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Empirical verification in industrial conditions of fracture mechanics models of cutting power prediction

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Abstract: *Empirical verification in industrial conditions of fracture mechanics models for cutting power prediction.* A comparison of experimental results obtained in the industrial conditions at a sawmill located in the Baltic Natural Forest Region (PL) and theoretical cutting power consumption forecasted with the models which include work of separation (fracture toughness) in addition to plasticity and friction has been described. In computations of cutting power consumption during rip sawing of Scots pine wood (*Pinus sylvestris* L.) values of fracture toughness and shear yield stresses were taken from previous empirical works, in which samples had been of the same provenance. The carried out analyses revealed conformity of experimental and theoretical results, especially for the model FM-CM, for which differences between them were lower than 3%.

Keywords: circular sawing machine, cutting power, fracture mechanics model, industrial measurements

INTRODUCTION

Reliable estimates for the power requirements necessary to cut wood are essential for the proper design of cutting tools/machines to assure safety of operation and to optimize production quality (Chuchala et al. 2014). Among a number of different methods, cutting forces (power) could be considered from a point of view of modern fracture mechanics (Laternser et al. 2003; Orlowski et al. 2013; Merhar and Bučar 2012; Stanzl-Tschegg and Navi 2009).

Cutting power values, in case of sawing of dry pine wood (originated from the Baltic Natural Forest Region, PL) on the circular sawing machine, obtained with the Manžos method (the classical approach, Pc_Man) and the cutting model that includes work of separation in addition to plasticity and friction (Pc_Frac) have been more or less the same (Orlowski et al. 2012; 2013). Nevertheless, the latter method allow the user to predict the cutting power for the sawing process more precisely because the wood derivation ought to be taken into account (Chuchala et al. 2014). In the models for a circular sawing machine kinematics described in works by Orlowski et al. (2012; 2013), similarly to metal milling, the sum of all uncut chip thicknesses of the simultaneously teeth engaged represented the mean uncut chip thickness. However, in reality the instantaneous uncut chip thickness at a certain location of the cutting tooth changes its value. Hence, Orlowski and Ochrymiuk (2013a) have converted the model described in the papers (Orlowski et al. 2012; 2013) into a new model in which besides variable uncut chip thicknesses additionally variable values of fracture toughness and shear yield stresses according to the tooth position in relation to the grains were taken into account. Thus, for this reason that kind of the model have been called as FM-FDM (fracture mechanics incorporated - full dynamical model) (Orlowski and Ochrymiuk 2013b). The conducted analyses have demonstrated that in each case values of RMS (root-mean-square) of cutting powers obtained with new developed dynamical models are larger than values computed with the use of the mean uncut chip thicknesses and mean values of raw material data such as fracture toughness *R* and shear yield stresses τ in the model (Orlowski and Ochrymiuk 2013a, b).

The sawing process experimentally has been investigated: in case of cutting with circular saw blades by Beljo-Lučić et al. (2004), in case of in industrial conditions by Cristóvão et. al (2013), and for wood crosscutting process (Krilek et al. 2014).

The aim of this study was to compare experimental results obtained in the industrial conditions at a sawmill located in the Baltic Natural Forest Region (PL) and theoretical cutting power consumption forecasted with the models which include work of separation (fracture toughness) in addition to plasticity and friction.

MATERIALS AND METHODS

Materials

Scots pine (*Pinus sylvestris* L.) samples originating from the Forest Inspectorate Lipusz in the Baltic Natural Forest Region (PL) were used as experimental samples. Samples were in the shape of rectangular blocks with dimensions of 100 mm (*H*) × 50 mm (*W*) × 2200 mm (*L*) with moisture content MC 35%. Raw material data of pine wood, which was taken for numerical computations, for MC 12% is presented in Table 1.

