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Application of fracture mechanics for energetic effects predictions while wood sawing

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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. On the other hand, cutting forces (or power—more interesting from energetic point of view) could be considered from a point of view of modern fracture mechanics. Cutting forces may be employed to determine not only toughness but also shear yield strength, which are then applied in the models. Furthermore, forecasting of the shear plane angle for the cutting models, which include fracture toughness in addition to plasticity and friction, broadens possibilities of energetic effects modelling of the sawing process even for small values of the uncut chip. Mentioned models are useful for estimation of energetic effects of sawing of every kinematics. However, for band saws and circular sawing machines, the chip acceleration power variation as a function of mass flow and tool velocity ought to be included in analysis of sawing at larger cutting speeds.

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 Springer

Introduction

Theoretical and experimental determination of values of forces acting in the cutting process belongs to the basic and simultaneously the most developed field of mechanics of this process. A great number of theoretical works, which were improved and experimentally verified, have been devoted to this problem. 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 k_c (cutting force per unit area of cut) (Fischer 2004; Scholz et al. 2009; Orlowski 2007), which in the case of wood cutting is the function of the following factors: wood species, cutting direction angle (cutting edge position in relation to wood grains), moisture content, wood temperature, tooth geometry, tooth dullness, chip thickness and some others which are less important (Agapov 1983; Orlicz 1988). Many of those traditional models are empirical and based upon limited information employing blades having standard thickness kerfs. Moreover, for each type of sawing kinematics, different values of specific cutting resistance k_c have to be applied (Manžos 1974; Orlicz 1988; Orlowski 2007). On the other hand, cutting forces could be considered from a point of view of modern fracture mechanics (Atkins 2003, 2009; Laternser et al. 2003; Williams 1998; Williams et al. 2010). In the quoted works, modelling of wood cutting process has been described as models with continuous chip formation. On the other hand, Merhar et al. (2011) and Merhar and Bučar (2012) have investigated the conditions of chip propagation or fracture in orthogonal oblique cutting of beech wood with the discontinuous chip formation process.

In analyses of sawing processes in which the offcut formation by shear occurs, Atkins's ideas (2009) can also be applied, for example in the real sawing process on a sash gang saw (Orlowski and Atkins 2007; Orlowski and Palubicki 2009; Orlowski 2010; Orlowski et al. 2010). In this paper, it is proved that cutting power models which are based on modern fracture mechanics are useful for estimation of energetic effects of sawing of every kinematics.

Theoretical background

Making an assumption that cutting force F_c acting in the middle of the cutting edge is an equilibrium of forces related to the direction of primary motion for a single saw tooth, the mechanical process of material separation from the sawn workpiece, that is, chip formation, can be described by the example of 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. 1.

According to Atkins (2009) and Orlowski (2010), furthermore, taking into account that the chips have to be accelerated to the same velocity as the cutting tool velocity v_c (Atkins 2009; Pantea 1999), cutting power for one saw blade during the cutting stroke on a sash gang saw, and during cutting on a band saw machine, because their sawing kinematics are similar (Fig. 2), has the following mathematical formula:
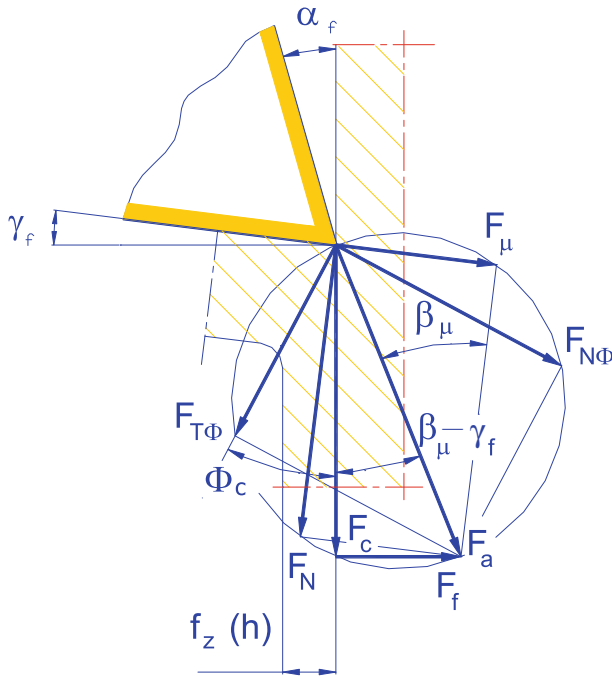
Fig. 1 Simplified cutting process model with Ernst and Merchant's force circle (Grotte and Antonsson 2008): F_a active force, F_c cutting force, F_f thrust force (passive), F_μ friction force on the rake face, F_N normal force to the rake face, $F_{T\Phi}$ the force required to shear the wood along the shear plane, $F_{N\Phi}$ normal force on the shear plane, α_f clearance angle, Φ_c shear angle, γ_f rake angle, β_μ friction angle

