RELATIONSHIP BETWEEN MECHANICAL AND ELECTRIC CUTTING POWER AT LONGITUDINAL SAWING

Andis Ābele, **Henn Tuherm**
Latvia University of Agriculture
Andis.Abele@llu.lv; Henn.Tuherm@llu.lv

Abstract
When the measurements of power consumed by cutting mechanism electromotor are made, the mechanical cutting power cannot be obtained, because they are different physical processes. However, determination of electricity power is relatively simpler. Therefore, both powers are determined in the study, in order to evaluate coherence between them. Computer numerical control machine was used for climb-sawing of aspen (*Populus tremula* L.) wood with a circular saw. Mechanical cutting power was calculated from measurements of cutting force, but the electric ones – from measurements of current and voltage. As a result, changes of both powers and of specific cutting work, on what the analytical calculation of cutting power is based, were obtained depending on length of the cutting trajectory. It is found out, that mechanical cutting power is greater than electric power, and it is useful to use for the analytical calculation, based on determination of the specific cutting work, wear coefficient of the cutter that depends not only on the duration of work of cutter, but also on feed speed and the length of the cutting trajectory.
Key words: circular saw, sawing, cutting power, cutting force, specific cutting work, aspen.

Introduction

Several methods can be used for determination of cutting power – the direct and analytical ones. Most commonly used methods for direct determination of cutting power are based on measurement of electricity consumed by motor for drive of cutting tool. One of such methods is the determination of changes in the electrical current that has been consumed by an electrical motor (Barcík et al., 2010). The other method though compares the power of the electrical motor before and during the cutting process, resulting in a difference that indicates the power that has been consumed (Ābele and Miončinskis, 2012; Cristóvão et al., 2013). However, only electrical power can be determined by using these two above mentioned methods. Thus, they do not provide direct and accurate results, knowing that the cutting process is characterized best by the mechanical power.

For the direct determination of mechanical cutting power, the most accurate method is measurement of torque of drive spindle (Kováč and Mikleš, 2010; Svatoš et al., 2011), because thus it is possible to determine the resistance created by wood when cutter is deepening in the wood. Cutting power in this case is calculated according to such equation (1) (Kováč and Mikleš, 2010):

$$N_{gr} = \frac{2 \cdot 1000 \cdot M \cdot v}{D}, \quad (1)$$

where N_{gr} is cutting power, W. M is torque of spindle, N m. v is cutting velocity, m s^{-1}. D is diameter of cutting circumference, mm.

However, the use of this method is related to greater investments of financial resources, because costs of torque transducer are greater than, for example, of wattmeter, by what the electric power is determined. Thus, the measurement of electric power is economically more favourable, but, in order to apply this to the mechanical cutting power, it is necessary to determine correlation between them.

For the analytical calculation of cutting power, equation (2) is developed, which is based on the specific cutting work:

$$N_{gr} = \frac{K \cdot b \cdot H \cdot u}{60}, \quad (2)$$

where N_{gr} is cutting power, W. K is specific cutting work, J cm^{-3}. b is kerf width, mm. H is kerf height, mm. u is feed speed, m min^{-1}.

For calculation of equation (2), the specific cutting work is usually determined by the method of correction coefficients (Бершадский, 1967). However, this method is not perfect, because it does not include all factors, but evaluation of the included factors is often inadequate and unobjective. Other authors also point out this (Porankiewicz et al., 2011). One of factors, evaluation of what is restricted, is a wear of cutter, because the determination of it provided only depending on duration of work of cutting tool.

Basis on the above mentioned objective of the study is to determine correlation between the mechanical and electric cutting power, which can be used for direct measurements of power and to improve evaluation of wear coefficient of the cutter, which is provided for analytical calculation of the power.

The tasks are the following:

1. to measure mechanical and electric power and to determine interrelationships between those in the longitudinal sawing;
2. to develop equation for the coefficient of cutting tool wear that evaluates not only duration of work of cutting tool.

Materials and Methods

A multifunctional computer numerical control (CNC) machine with a separate drive mechanism of the circular saw 'Biese Rover 325' was used in this study. Parameters of the CNC machine are given in Table 1.