Table 1. Raw material data (Orlowski et al. 2013)

Region	ρ	$R_{\perp}$	$\tau_{\gamma\perp}$	MOR*
	kgm^{-3}	Jm^{-2}	kPa	MPa
Baltic	520	1295.33	20861	41,6
ρ – density, MOR – modulus of rupture in bending (* values were taken from Krzosek [10])				

Tool and machine tool data

The cutting experiment was carried out on the one shaft multi rip sawing machine PWR301 (TOS Svitavy, CZ) at the Complex sawmill in Dziemiany (the Baltic Natural Forest Region, PL). The machine settings were as follows: number of saw blades n_b = 1, spindle rotational speed 3800 rpm, cutting speed v_c = 69.64 ms^{-1}, feed speed v_f = 10 and 40 $m{\cdot}min^{-1}$, (feed per tooth f_z =0.15 and 0.58 mm, average of uncut chip thickness h = 0.094 and 0.373 mm), clearance of a circular saw blade over the workpiece 5 mm, cutting kinematics – up-sawing, electric engine power P_{EM} = 45 kW. One circular saw blade was applied with data as follows: 350 mm (*D*) × 80 mm (*d*) × 2.5 mm (*s*), overall set S_t = 3.9 mm, number of carbide tipped teeth z = 18, and side rake angle γ_f = 25º (Gasstech, PL).

Industrial cutting power measurements

The measurements were performed using a measuring system consisting of a probe AC/DC current transducer DHR 100C10 (LEM USA Inc.), high-accuracy isothermal terminal block NI SCXI 1328 (National Instruments, USA), an 8-channel isolation amplifier NI SCXI 1125 (National Instruments, USA), 4-Slot Chassis NISCXI 1000DC (National Instruments, USA) and computer with the NI PCI 6281 card (National Instruments, USA). The measuring card NI PCI-6281 allowed the registration of the signal with a resolution of 18 bits and an acquisition frequency for one channel 625 kS/s. The sampling rate of the probe in connection with the parameters of the measurement channel enables precise measurement of changes in current. Schematically, the measuring system is shown in Figure 1. The measurement probe was installed on the single-phase power cable of electric engine (three-phase electric engine). Changes in current as a function of time for different types of wood and for no-load operation were measured during the experiment. During measurements sampling frequency was 1000 Hz. The cutting power was calculated as a difference of a total electric power P_{ET} and an electric idling power P_{Eid}. Since the measurements were carried out in one phase it was assumed that in other phases values of current have been the same. The real electric power can be calculated as (Three-phase 2014):

$$P_E = \sqrt{3} \cdot U \cdot I \cdot PF \tag{1}$$

where: U is voltage (V, U = 400 V), I is measured current (A), PF is power factor ($PF = \cos\Phi$). For cutting process with feed speed v_f = 40 m·min^{-1} it was assumed that the value of PF = 0.8, and for idling PF was equal 0.3. Additionally, it was assumed that in the range of feed speed changes a PF function is linear, so for feed speed v_f = 10 m·min^{-1} PF was equal to 0.42. It should be emphasised that for purely resistive load PF = 1.

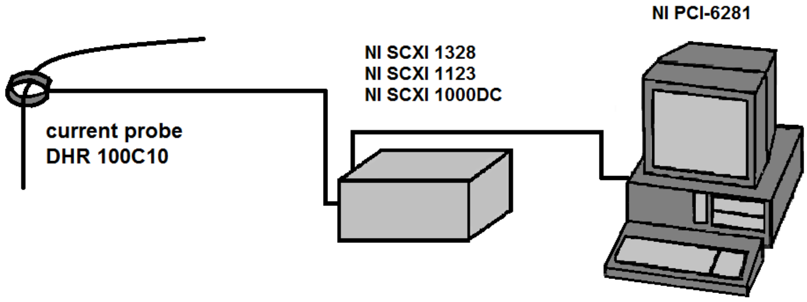

Figure 1. Schematic diagram of the measurement system

Theoretical cutting power consumption

In computations of the theoretical cutting power consumption models in which fracture toughness was incorporated were used. The comparison has concerned models as follows: FM-CM – classic model in which the sum of all uncut chip thicknesses of the simultaneously teeth engaged represented the mean uncut chip thickness (Orlowski et al. 2012; Orlowski et al. 2013), and FM-FDM – full dynamical model in which besides variable uncut chip thickness additionally variable values of fracture toughness and shear yield stresses according to the tooth position in relation to the grains were taken into account (Orlowski and Ochrymiuk 2013a, b). Numerical calculations were done for feed speeds v_f = 10 and 40 m·min^{-1}. It ought to be emphasised, that part of the samples investigated by Krzosek (2009) has been explored within the previous cutting research, in which the raw material data given in Table 1 has been determined according to the procedure described in paper by Orlowski and Palubicki (2009). Because data from Table 1 concerns pine wood of MC 12%, the computed values of theoretical cutting power were multiplied by 1.05 (Manžos 1974) to have the same level of MC as the samples in the cutting tests in the sawmill.