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

where $z_a = \left(\frac{H_p}{P} \right)$ is the number of teeth being in contact with the kerf (average) (Dmochowski 1981; Olszak 2008), H_p is workpiece height (cutting depth), τ_γ is the shear yield stress, γ is the shear strain along the shear plane, which is given by:

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

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

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

For least force F_c, the shear angle Φ_c satisfies (Atkins 2003):

$$\left[1 - \frac{\sin\beta_\mu \sin\Phi_c}{\cos(\beta_\mu - \gamma_f) \cdot \cos(\Phi_c - \gamma_f)}\right] \cdot \left[\frac{1}{\cos^2(\Phi_c - \gamma_f)} - \frac{1}{\sin^2\Phi_c}\right]$$

$$= -[\cot\Phi_c + \tan(\Phi_c - \gamma_f) + Z] \cdot \left[\frac{\sin\beta_\mu}{\cos(\beta_\mu - \gamma_f)}\left\{\frac{\cos\Phi_c}{\cos(\Phi_c - \gamma_f)} + \frac{\sin\Phi_c \sin(\Phi_c - \gamma_f)}{\cos^2(\Phi_c - \gamma_f)}\right\}\right]$$

(4)

in which $Z = \frac{R}{\tau_\gamma \cdot f_z}$ is the parameter which makes Φ_c material dependent. Since wood is an anisotropic material, its physical and mechanical properties differ in the three principal directions relative to the trunk of the tree (Fig. 3): longitudinal (L, axial): parallel to tree trunk and parallel to long axis of longitudinally oriented cells (tracheids and fibre tracheids); radial (R): perpendicular to longitudinal direction and parallel to radius of trunk and wood rays; and tangential (T): perpendicular to longitudinal direction and parallel to growth rings (FPL 1980). For that reason, values of R and τ_γ should be applied accordingly to the cutting speed direction in regard to the wood grain direction (Jeronimidis 1980; Green et al. 1999; Stanzl-Tschegg and Navi 2009), which is mainly a function of the sawing kinematics. Equation (4) is solved numerically (Orlowski and Ochrymiuk 2010).

The chip acceleration power P_{ac} variation as a function of mass flow and tool velocity is given by:
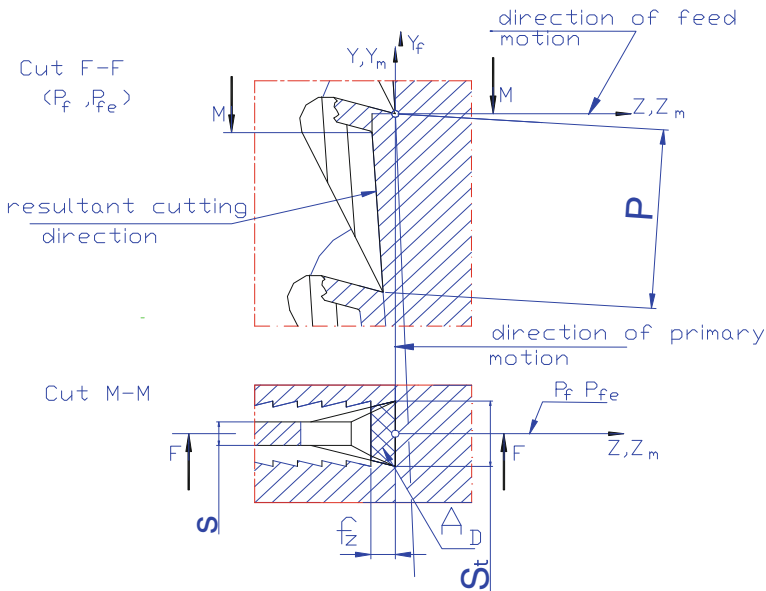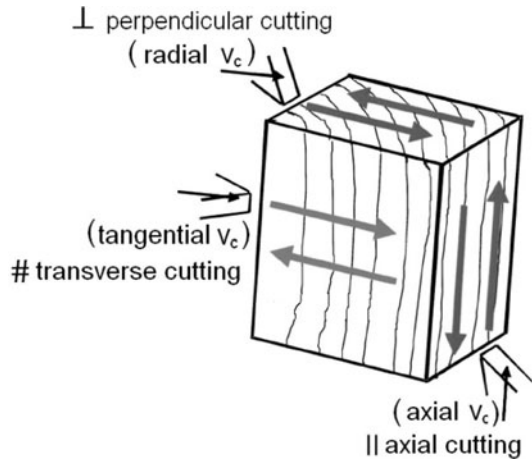

