *et al*. 2013),

$$\bar{P}_{cw} = z_a \cdot \frac{\tau_{\gamma\parallel\perp} S_t \gamma}{Q_{shear}} v_c \bar{h} + z_a \cdot \frac{R_{\parallel\perp} S_t}{Q_{shear}} v_c \tag{5}$$

where $z_a = \left(\frac{\varphi_2 - \varphi_1}{\varphi_t} \right)$ is the number of teeth in the contact with the kerf (on average); φ_1 is the angle of tooth entrance 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 the diameter of the circular saw blade; an average uncut chip thickness is given by $\bar{h} = f_z \sin \bar{\varphi}$; an average angle of tooth contact with a workpiece $\bar{\varphi}$ is calculated as $\bar{\varphi} = \frac{\varphi_1 + \varphi_2}{2}$; $R_{\|\perp}$ is the fracture toughness for indirect position of cutting speed, defined by $\bar{\varphi}$; and $\tau_{\gamma\|\perp}$ is the shear yield stress for the indirect cutting speed direction, also defined by $\bar{\varphi}$. In Eq. 5, it was assumed that teeth of the circular saw are sharp, and because of rather intermediate feed speeds values in tests, both the ploughing effect and chip momentum are disregarded.

Kopecký *et al*. (2014) developed methodology for determining raw material data including $\tau_{\gamma\|\perp}$ and $R_{\|\perp}$ for the indirect cutting speed direction. However, it must be emphasized that the values obtained are valid only at the position of the tooth cutting edge oriented by the average angle of tooth contact with a workpiece $\bar{\varphi}$.

The results of using both methodologies to determine raw material features on the basis of sawing processes are described by Orlowski and Palubicki (2009), for the case of sawing on the sash gang saw and Kopecký *et al*. (2014), for circular sawing. By combining these methodologies, it is possible to compute the fracture toughness $R_{\|}$ and shear stress $\tau_{\gamma\|}$.

Taking into account the position of the cutting edge in relation to the grain, for indirect positions of the cutting edge (cutting speed direction is in disagreement with the principal axes of wood), 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,

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

and

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

where $\Phi_{G\text{-}vc}$ is the angle between the grain and the cutting speed direction (Fig. 3), which in this approach equals $\bar{\varphi}$. In the present approach of combining the two described sawing technologies to determine the fracture toughness $R_{\|}$ and shear stress $\tau_{\gamma\|}$, Equations 6 and 7 can be transformed as follows,

$$R_{\|} = \frac{R_{\|\perp}(\Phi_{G-vc} = \bar{\varphi}) - R_{\perp} \sin^2(\Phi_{G-vc} = \bar{\varphi})}{\cos^2(\Phi_{G-vc} = \bar{\varphi})} \tag{8}$$

and

$$\tau_{\gamma\parallel} = \frac{\tau_{\gamma\parallel\perp}\left(\Phi_{G-vc} = \varphi\right) - \tau_{\gamma\perp}\sin^2\left(\Phi_{G-vc} = \varphi\right)}{\cos^2\left(\Phi_{G-vc} = \varphi\right)} \tag{9}$$

EXPERIMENTAL

Materials

Beech wood (*Fagus sylvatica* L.) samples originating from the Training Forest Enterprise Masaryk Forest Křtiny (TFE), an organizational part of the Mendel University of Agriculture and Forestry in Brno (CZ), were used as experimental samples. They were in the shape of rectangular blocks with dimensions of 55 mm (H) × 55 mm (W) × 564 mm (L) and a density of 691 kg/m^3 and were conditioned to 8% to 12% moisture content (MC).