RESULTS AND ANALYSES

In Figure 2 the course of the registered current in one phase of the electric motor of the circular sawing machine PWR301 during rip sawing of pine wood (*Pinus sylvestris* L.) 100 mm in height, with feed speed v_f = 40 m·min^{-1}, with idling current included, is shown. For idling and for cutting parts of the course values of the real electric powers were calculated as average values.

Results of predictions of cutting powers obtained with the use of the FM_FDM cutting model that include work of separation in addition to plasticity and friction in the case of sawing of pine (the Baltic Natural Forest Region provenance) with one circular saw blade, at the feed speed $v_f = 40\ \mathrm{m \cdot min^{-1}}$, for one full revolution of the tool (the first one), are presented in Figure 3. Because of the range of power changes for a stable condition of cuting power changes RMS values were computed.

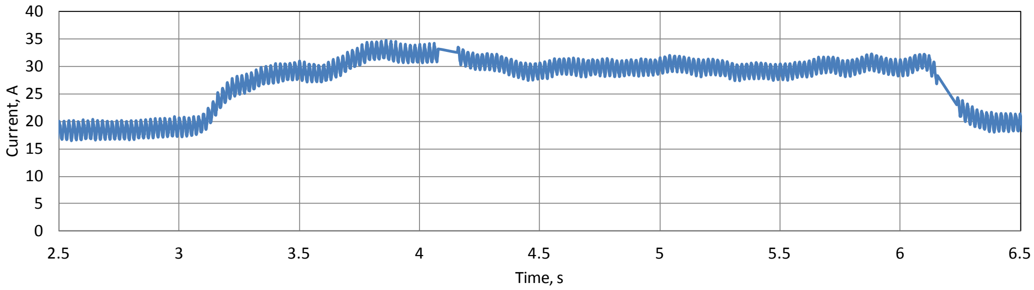

Figure 2. Registered current in one phase of the electric motor of the circular sawing machine PWR301 during rip sawing of pine wood (*Pinus sylvestris* L.) 100 mm in height, with feed speed $v_f = 40\ \mathrm{m \cdot min^{-1}}$

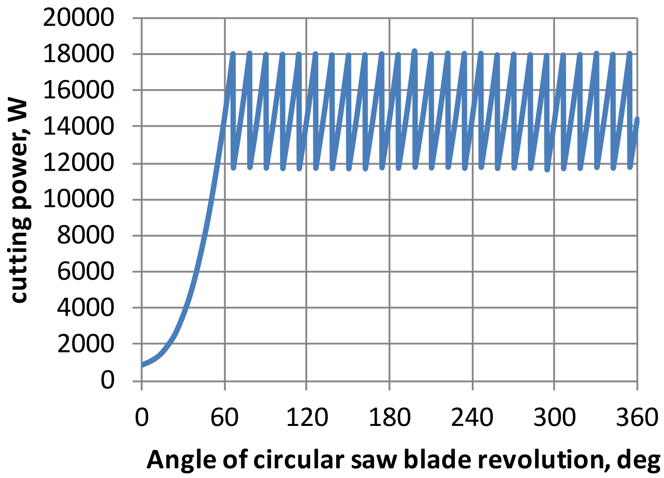

Figure 3. Predictions of cutting power obtained with the use of the FM_FDM cutting model that include work of separation in addition to plasticity and friction for the circular sawing machine with one circular saw blade in the case of pine sawing from the Baltic Natural Forest Region (PL) with feed speed $v_f = 40\ \mathrm{m \cdot min^{-1}}$