Fig. 2 Sawing kinematics on the sash gang saw and band sawing machine: f_z feed per tooth, s saw blade thickness, A_D area of the cut, P pitch, Y, Z and Y_M, Z_M machine coordinate and setting axes, Y_f f-set coordinate axis, P_{fe} working plane

Fig. 3 Tooth cutting edge
principal positions and cutting
speed directions (adapted from
Laternser et al. 2003)

$$P_{ac} = \dot{m}\, v_c^2 \tag{5}$$

where $\dot{m}$ (kgs^{-1}) represents the mass of wood (chips) evacuated in a certain period
of time at a certain cutting tool velocity v_c (cutting speed), which can be calculated
as follows:

$$\dot{m} = H_P S_t v_f \rho \tag{6}$$

In Eq. (6), v_f is feed speed and ρ is density of sawn wood. It should be emphasized
that in these analyses, it was assumed that the power P_{ac} is not a function of the
number of working teeth.

Kinematics of sawing on circular sawing machines (Fig. 4) differs from
kinematics of cutting on sash gang saws and band sawing machines. In case of
cutting with circular saw blades, uncut chip thickness $\bar{h}$ (e.g. an average value)
instead of feed per tooth f_z should be taken into account; hence, the cutting power
may be expressed as:

$$\overline{P}_{cw} = F_c v_c + P_{ac} = \left[z_a \cdot \frac{\tau_\gamma S_t \gamma}{Q_{shear}} v_c \bar{h} + z_a \cdot \frac{RS_t}{Q_{shear}} v_c \right] + P_{ac} \tag{7}$$

where $z_a = \left(\frac{\varphi_2 - \varphi_1}{\varphi_t} \right)$ is the number of teeth being in contact with the kerf (average),
φ_1 is an angle of teeth entrance which is 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 a diameter of circular saw
blade, an average uncut chip thickness is given by $\bar{h} = f_z \sin \bar{\varphi}$, and an average angle
of tooth contact with a workpiece $\bar{\varphi}$ is calculated from $\bar{\varphi} = \frac{\varphi_1 + \varphi_2}{2}$.

Furthermore, it is difficult to assume that in 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°, as it was assumed for the sash gang saw
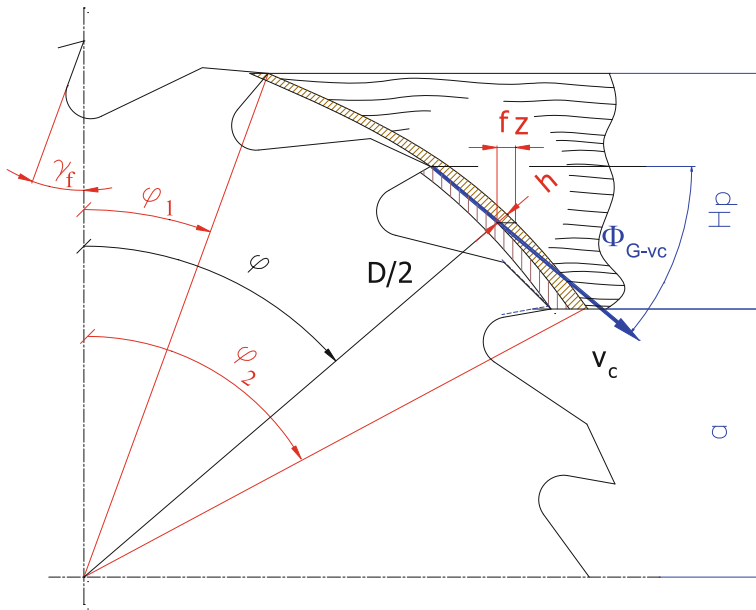and the band sawing machines. Hence, taking into account the position of the

Fig. 4 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, Φ_{G-vc} an angle between grains and the cutting speed direction

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 from 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:

$$R_{\|\perp} = R_\| \cos^2 \Phi_{G-vc} + R_\perp \sin^2 \Phi_{G-vc} \tag{8}$$

and

$$\tau_{\gamma\|\perp} = \tau_{\gamma\|} \cos^2 \Phi_{G-vc} + \tau_{\gamma\perp} \sin^2 \Phi_{G-vc} \tag{9}$$

where Φ_{G-vc} is an angle between grains and the cutting speed direction (Fig. 4).