A unique circular saw has been designed for the experimental work (according to Ābele and Tuherm, 2013). The circular saw was produced by the cutting tool producer from Latvia – 'Nook Ltd.'. Cold-rolled steel 75Cr1 (according to LVS EN 10027-1:2005) was used for body manufacturing of the circular saw. Chemical composition of the 75Cr1 steel is the following: C 0.70 – 0.80%, Mn 0.60 – 0.80%, Cr 0.30 – 0.40%, Si 0.25-0.50%. Tips of the circular saw were made of tungsten cemented carbide K10 (according to ISO) and its chemical composition is the following: WC (tungsten carbide) 94.12%, Co 5.60%, other chemical elements 0.28%. The parameters of the circular saw are indicated in Table 2. This circular saw consists only of two teeth that are located on the opposite circumference points of the circular saw. Therefore, it takes less time to reach the prescribed load capacity for the saw teeth comparing to standard circular saws. This is characterized by an efficient cutting distance per tooth that is 10,000 m related to a single tooth of the circular saw.

Samples of aspen wood with a moisture content of 8 to 10% were used during the experiment work of the study. Climb-sawing was carried out by creating longitudinal kerfs next to each other on both wider sides of the wood sample, leaving 3 mm wide partition between the kerfs (Figure 1). Therefore, an enclosed cutting process was ensured for every kerf, what is a normal characteristic of sawing. Overall, ten kerfs were deposited in one wood sample (five on the one side and five on the other side). Kerfs were performed in depth of 24 mm what gives a 56.1 mm long length of the cutting trajectory for every rotation of the spindle. For the length of the cutting trajectory at one rotation of the spindle calculating the following equation (3) was used:

$$l = \frac{10^3 \cdot u}{n \cdot z} + \frac{\pi \cdot D}{360} \arccos\left(1 - \frac{2 \cdot H}{D}\right), \quad (3)$$

where l is length of the cutting trajectory at one rotation of the spindle, mm. u is feed speed, m min^{-1}. n is rotation frequency of spindle, min^{-1}. z is number of teeth of the circular saw. π is the constant ($\pi = 3.14$) D is diameter of cutting circumference, mm. H is kerf height, mm.

The total length of the cutting trajectory related to the one saw tooth was calculated by the following equation (4):

Table 1

Technical parameters of the computer numerical control machine

Characteristics	Value
Rotation frequency of spindle, min^{-1}	0…18000
Feed speed, m min^{-1}	0…60
Power of electromotor, kW	3.4
Electromotor power factor cos φ	0.85
Maximum processing length of the x-axis direction, mm	3000
Maximum processing length of the y-axis direction, mm	900

Table 2

Parameters of the cutting regime

Characteristics	Value
Diameter of cutting circumference D, mm	120
Body thickness s, mm	2
Kerf width b, mm	3
Clearance angle α, degree	35
Sharpness angle β, degree	40
Rake angle γ, degree	15
Cutting velocity v, m s^{-1}	50
Feed speed u, m min^{-1}	8
Rotation frequency n, min^{-1}	7958
Feed per tooth u_z, mm	0.503
Kerf height H, mm	24