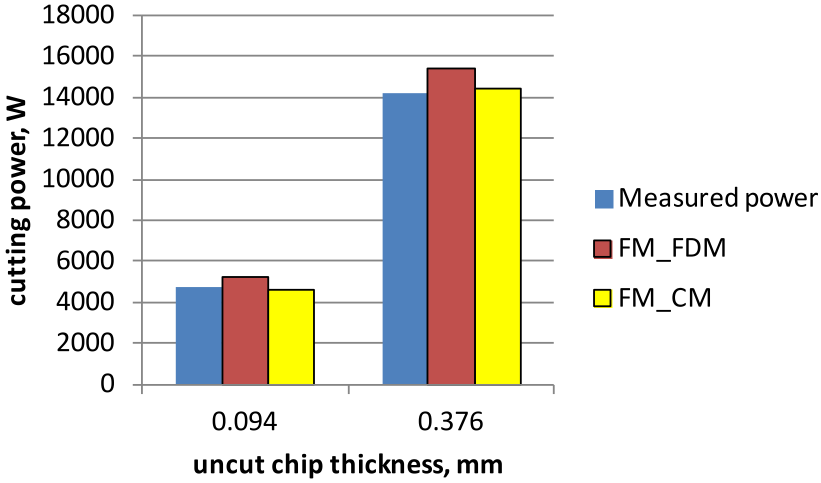

Figure 4. Comparison of cutting power values for the circular sawing machine PWR301 with one circular saw blade in the case of sawing of pine wood from the Baltic Natural Forest Region (PL), where: Measured power – measurements in industrial conditions, FM_FDM – full dynamical model theoretical predictions, FM_CM – theoretical determinations with the classical approach

In Figure 4, the effect of the determination method on the cutting power value for the circular sawing machine with one circular saw blade in the case of pine sawing is shown. While the classic approach FM_CM is used, it meant that the sum of all uncut chip thicknesses of the simultaneously teeth engaged represented the mean uncut chip thickness, the computed theoretical value of the cutting power has a similar value to the measured cutting power in the industrial conditions. The difference in cutting powers is 2.7% for feed speed equal to $v_f = 10$ m·min^{-1}, and 1.6% for feed speed of $v_f = 40$ m·min^{-1}. The differences between the measured values and computed with the FM_FDM are larger and are equal to 9% for $v_f = 10$ m·min^{-1}, and 8% for $v_f = 40$ m·min^{-1}.

CONCLUSIONS

The carried out results analyses revealed conformity of experimental and theoretical results.

1. While the classic approach FM_CM is used, it meant that the sum of all uncut chip thicknesses of the simultaneously teeth engaged represented the mean uncut chip thickness, the computed theoretical value of the cutting power has a similar value to the measured cutting power in the industrial conditions. The difference in cutting powers is 2.7% for feed speed equal to $v_f = 10$ m·min^{-1}, and 1.6% for feed speed of $v_f = 40$ m·min^{-1}.
2. The values of predicted cutting power with the FM_FDM are larger than experimental ones, and the values obtained with the FM_CM model of cutting. The differences between the measured values and computed with the FM_FDM are larger, and are equal to 9% for feed speed $v_f = 10$ m·min^{-1}, and 8% for feed speed $v_f = 40$ m·min^{-1}.

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Streszczenie: *Doświadczalna weryfikacja w warunkach przemysłowych prognozowania mocy skrawania za pomocą modeli bazujących na mechanice pękania*. W niniejszym artykule przedstawiono porównanie wyników uzyskanych w warunkach przemysłowych tartaku usytuowanego w Bałtyckiej Krainie Przyrodniczo-Leśnej z wynikami prognozowania mocy skrawania za pomocą modeli zawierających elementy współczesnej mechaniki pękania (energię właściwą na tworzenie nowej powierzchni (wiązkość), naprężenia tnące w strefie ścinania oraz tarcie). W obliczeniach mocy skrawania w procesie rozpiłowywania wzdłużnego na pilarce tarczowej drewna sosnowego (*Pinus sylvestris* L.) stosowano wartości wiązkości i naprężeń tnących w strefie ścinania uzyskane podczas wcześniejszych badań doświadczalnych z wykorzystaniem próbek pochodzących z tej samej Krainy Przyrodniczo-Leśnej. Stwierdzono, zgodność wyników empirycznych i teoretycznych mocy skrawania, szczególnie dla modelu FM-CM (model klasyczny, w którym suma wszystkich grubości warstwy skrawanej ostrzy będących w kontakcie z przedmiotem obrabianym odpowiadała wartości średniej grubości niezeskrawanego wióra), gdzie ta różnica pomiędzy nimi nie przekraczała 3%.

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