Material and examined sawing machines data

Predictions of cutting powers have been made for the case of sawing on three types of basic sawing machines such as the sash gang saw (HDN, f. EWD), the band sawing machine (EB 1800, f. EWD) and the circular sawing machine (HVS R200, f. HewSaw), which are used in Polish sawmills. The basic sawing machines data and cutting parameters for which computations were done are shown in Table 1. Computations were carried out in each case for one saw blade. The raw material was pine wood (*Pinus sylvestris* L.) of depth of cut equal to H_p (Table 1) derived from

the Baltic Natural Forest Region in Poland. The indispensable raw material data for computation such as fracture toughness $R_\perp = 840$ Jm^{-2} and the shear yield stress $\tau_{\gamma\perp} = 22{,}636$ kPa were determined according to the methodology described in the works by Orlowski and Atkins (2007) and Orlowski and Palubicki (2009). The latter data determination tests of raw material were carried out on the sash gang saw PRW15 M (Wasielewski and Orlowski 2002; Orlowski 2010) with stellite tipped saw blades with a kerf equal to $S_t = 2$ mm. The average density of samples was $\rho = 525$ kgm^{-3} at moisture content MC 8.5–12 %. The value of friction coefficient $\mu = 0.6$ for dry pine wood was taken from the work by Beer (2002). The chip acceleration power P_{ac} variation was estimated for each kind of sawing kinematics for depth of cut equal to $H_p = 100$ mm.

In the case of circular sawing in which indirect positions of the cutting edge are present, R and τ_γ have to be calculated from formulae (8) and (9). According to Aydin et al. (2007), it was assumed that fracture toughness for pine for longitudinal (axial) cutting $R_\parallel = 0.05R_\perp$. Moreover, an assumption was made that in case of pine wood for axial cutting, the shear yield stress $\tau_{\gamma\parallel}$ is equal to 0.125·MOR [modulus of rupture in bending (Green et al. 1999; Krzysik 1974)]. The average value of MOR for pine wood derived from the Baltic Natural Forest Region (PL) was equal to MOR = 41.6 MPa (Krzosek et al. 2008; Krzosek 2009). Hence, at the tooth position of the circular saw equal to an average angle of tooth contact with a workpiece $\bar{\varphi}$, fracture toughness was equal to $R_{\parallel\perp} = 714$ Jm^{-2} and the shear yield stress was $\tau_{\gamma\parallel\perp} = 9{,}559$ kPa.

Results and discussion

Predictions of cutting model that includes work of separation in addition to plasticity and friction in the case of sawing dry pine wood on examined sawing

Table 1 Tool and machine tool data

Parameter	Sash gang saw HDN (f. EWD)	Circular sawing machine HVS R200 (f. HewSaw)	Band sawing machine EB 1,800 (f. EWD)
H_p (mm)	140	80	140
S_t (mm)	4.0	3.6	3.1
P (mm)	25	–	50
γ_f (°)	14	22	28
z (−)	32	24	217
v_c (m/s)	6.4	64.14	35
v_f (m/min) [(m/s)]	0–15 (0–0.25)	70–150 (1.16–2.5)	40–70 (0.67–1.167)
f_z (mm)	0–1.953	1.23–1.56	0.95–1.67
h (mm)	0–1.953	0.59–0.747	0.95–1.67
P_{EM} (kW)	160	2 × 90	4 × 110

P pitch, z teeth number, P_{EM} power of installed electric motors

machines are shown in Fig. 5. The reductions in Φ_c (Fig. 5a) and increases in γ (Fig. 5b) are visible in plots, which concerns what happens near the origin of both Φ_c versus h (f_z) and γ vs. h (f_z) plots. Those changes at small depths of cut are the reasons for the increase in cutting pressure for small values of feed per tooth (the so-called 'size effect') (Atkins 2003, 2009; Orlowski et al. 2010). Furthermore, an increase in shear plane angle Φ_c is observed when rake angle γ_f has a larger value.