Methods

Sash gang saw: Determination of cutting forces (cutting power)

In this part, the methodology of determining cutting forces (cutting power) as proposed in the work of Chuchala *et al*. (2014) was applied. A series of cutting tests to empirically determine the cutting power was carried out on a PRW15M sash gang saw (a prototype designed at the Gdansk University of Technology, PL, and manufactured by the firm REMA-Reszel, PL), a frame sawing system with elliptical tooth trajectory and a hybrid, dynamically-balanced drive, as described by Wasielewski and Orlowski (2002). The machine settings were as follows: number of strokes of saw frame per min (n_F), 685 spm; saw frame stroke (H_F), 162 mm; number of saws in the gang (n), 5; and average cutting speed (v_c), 3.69 m/s. The saw blades had stellite tipped teeth: overall set (kerf width) (S_t), 2 mm; saw blade thickness (s), 0.9 mm; free length of the saw blade (L_0), 318 mm; tension stresses of saws in the gang (σ_N), 300 MPa; blade width (b), 30 mm; tooth pitch (P), 13 mm; tool side rake (γ_f), 8.46° (measured value); and tool side clearance (α_f), 9.3° (measured value). Even though the saw blades were new, the tooth cutting edge radius had an average value (ρ_{CE}) of around 55 μm (measured with a system for image analysis and processing NIS – Elements AR (ver. 2.3), equipped with the digital camera Nikon DS – Fi1, 5 Mpix, with macrolens Navitar, in Brno, CZ), meaning that it was not the normal “sharp” tool (Orlicz 1988; Blackman *et al*. 2013). The only varying cutting parameter was the feed speed, which was applied at two levels: $v_{f1} \approx 0.4$ m/min and $v_{f2} \approx 1.1$ m/min. Lamellae with thicknesses of 5 ± 0.2 mm were obtained as a result of the re-sawing process. The friction coefficient value $\mu = 0.8$ for dry beech wood was taken from the work of Kopecký *et al.* (2014).

The corresponding cutting forces (F_c) (related to one tooth of the saw blade) were calculated according to the method described by Orlowski and Palubicki (2009) and Orlowski (2010). The average idle power ($\overline{P_I}$) was measured immediately before and after cutting (Fig. 4). The total power of the main driving system ($\overline{P_{cT}}$) was recorded during all wood sawing tests with a sampling frequency of 80 Hz (number of samples = 8192). Subsequently, the average cutting power ($\overline{P_c}$) and the mean cutting force in the working stroke ($\overline{F}_{cw}$), per tooth, were determined. Eventually, all of the resulting cutting forces were calculated by linear regression using a function of feed per tooth (uncut chip thickness). The linear regressions, Pearson’s *r* coefficients, and their significances (t-test) were computed with Statistica 8.0 software (StatSoft Inc., USA) (StatSoft 2015). Statistical analyses were done for the confidence level α = 0.05.

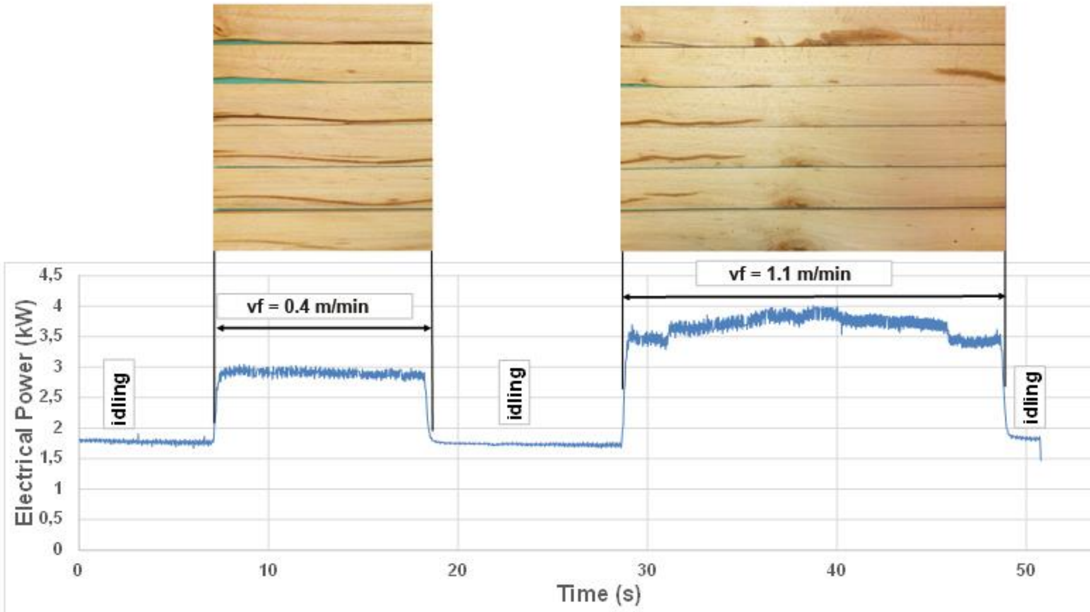

Fig. 4. Change of electrical power consumption over time while sawing beech wood at two feed speeds on the sash gang saw