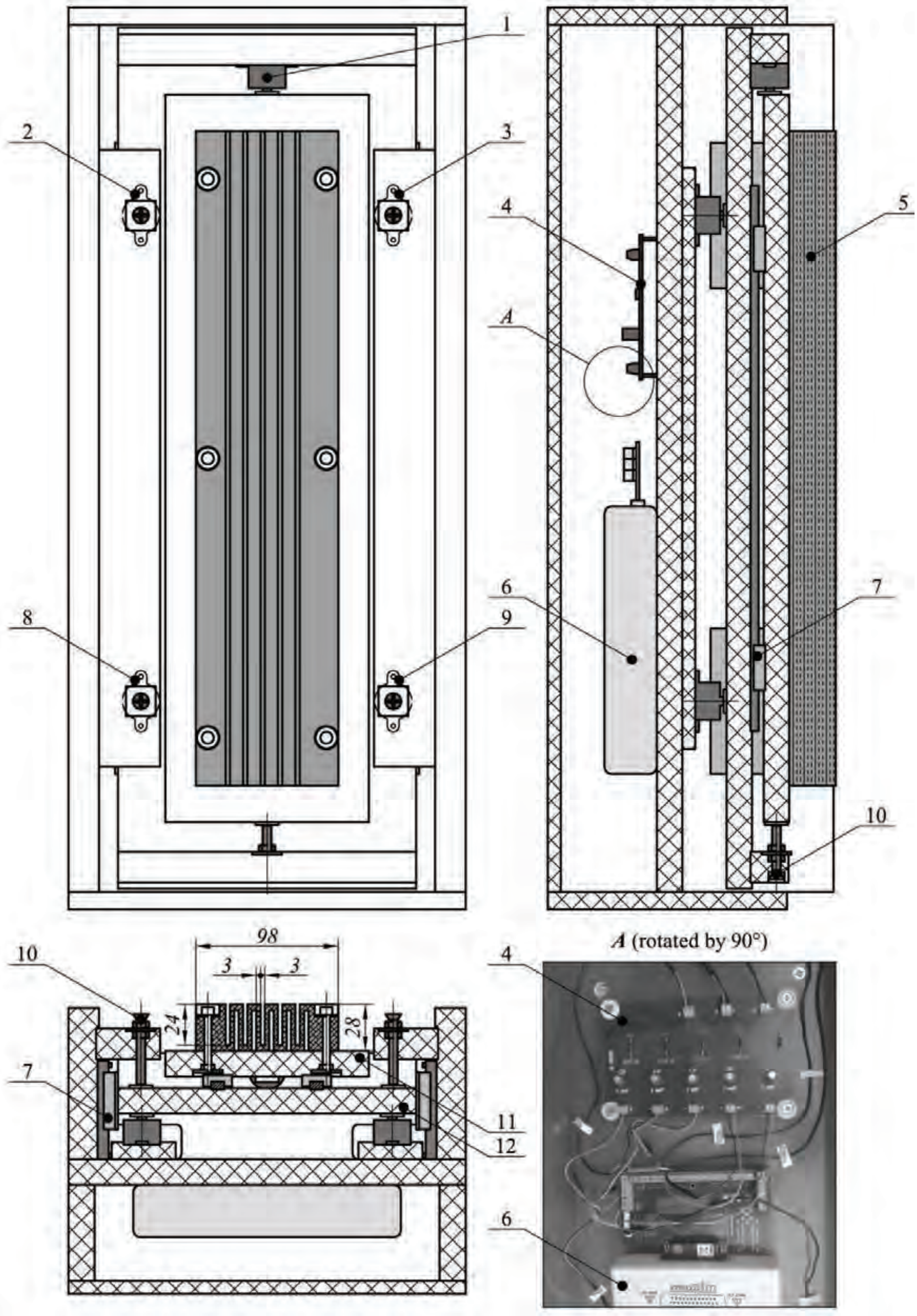

Figure 1. Cutting force measurement device.
1 – horizontally force sensor; 2, 3, 8, 9 – vertically force sensors; 4 – direct current ripple reduction filter; 5 – wood sample; 6 – data logger; 7 – linear guide rails; 10 – adjustment screws; 11 – horizontally movable platform; 12 – vertically movable platform.

$$L = \frac{l \cdot n \cdot l_p}{10^6 \cdot u \cdot z} \cdot m_{ie} \cdot m_p, \qquad (4)$$

where L is total length of the cutting trajectory, m. l is length of the cutting trajectory at one rotation of the spindle, mm. n is rotation frequency of spindle, min^{-1}. l_p is length of the wood sample (l_p = *450*), mm. u is feed speed, m min^{-1}. z is number of teeth of the circular saw. m_{ie} is number of kerfs in one wood sample. m_p is number of wood samples.