Figure 6 shows the chip acceleration power P_{ac} variations as a function of feed speed v_f and cutting speed v_c for the sash gang saw HDN (Fig. 6a), the circular sawing machine HSV R200 (Fig. 6b) and the band sawing machine EB1800
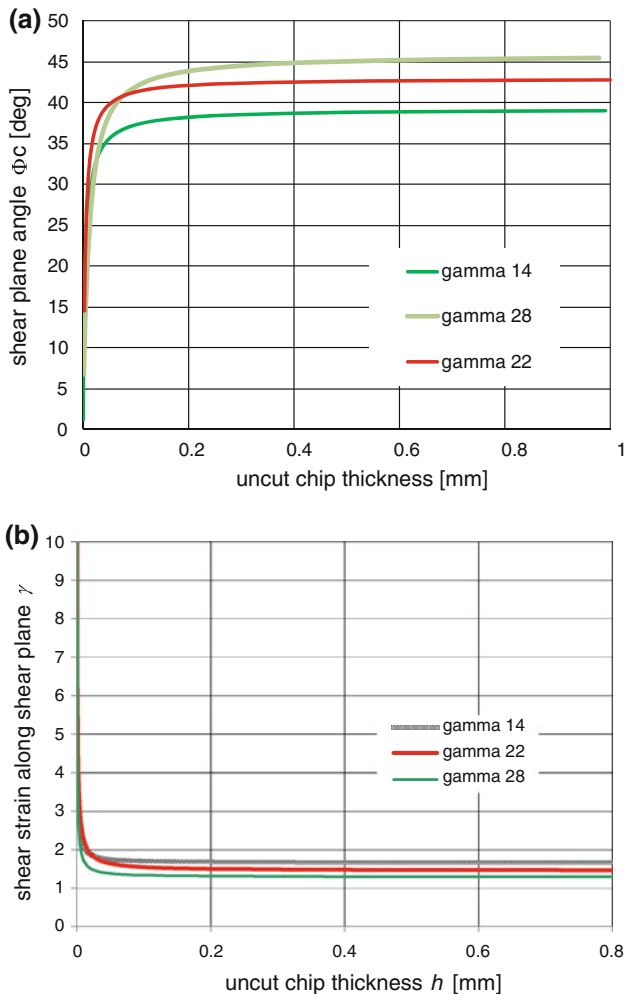

Fig. 5 Predictions of cutting model that includes work of separation in addition to plasticity and friction in the case of sawing dry pine wood on examined sawing machines (**a**) shear plane angle Φ_c versus f_z, (**b**) primary shear strain γ versus f_z, where gamma 14 (sash gang saw HDN), gamma 22 (circular sawing machine HSV R200), gamma 28 (band sawing machine EB1800) are rake angles

(Fig. 6c) for the cutting processes with one saw blade while sawing dry pine wood for depth of cut equal to $H_p = 100$ mm. For sash gang saws, a maximum value of the chip acceleration power P_{ac} equals to $\cong 2.5$ W. Thus, in those machine tools where cutting speeds and feed speeds are rather small compared with circular saws and band saws, chip momentum may be disregarded, the same as in the case of metal cutting where it is customarily ignored (Atkins 2009). In case of both the circular sawing machine and the band sawing machine, the chip acceleration power P_{ac} is several hundreds larger in comparison with the sash gang saw.

Comparison of predictions of cutting powers obtained with the use of cutting models that include work of separation in addition to plasticity and friction, and chip acceleration power variation in the case of dry pine sawing with one saw blade for three examined typical sawing machines are shown in Fig. 7.
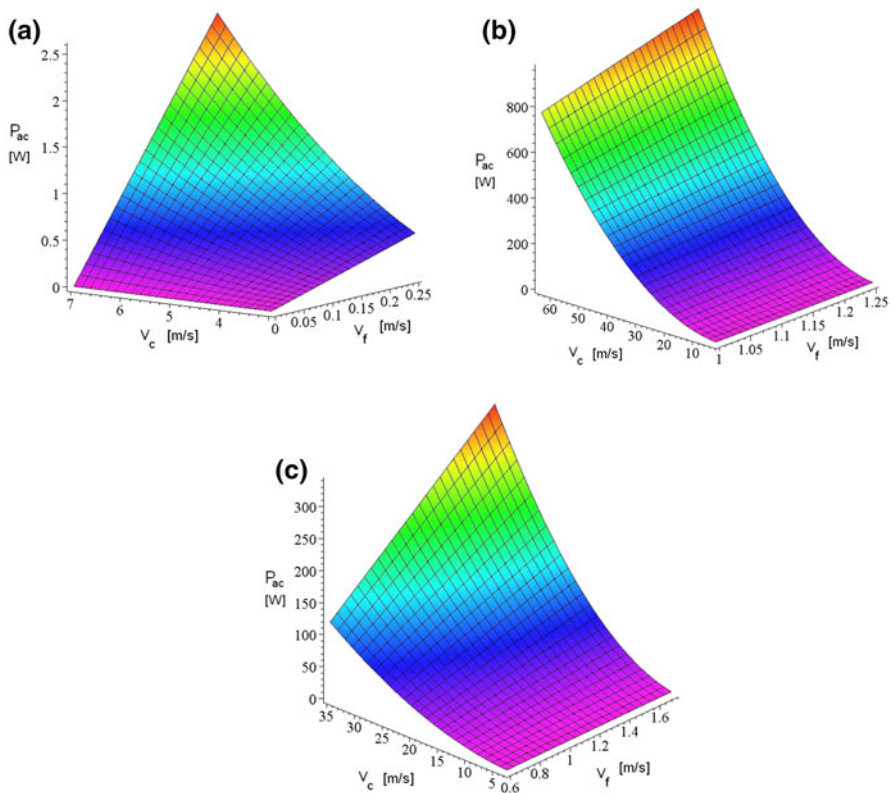