Circular sawing machine: Determination of cutting forces

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 stand simulated, as closely as possible, the conditions of a circular sawing machine (CSM) in actual operation. During the cutting process, the cutting moment (cutting force F_c; feed force F_f; spindle rotational speed, and feed speed v_f) was measured. Signals from the sensors were transferred to the Spider 8 (f. Hottinger Baldwin Messtechnik, D), and they were subsequently processed into tables and graphs using Conmes Spider software (f. Consymea s.r.o.). The machine settings were as follows: optimum operating rotational speed = 3800 rpm (Veselý *et al*. 2012) for the applied circular saw blade (*i.e.*, operating at the cutting speed v_c = 69.6 m/s); and the feed rate (v_f) varied between 2 and 22 m/min with a step size of 2 m/min. This corresponded to changing of the feed per tooth f_z (uncut chip thickness $\bar{h}$). The circular saw blade (f. Flury Systems AG, CH) had straight, sharp, carbide-tipped teeth; the diameter of the circular saw blade (D_{cs}) was 350 mm. The diameter of the hole (d) was 30 mm; the overall set (kerf width) (S_t) was 3.5 mm; the teeth number (z) was 28; the saw blade thickness (s) was 2.5 mm; the tool side rake (γ_f) was 20°; and the tool side clearance (α_f) was 15°. The tooth cutting edge radius had an average value (ρ_{CE}) of around 8 µm meaning that it was a normal "sharp" tool (Orlicz 1988; Blackman *et al*. 2013). The friction coefficient value μ = 0.83 for dry beech wood was taken from the work of Kopecký *et al.* (2014). The linear regressions, Pearson's r coefficients, and their significances (t-test) were computed with Statistica 8.0 software (StatSoft Inc., USA) (StatSoft 2015). Statistical analyses were done for the confidence level α = 0.05.

Figure 5 presents the recorded signals of the cutting moment (cutting force F_c) during sawing with feed speed v_f = 19 m/min.

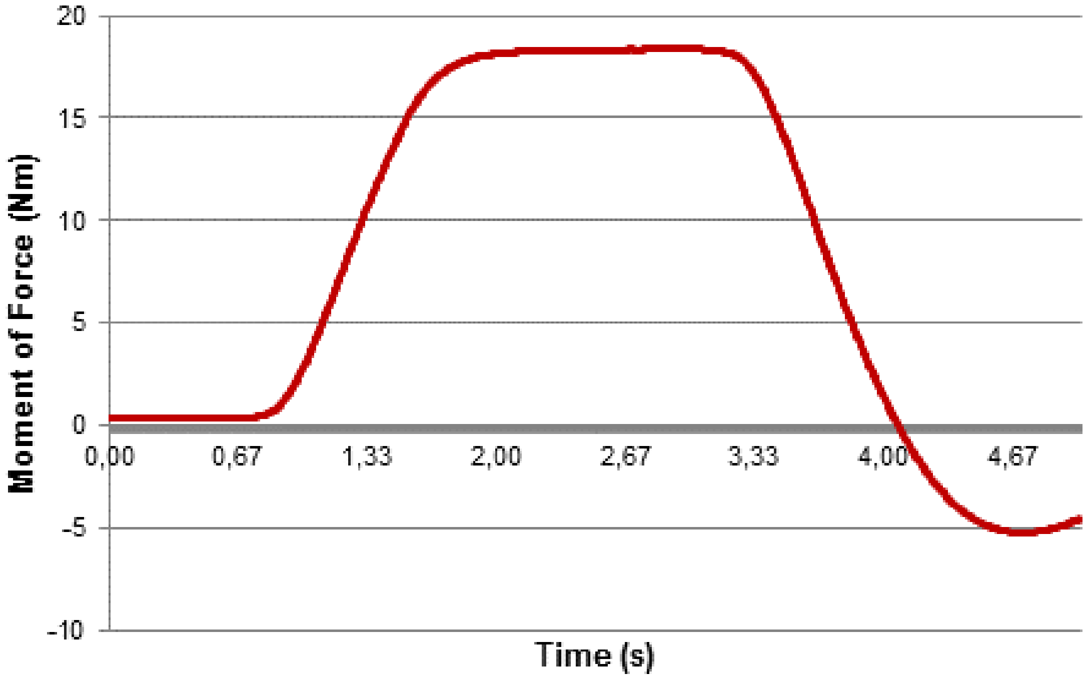

Fig. 5. Change of cutting moment (Moment) over time while sawing beech wood with a circular saw blade at feed speed v_f = 19 m/min