During the sawing samples of wood were fastened in a device of special construction (Figure 1) provided for determination of the cutting force. The device consists of two platforms; it is possible to move one of them in a horizontal direction, but the other one – in a vertical direction by the use of linear guide rails. Besides, the platform that can be moved horizontally was connected to the platform that can be moved vertically. Therefore, the sample of wood directly fixed on the platform that can be moved horizontally, can move both horizontally and vertically. For the measurement of force, there are mounted sensors of force 'Measurement Specialities™' FC22 (measuring range: 0 to 100 lbf) in the device; working of them is based on changes of voltage of supplied power depending on the force with what pressure is applied on the sensible surface. One of the sensors is located at the end of the platform that can be moved horizontally, but four force sensors are placed under the platform that can be moved vertically. There are adjustment screws located opposite to each sensor, with what platforms are pressed to the sensors. Thus, it is ensured that during cutting platforms are in continuous contact with the sensors and cannot move freely away from them, but at the same time a possibility of moving is given to them in the direction to the sensors, so that they could apply pressure to the sensible surfaces of sensors. Each sensor was connected to data logger PicoLog ADC-20 through terminal board by the use of single ended channels. Considering that only four sensors can be connected to the data logger, but it is necessary to carry out measurements with five sensors, vertically located sensors were connected in pairs (2 with 3 and 8 with 9; Figure 1), i.e., (+) terminal of one of sensors connected in a pair and (-) terminal of the other sensor connected in the same pair was connected to the data logger, but (-) terminal of the first sensor was connected to (+) terminal of the other sensor. Thus, one result of measurement is obtained from sensors connected in a pair. Three 5 V stabilized power supply modules are used for supply of sensors with input voltage – for one of sensors connected in each pair a separate power supply module is used, but for other sensors one common power supply module is used. Besides, the direct current ripple reduction filter is included in the electric circuit of each power supply of sensor. It consists of the resistor (270 Ω) connected in series circuit and capacitor (1000 μF) connected in parallel.

Direction of the cutting force vector for circular saws depends on its turning angle and therefore is not constant. Therefore, with the device of measurement of force, it is possible to state only vertical and horizontal components of the cutting force. The horizontally placed sensor registers the horizontal component of cutting force, but four vertically placed sensors – the vertical component of cutting force. The total value of the vertical component is obtained by summing of two results of measurements obtained from both pairs of vertical sensors. When sawing of wood sample is started, the cutter of circular saw applies greater pressure on the pair of vertical sensors placed closer to them. When the circular saw gradually moves further, it is applying more and more pressure on the other pair of vertical sensors, but pressure applied to the first pair diminishes, and at the end of cutting, the greatest force of pressure is already applied on the other pair of sensors. This means that the total component of vertical force is divided on both pairs of sensors.

Data logger transmitted the data registered by force sensors to computer, in what by use of software PicoLog Recorder results of performed measurements were stored in both characteristic curves and numeric data (spreadsheet). From obtained data the value of the resulting vector of the cutting force (5) and value of the mechanical cutting power (6) were calculated by the use of such equations:

$$P_{gr} = k \cdot \sqrt{P_{//}^2 + \left(P_{\perp 1} + P_{\perp 2}\right)^2}, \qquad (5)$$

$$N_{gr}^m = P_{gr} \cdot v, \qquad (6)$$

where P_{gr} is cutting force, N. k is conversion factor from lbf to N $(k = 4.448222)$. $P_{//}$ is horizontally component of cutting force, lbf. $P_{\perp 1}$ and $P_{\perp 2}$ are vertically components of cutting force, lbf. N_{gr}^m is mechanical cutting power, W. v is cutting velocity, m s^{-1}.

For the determination of consumed electric power of electromotor of cutting mechanism, measurements of voltage and current were used. Measurements of phase voltage were performed with analogue voltmeter ABB VLM1 (measuring range: 0 to 500 V, point value 20 V) only between one of phases and neutral, because star connection of the electromotor has a symmetric load. This means that voltage is equal between each of phase wires and neutral wire. For the measurement of current, sensors of electromagnetic loops were put around each of three line wires. Current was measured in line wires, because in star connection a line current is equal to the phase current. All three current sensors were connected with the data logger PicoLog CM3 that transmitted the registered data to computer, where they were processed by software PicoLog Recorder. Only differences of current between the consumed current during the cutting process and the consumed current during the idle running were used in calculations. The active electric cutting power was calculated by such equation (7):

$$N_{gr}^{el} = U_F \cdot (I_{L1} + I_{L2} + I_{L3}) \cdot \cos\varphi, \qquad (7)$$

where N_{gr}^{el} is electric power, W. U_F is phase voltage, V. I_{L1}, I_{L2} and I_{L3} are line amperages, A. φ is phase difference angle between voltage and current degree.