Fig. 6 Predictions of chip acceleration power variation P_{ac} as a function of cutting speed v_c and feed speed v_f for sawing of the pine workpiece of 100 mm in height with one saw blade on sash gang saw HDN (**a**), circular sawing machine HSV R200 (**b**) and band sawing machine EB 1800 (**c**)
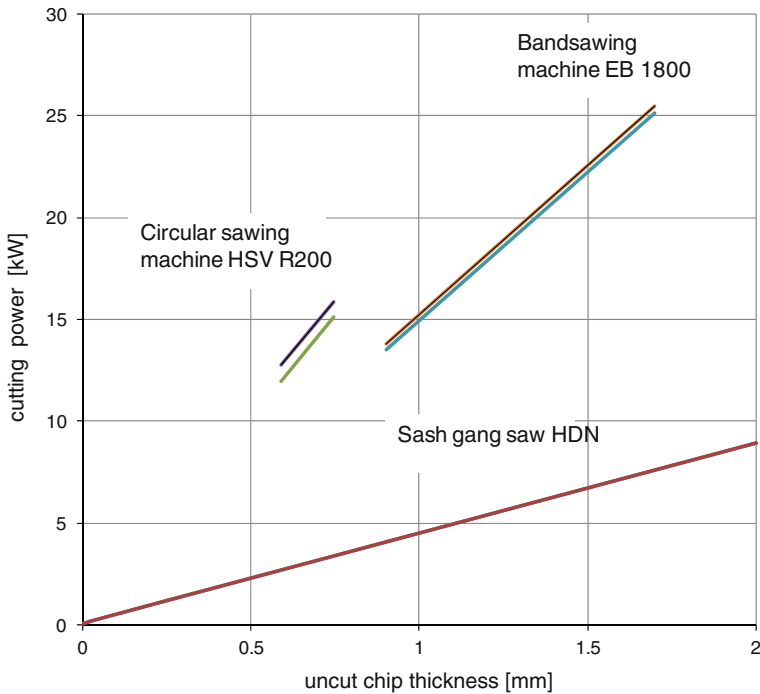
Fig. 7 Comparison of predictions of cutting powers obtained with the use of cutting models that include work of separation in addition to plasticity and friction (*lower lines*), with chip acceleration power variation added (*upper lines*, for the circular sawing machine course and the band sawing machine plot) in the case of dry pine sawing with one saw blade

Specific cutting resistance versus the method of power estimation

The predicted values of cutting powers were used for determination of the specific cutting resistance for each type of the sawing machine. In computations, the following formula was applied:

$$k_c = \frac{P_c}{S_t \cdot H_p \cdot v_f} \tag{10}$$

In the next step, the obtained results were compared with specific cutting resistances taken from the book by Manžos (1974) for all kinds of sawing machines, and additionally with calculated specific cutting resistances (Eq. 10) for the circular sawing machine and the band sawing machine on the basis of cutting power values received from the software accessible in the Internet (Web sources 1 and 2). The compared results are shown in Fig. 8a–c. This comparison revealed that the size effect is present for the cutting power prediction method which bases on the fracture mechanics (kc_FRAC) for each type of the machine tool and also in the case of circular sawing for Manžos's method (kc_Man, Fig. 8c). In all remaining cases, the scale effect is not imperceptible. This phenomenon has its roots in empirical

formulae which are used. For example, Manžos (1974) recommend calculating specific cutting resistance for a band sawing machine in the case of pine sawing as follows:

$$k_c = 9.91\big(5.3 + 0.01H_p - 0.03v_f\big) \tag{11}$$

where H_p is in mm and v_f is m·min^{-1}.

On the other hand, Web sources 1 and 2 (2011a, b) for determination of the cutting power for both the band saw machine and the circular sawing machine apply the same formula in which the power is a function of the wood specific gravity SG. Thus, this kind of approach could be applied to rough estimations of cutting power while wood sawing, the more so because the correlation coefficients between strength properties (modulus of elasticity and density, bending strength and density and modulus of elasticity and bending strength) and wood density are in the range of 0.50–0.70. Moreover, the geographical location of the forest in which the trees were harvested strongly affects this correlation and timber grade (Krzosek 2009, 2011).