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. 6 for cutting on the sash gang saw and Fig. 7 for processing with the circular saw blade. The models were characterized by Pearson's *r* values of 0.945 (for sash gang saw) and 0.996 (circular sawing machine), respectively. Both cutting force trends were linear, and they were in the form as expressed in Eqs. 1 and 5, respectively.

The cutting force per tooth for the sash gang saw, in N, for kerf width (S_t) 2 mm is as follows,

$$F_c^1 = 328060 f_z + 7.77 \ \text{(N)} \tag{10}$$

The average (medium) cutting force per tooth for processing 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 $\overline{\varphi}$ = 37.47°, is described as,

$$F_c^1(\overline{\varphi} = 37.47°) = 301816\overline{h} + 3.792 \ \text{(N)} \tag{11}$$

In the first step, characteristic data for other materials and cutting processes were estimated according to Atkins (2005). The value of the slope was determined as 328060 (N/m) for sash gang saw (Eqs. 1 and 10) and 301816 (N/m) for circular saw blade (Eqs. 5 and 11). Application of the mechanics approach to the sawing processes of beech on both the sash gang saw and the circular sawing machine yielded fracture toughnesses $R_{\perp}$, $R_{\parallel\perp}(\overline{\varphi} = 37.47°)$, and $R_{\parallel\perp}$ and shear yield stresses $\tau_{\gamma\perp}$, $\tau_{\gamma\parallel\perp}(\overline{\varphi} = 37.47°)$, and $\tau_{\gamma\parallel}$. Additionally, calculations determining shear yield stresses τ_{γ} were conducted for uncut chip thicknesses $h > 0.12$ mm, when the cutting resistance is practically constant (Orlowski 2003). The orientation of the shear plane with regard to the cut surface could be calculated with Eq. 4. The computed data input, such as the shear strain along the shear plane γ (Eq. 2); the shear angle Φ_c (Eq. 4); the friction correction Q_{shear} (Eq. 3); and the friction angle β_{μ}, given by $\tan^{-1}\mu = \beta_{\mu}$, are presented in Table 1.

Table 1. Sawing Processes Characteristic Data

Machine Tool	γ_f (°)	μ (-)	β_{μ} (°)	Φ_c (°)	γ (-)	Q_{shear} (-)
PRW15M	8.46	0.8	38.65	29.90	2.2952	0.6129
CSM	20	0.8	38.65	35.67	1.7006	0.6007