Specific cutting work was calculated by the following equation (8) (Marthy and Cismaru, 2009):

$$K = \frac{N_{gr}^{m} \cdot 60}{b \cdot H \cdot u}, \qquad (8)$$

where K is specific cutting work, J cm^{-3}. N_{gr}^{m} is mechanical cutting power, W. b is kerf width, mm. H is kerf height, mm. u is feed speed, m min^{-1}.

Regression was used for interaction's analysis between cutting power and length of the cutting trajectory because it is the most suitable for cutting process models (Naylor et al., 2012). According to F-test with a p-value (with software IBM SPSS Statistics 19) hypotheses about the significance of the regression equations were tested ($H_0 : \rho^2 = 0$, $H_1 : \rho^2 > 0$); but with p-value of t-test hypotheses about the significance of the regression coefficients $H_0 : \beta_1 = \beta_1^0$ were tested. P-value was compared with significance level $\alpha = 0.01$.

Results and Discussion

The diagram of changes of cutting power (Figure 2) indicates that cutting power evenly increases in the entire length of the cutting trajectory. This can be observed both for the mechanical and electric cutting power. In addition, both trend lines have very similar intensity of increase and essential dependence on length of the cutting trajectory ($p < 0.01$) what means that with one of them the other one can be explained. The most important difference that emerges between the mechanical and electric cutting power is their actual value. At the beginning of experiment, the mechanical cutting power is 1.11 times greater than the electric cutting power, but at the end of the experiment, this proportion is 1.34. These differences confirm the fact that by the measurement of the electric power, the true cutting power cannot be obtained.. It is possible to get the true cutting power only from measurements of the mechanical power, because they result directly from the cutting force. The power of electric energy consumed by the motor is only an indirect describer, but it can be simply determined. Therefore, in processes of longitudinal climb-sawing of aspen wood, in order to determine mechanical cutting power, if the electric power is known and if cutting regime corresponds to the regime used in the study, such equation (9) can be used:

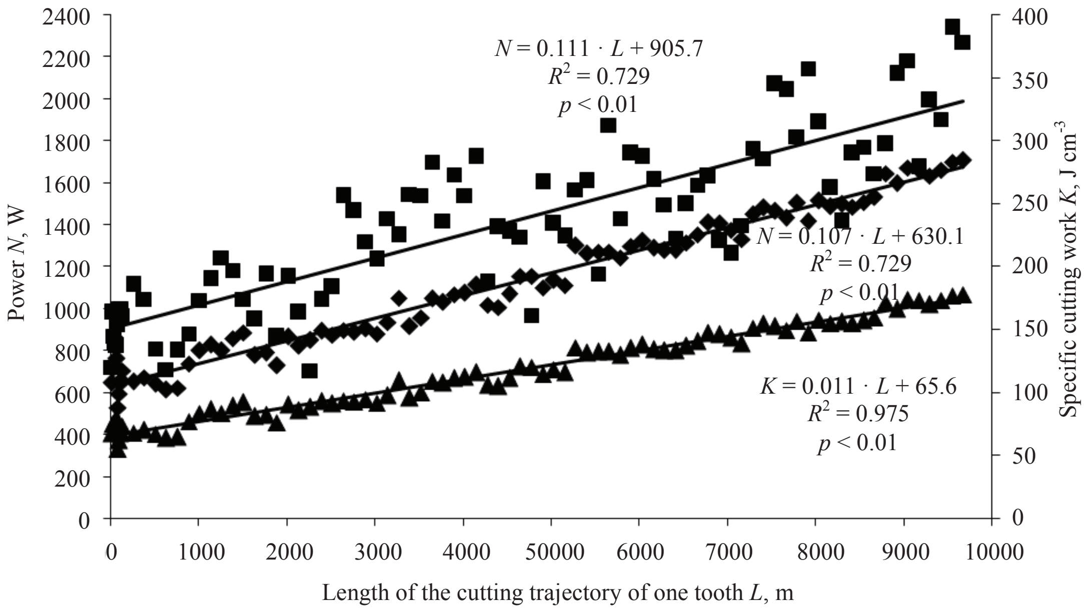

Figure 2. Cutting power and specific cutting work relative to length of the cutting trajectory.
◆ – mechanical cutting power; ■ – electric power; ▲– specific cutting work.