Obtained values of cutting powers (Fig. 7) for those machines seem to be reasonable when compared to the power P_{EM} of installed electric motors (Table 1). Furthermore, the specific cutting resistance is in conformity with values calculated using empirical calculation models (Fig. 8a–c). Hence, it has been proved that prediction of cutting powers obtained with the use of cutting models that include work of separation in addition to plasticity and friction together with the chip acceleration power variation is a useful tool for estimation of energetic effects of sawing of every kinematics.
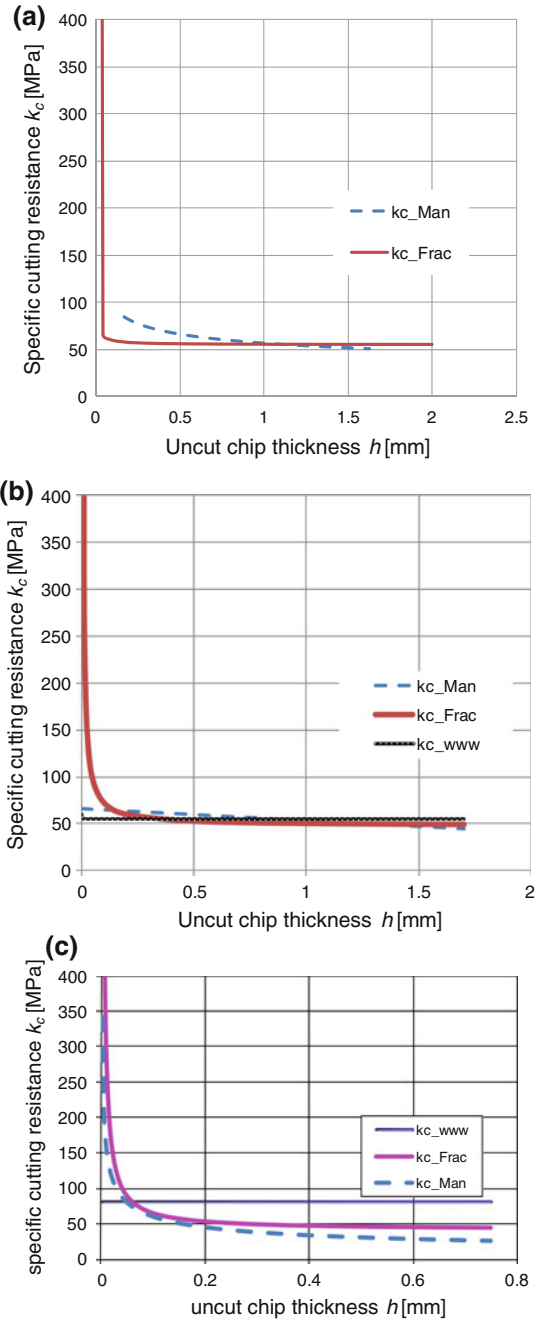
Cutting power normalization

Since the cutting power for each kind of sawing machine has been calculated for different kerf values and also various workpiece heights (cutting depths, see Table 1) for a more general discussion the obtained results were normalized. The specific cutting power per one active tooth was calculated as follows:

$$P_c'^{1} = \frac{P_c}{S_t \cdot z_a} \tag{12}$$

In the presented approach of energetic effects determination, the cutting power consists of three main terms (see Eqs. 1, 7): the first—combined with shearing and friction; the second—connected with work of separation (fracture toughness); and the third—incident with the chip acceleration. Contributions of those components to the total specific cutting power per one active tooth while pine wood sawing were computed, and the results are presented in Fig. 9. For lower values of uncut chip thicknesses (Fig. 9a) in the total specific cutting power per one tooth, the component connected with the work of separation is a dominant character whereas shearing with friction has much lower importance. The acceleration factor has no significance. On the other hand, for larger values of uncut chip thicknesses (Fig. 9b), the opposite phenomenon is observed in which the term connected with shearing is featured.