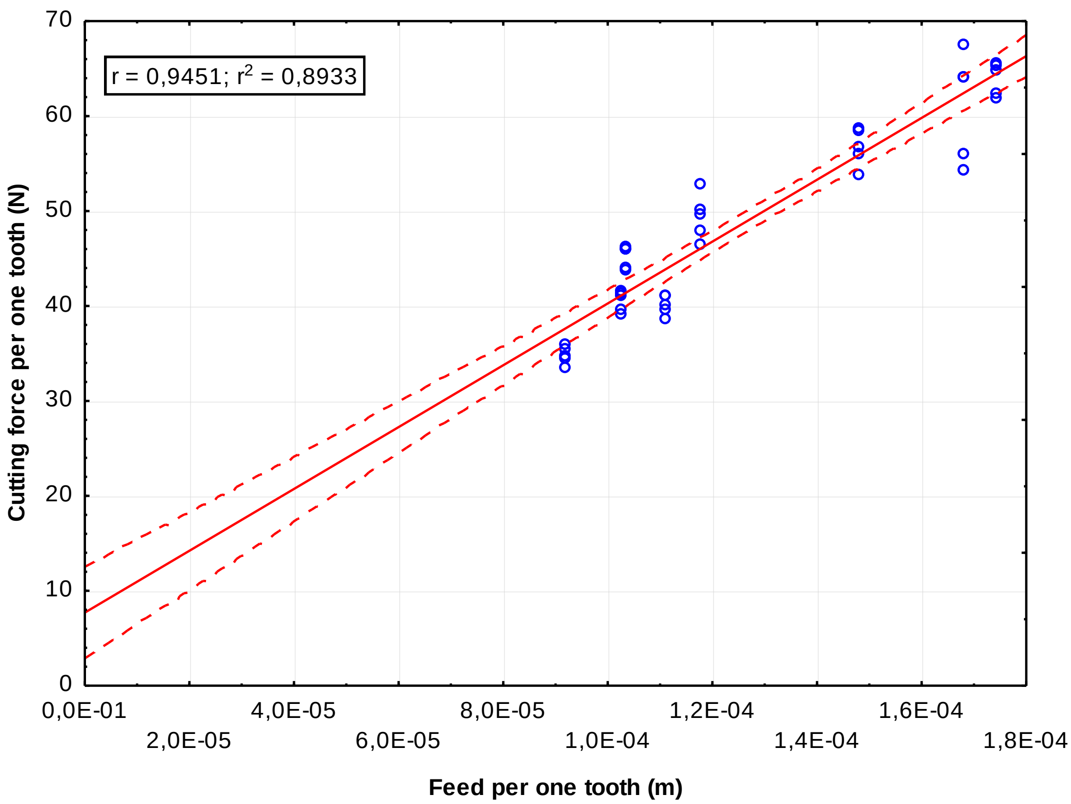

Fig. 6. Cutting force per one tooth in a function of feed per tooth with 95% confidence intervals while sawing beech wood on the sash gang saw

The toughness $R_{\perp}$ was determined from the experimental ordinate intercept, where value of the intercept was 7.77 (N) (Eq. 10) for sash gang saw and $R_{\parallel\perp}(\overline{\varphi} = 37.47°)$ was determined from the value of experimental ordinate intercept 3.792 (N) (Eq. 11) 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_c = 0 (Orlowski and Atkins 2007; Orlowski and Palubicki 2009; Orlowski 2010). Since the tool cannot be perfectly sharp, the lower portion of the tool tip can result in a ploughing of the testing material during the cutting process (Balckman *et al*. 2013; Wang *et al*. 2013). Thus, the fracture toughness from measurement results could be an overestimate, especially in case of processing on the sash gang saw with stellite tipped teeth, which were not “sharp”.