$$N_{gr}^{m} = \frac{N_{gr}^{el} \cdot (0.107 \cdot L + 630.1)}{0.111 \cdot L + 905.7}, \quad (9)$$

where N_{gr}^{m} is mechanical cutting power, W. N_{gr}^{el} is electric power, W. L is length of the cutting trajectory, m.

Unfortunately, changes of the cutting power do not allow distinguishing separate wear periods, because they have a linear character. Also in researches made by other authors, it is found out that the increase of the cutting force (influencing directly the cutting power) is linear (Axelsson et al., 1993). However, Bier and Hanicke, 1963 point out that changes of the cutting force are just the same as changes of rounding of cutting edge, and also those can be divided in three periods. The linear character of changes in this research could be explained by uneven density of wood samples to be processed that changed within the range from 400 up to 550 kg m^{-3}. However, also changes of index obtained by dividing values of cutting power with density of the corresponding wood sample indicate the same linear relationship.

When values of cutting power obtained as a result of measurement (Figure 2) are compared with the calculated ones (using equation 2), it is possible to ascertain that the measured power is greater than the calculated values. Similar tendencies are also observed in researches made by other authors (Aguilera and Martin, 2001). This indicates imperfections in calculation formulas, because equation for determination of the specific cutting work not only disregards mechanical properties and density of wood (as mentioned Porankiewicz et al., 2011), but also wear of cutter and cutting direction relative to feed direction, because studies have shown that climb-sawing require greater cutting power compared to counter-sawing (Cristóvão et al., 2013). The wear of cutter is characterized there with coefficient a_ρ depending on duration of work of cutter. However, duration of work of the cutter is a very relative index, because it depends on feed speed. Although the impact of feed speed on cutting power is less significant (Barcík et al., 2008) compared to cutting speed (although Naylor et al., 2013 points out that also cutting speed does not have an essential impact on cutting force, several other studies point out that it is a significant factor); nevertheless, it essentially affects the determination of the coefficient a_ρ by which the wear of cutter is evaluated. It can be explained by the fact that within the same time with a different feed speed, different length of the cutting trajectory can be achieved; therefore, a different wear of cutter will be caused, too. The value of the specific cutting work under particular circumstances of cutting regime is constant (Bučar and Bučar, 2002). Therefore, the increase of it depending on the length of the cutting trajectory (Figure 2) is caused by the impact of the wear of cutter. This means that in regression equation, $0.011 \cdot L$ is equivalent to the increase of coefficient a_ρ. Thus, for the improvement of accuracy of calculation of the specific cutting work, within the framework of the given cutting regime parameters, following equation (10) can be used, where the length of the cutting trajectory is replaced by an equal relationship formed by simpler determinable parameters of cutting regime – rotation frequency of cutting tool, length of the cutting trajectory at one rotation of the spindle and duration of work of cutter:

$$a_\rho = 1 + \frac{0.011 \cdot n \cdot l \cdot T}{65.6 \cdot 10^3 \cdot z}, \quad (10)$$

where a_ρ is a coefficient that evaluates the cutting tool wear. n is rotation frequency of spindle, min^{-1}. l is the length of the cutting trajectory at one rotation of the spindle, mm. T is duration of cutting tool work after sharpening, min. z is number of teeth of the circular saw.

The cutting power and coefficient, by which the wear of cutter is evaluated, are determined, while cutting regime parameters are constant. Therefore, in further researches, it is necessary to find out the impact of the other cutting regime parameters on them and also other coefficients for calculation of the specific cutting work that have been given in literature (Бершадский, 1967).