Fig. 8 Specific cutting
resistance comparison in case of
a sawing on the frame sawing
machine HDN, **b** sawing on the
band sawing machine EB 1,800
and **c** sawing on the circular
sawing machine HVS R 200
where: *kc_Frac* predicted values
with the use of cutting model
that include work of separation
in addition to plasticity and
friction, *kc_Man* empirical
values from the literature
(Manžos 1974), *kc_www*
empirical values on the basis of
the software results (Web source
1 and 2, 2011a, b)

The normalization of the cutting power by the kerf value and number of active
teeth allowed to explain that for the constant value of the uncut chip thickness, the
specific cutting power for circular sawing machine is lower in comparison with the
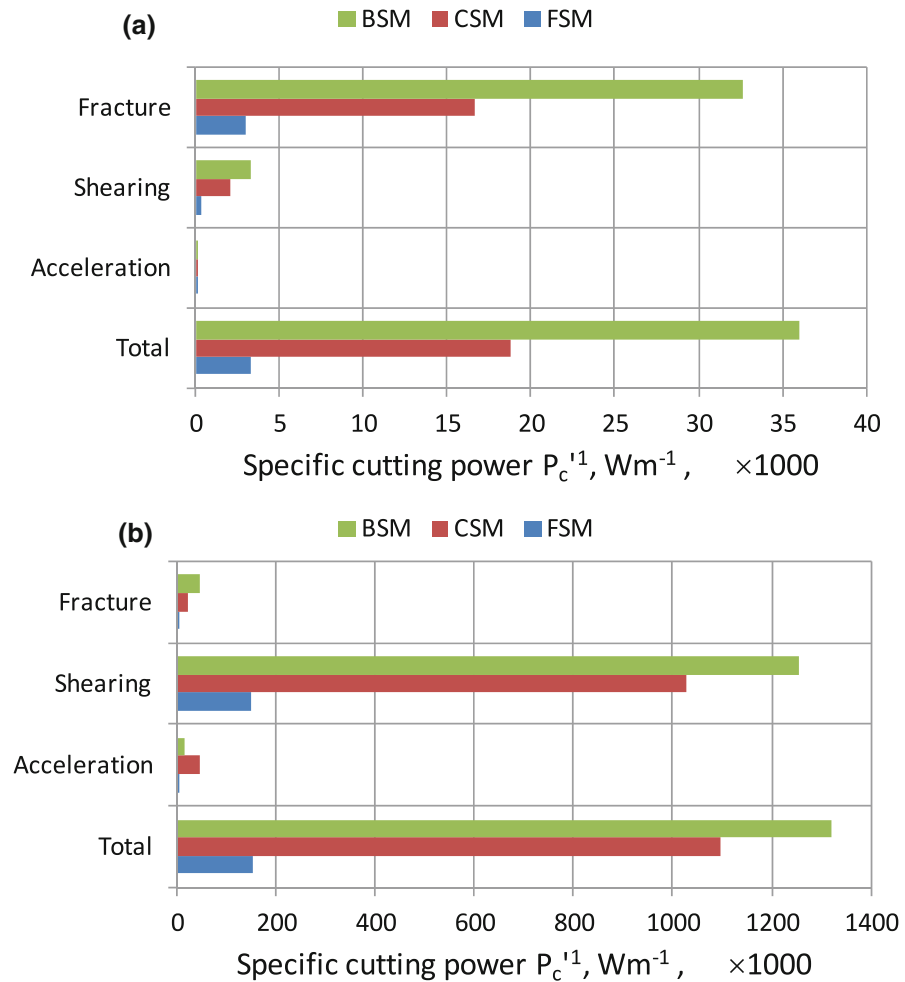
Fig. 9 Contributions of chip acceleration (Acceleration), fracture and shearing together with friction (Shearing) to the total specific cutting power per one active tooth while pine wood sawing on band sawing machine (BSM), circular sawing machine (CSM) and frame sawing machine (FSM) for uncut chip thickness $h = 0.0075$ mm (**a**) and $h = 0.75$ mm (**b**)

band sawing machine, although the cutting speed is almost double, because the raw material properties during sawing with a circular saw blade are the result of a case of axial-perpendicular cutting.

Conclusion

The conducted analyses of energetic effects using cutting models that include work of separation in addition to plasticity and friction corroborated their versatility and revealed the usefulness for every known type of sawing kinematics. The analyses of

the specific cutting resistance disclosed the presence of the size effect for each type of machine tool for the cutting power prediction method which bases on the fracture mechanics.

Moreover, in the estimation of cutting power for sash gang saws chip momentum may be disregarded. On the other hand, in case of cutting on band sawing machines and circular sawing machines, the chip acceleration power P_{ac} has to be taken into account.

Contributions of fracture, shearing together with friction and chip acceleration to the total specific cutting power per one active tooth while pine sawing depend on the uncut chip thickness. For low values of the uncut chip thickness, the component connected with the work of separation is a dominant character, whereas for larger values of this parameter, the term connected with shearing is featured.

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