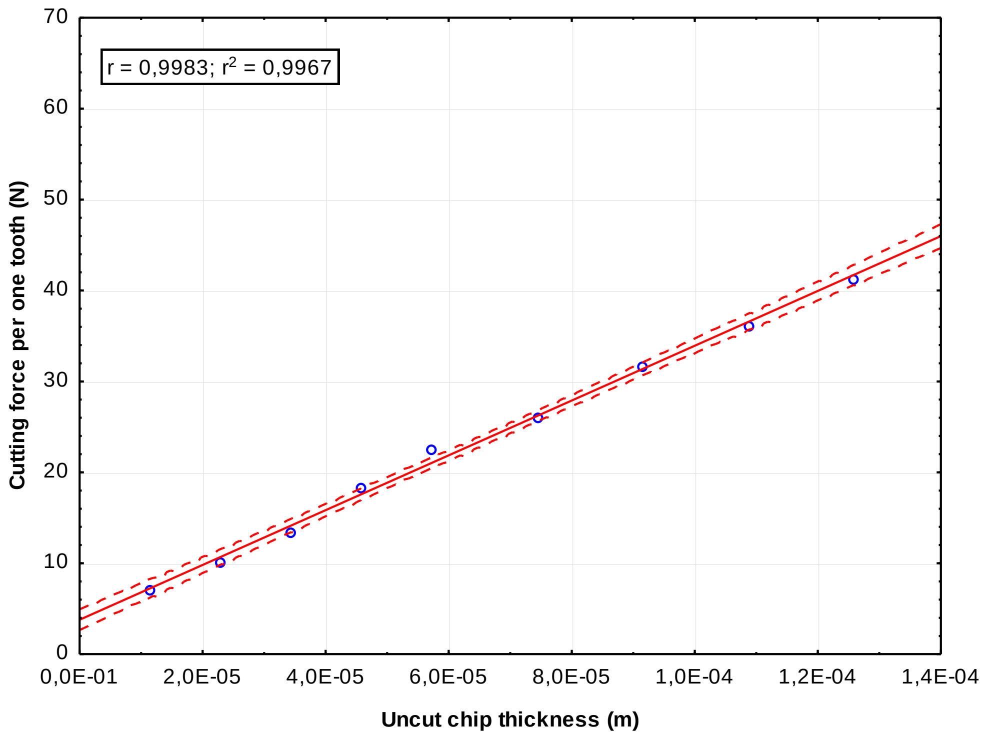

Fig. 7. Cutting force per tooth *versus* uncut chip thickness, with 95% confidence intervals, while sawing beech wood on circular sawing machine

According to Blackman *et al.* (2013), it was assumed that half of the size of the tip radius ρ_{CE} contributed to the ploughing process, such that the fracture toughness overestimated by ploughing could be approximated by,

$$R_p = 0.5\rho_{CE}\tau_\gamma \qquad (12)$$

where τ_γ is the shear yield stress determined from the cutting test.

The computed shear stresses τ_γ, fracture toughnesses from experiments R', fracture toughness reductions R_p, and $R_{||}$ and $\tau_{\gamma||}$ as calculated from Eqs. 8 and 9 are shown in Table 2.

Table 2. Shear Yield Stress and Fracture Toughness of Beech Wood (*Fagus sylvatica* L.)

$\tau_{\gamma\perp}$	$\tau_{\gamma||\perp}$*	$\tau_{\gamma||}$	$R'_{\perp}$	$R_{\perp p}$	$R_{\perp}$	$R'_{||\perp}$*	$R_{||\perp p}$*	$R_{||\perp}$*	$R_{||}$
MPa	MPa	MPa	J/m^2	J/m^2	J/m^2	J/m^2	J/m^2	J/m^2	J/m^2
43.86	30.46	22.62	3886	1204	2682	1083	76.1	1007	23.3

*data for indirect position of the cutting edge defined by the average angle of tooth contact with a workpiece, $\overline{\varphi}$ = 37.47°

Determined on the basis of empirical results from the sawing process (on the sash gang saw), the fracture toughness $R_{\perp}$ for beech wood is about 2 times larger than the average values for Polish pine wood (*Pinus sylvestris* L.) (Orlowski and Ochrymiuk 2013). Moreover, the fracture toughness $R_{\parallel}$ obtained from the results of cutting processes (on the sash gang saw and the circular sawing machine) on basis of the proposed, combined method was several times lower than $R_{\perp}$. Additionally, the ratio of $R_{\parallel}/ R_{\perp}$ was calculated, and the value achieved for beech wood was $R_{\parallel}/R_{\perp} = 0.009$, whereas for pine fir this ratio is about 0.035 (Aydin *et al*. 2007).

Furthermore, when comparing the shear stresses $\tau_{\gamma\perp}$ of Polish pine wood (Orlowski and Ochrymiuk 2013; Orlowski *et al*. 2014) and beech wood, the latter value is around 2 times higher. The calculated ratio $\tau_{\gamma\parallel}/ \tau_{\gamma\perp}$ for beech wood was 0.52, whereas for Polish pine wood it is 0.23 (Orlowski *et al*. 2013). It should be emphasized that in case, of Polish pine wood, a shear strength value for the axial cutting direction (Orlowski *et al*. 2013, 2014) was estimated on the basis of the MOR (modulus of rupture in bending).

The determined values of sawn 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.

CONCLUSIONS

1. The application of the results obtained by experimental cutting on both the sash gang saw and the circular sawing machine allowed for the determination of the toughness and shear yield strength of sawn wood for both the perpendicular and axial cutting directions.
2. The toughness and shear yield stresses of the cut wood depended strongly on the cutting speed direction as related to the grain.
3. It must be emphasized that the fracture toughness values obtained from sawing processes could be affected by dull teeth and that the toughness may have been overestimated. In this case, the phenomenon of ploughing must be taken into account.

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