Conclusions

1. Mechanical cutting power obtained from measurements of cutting force is not equal to electric power obtained from measurements of current and voltage. Mechanical cutting power, when aspen wood is sawed, is 1.11 to 1.34 times greater than electric cutting power.
2. Specific cutting work changes that cause the wear of cutter, have essential dependence on length of the cutting trajectory ($p < 0.01$, $R^2 = 0.729$). Therefore, the coefficient for calculation of the specific cutting work, by which the wear of cutter is evaluated, can be determined by the developed formula (10) that includes not only duration of work of cutter after sharpening, but also other cutting regime parameters.

References

1. Aguilera A., Martin P. (2001) Machining qualification of solid wood of *Fagus silvatica* L. and *Picea excelsa* L.: cutting forces, power requirements and surface roughness. *Holz als Roh- und Werkstoff*, 59(6), pp. 483 – 488.
2. Axelsson B.O.M., Lundberg Å.S., Grönlund J.A. (1993) Studies of the main cutting force at and near a cutting edge. *Holz als Roh-und Werkstoff*, 51(2), pp. 43 – 48.
3. Ābele A., Miončinskis U. (2012) Parameter changes which characterize the wear of the cutting tool in the milling process of aspen wood. *Pro Ligno*, 8(3), pp. 74 – 88.
4. Ābele A., Tuherm H. (2013) Research methodology of cutting processes of aspen wood. In: Gaile Z., Zvirbule-Bērziņa A., Arhipova I., Assouline G., Ciproviča I., Bāliņa S., Kaķītis A., Dumbrauskas A., Jansons Ā. (eds) Research for Rural Development 2013. *Annual 19th International Scientific Conference Proceedings*, Volume 2, Latvia University of Agriculture, Jelgava, Latvia, pp. 88 – 94.
5. Barcík Š., Kminiak R., Řehák T., Kvietková M. (2010) The influence of selected factors on energy requirements for plain milling of beech wood. *Journal of Forest Science*, 56(5), pp. 243 – 250.
6. Barcík Š., Pivolusková E., Kminiak R. (2008) Effect of technological parameters and wood properties on cutting power in plane milling of juvenile poplar wood. *Drvna industrija*, 59(3), pp. 107 – 112.
7. Bier H., Hanicke P. (1963) Die spezifische Schnittkraft als Funktion der Schneidenabstumpfung beim Fräsen (The specific cutting force as a function of blunt cutting during milling). *Holztechnologie* 4(2), S. 158-162. (in German).
8. Bučar B., Bučar D.G. (2002) The influence of the specific cutting force and cross-sectional geometry of a chip on the cutting force in the process of circular rip-sawing. *Holz als Roh- und Werkstoff*, 60(2), pp. 146 – 151.
9. Cristóvão L., Ekevad M., Grönlund A. (2013) Industrial Sawing of *Pinus sylvestris* L.: Power Consumption. *BioResources*, 8(4), pp. 6044 – 6053.
10. Kováč J., Mikleš M. (2010) Research on individual parameters for cutting power of woodcutting process by circular saws. *Journal of Forest Science*, 56(6), pp. 271 – 277.
11. LVS EN 10027-1:2005 *Designation systems for steels - Part 1: Steel names*, 25 p.
12. Marthy M., Cismaru I. (2009) Experimental study concerning the power consumption at the milling of pear wood. *ProLigno*, 5(3), pp. 47 – 52.
13. Naylor A., Hackney P., Perera N., Clahr E. (2012) A Predictive Model for the Cutting Force in Wood Machining Developed Using Mechanical Properties. *BioResources*, 7(3), pp. 2883 – 2894.
14. Naylor A., Hackney P. (2013) A Review of Wood Machining Literature with a Special Focus on Sawing. *BioResources*, 8(2), pp. 3122 – 3135.
15. Porankiewicz B., Axelsson B., Grönlund A., Marklund B. (2011) Main and normal cutting forces by machining wood of *Pinus sylvestris*. *BioResources*, 6(4), pp. 3687 – 3713.
16. Svatoš M., Kopecký Z., Rousek M. (2011) Effects of the technology of machining on the surface quality of selected wood. *Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis*, 59(6), pp. 329 – 336.
17. Бершадский А.Л. (1967) *Расчет режимов резания древесины* (*Calculation of wood cutting regimes*). Издательство Лесная Промышленность, Москва, 176 с. (in Russian).