Methods of determining cutting forces during woodcutting

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Abstract: *Methods of determining cutting forces during woodcutting.* In this paper basic methods of determining the woodcutting forces, which underwent modification with the progress resulting from research of the process are presented. The methods were divided into two groups: the classic approach and an innovative approach using fracture mechanics, which take into account the different properties which affect the cutting process. The classic method based on the specific cutting resistance and also a new approach which bases on modern fracture mechanics, in which the effect of fracture toughness of the machined material is taken into account, are characterised.

Keywords: wood, cutting force, specific cutting resistance, toughness fracture

INTRODUCTION

The methods of woodworking by cutting undergoes changes within the space of years. The modifications enclose also the tools. This development is caused by intention to restrict waste of raw material, loss of energy and increase accuracy of dimension [1 Orlowski]. The continuous development of woodcutting's technologies is accompanying by the new more adequate to actual conditions methods of cutting forces determining. The almost all of them are based on specific cutting resistance k_c [MPa]. Some, as this presented by Orlicz (1988), was elaborated a few decades ago, but in some cases are the best choice. The others, more high-tech are based on contemporary fracture mechanic, which includes specific work of surface formation R [J/m^2] [3 Atkins]. Orlowski (2003) suggested some modification to the method of determining of the specific cutting resistance formulated by Orlicz (1988) and proposed instead of the classical cutting resistance a new coefficient called a surface-friction cutting resistance. It is especially useful for determination of cutting forces and cutting power consumption during woodcutting with narrow kerf saws.

Nomenclature	
A_D	cross- sectional area of the cut [mm^2]
F_C	cutting force, parallel to the cut surface [N]
F_V	thrust force (passive), do F_C [N]
F_S	shear force, [N]
S_t	kerf (overall set, width of cut) [mm or m]
R	fracture toughness, specific work of fracture [J/m^2]
Q	friction factor [-]
c_r	coefficient taking into account a kind of wood [-]
c_w	coefficient taking into account a moisture content of wood [-]
c_δ	coefficient taking into account a cutting angle [-]
c_g	coefficient taking into account a chip thickness [-]
c_s	coefficient taking into account a dulling of the tool [-]
c_t	coefficient taking into account a wood temperature [-]
c_v	coefficient taking into account a machining velocity [-]
c_k	coefficient taking into account a dimensions and a shape of cutting edge [-]
c_n	coefficient taking into account a pressure on wood in front of a cutting tool [-]
c_f	coefficient taking into account a wood-cutting edge friction effect [-]
f_z	feed per tooth (uncut chip thickness, depth of cut) [mm]

k_c	specific surface cutting resistance [MPa]
k_φ	basic value of specific surface cutting resistance taking into account a positions of machining with reference to grain direction [MPa]
t_o	uncut chip thickness (depth of cut) [mm]
Φ_c	orientation of primary shear plane with respect to cut surface [°]
β_μ	friction angle given by $\tan^{-1}\mu = \beta_\mu$, [rad]
γ	shear strain along primary shear plane [-]
γ_f	tool rake angle (measured form the normal to the cut surface) [°] or [rad]
μ	coefficient of Coulomb friction on rake face of tool [-]
τ_y	shear yield stress along primary shear plane [Pa]
φ_r	directional angle of a work movement [°]
φ_k	directional angle of a cutting edge [°]
φ_k	directional angle of a chip thickness [°]

CLASSICAL APPROACH

The forces during woodcutting are usually determined in a function of specific surface cutting resistance. One of the method of evaluating is based on its experimental values determined in defined conditions of both the flank surface and the rake during machining with elementary cutting tool and the corrective factors taking deviation from the basic conditions into consideration.

$$k_c = c_r \cdot c_w \cdot c_\delta \cdot c_g \cdot c_s \cdot c_t \cdot c_v \cdot c_k \cdot c_n \cdot c_f \cdot k_\varphi \tag{1}$$

This method was diffused by Manžos and Orlicz [2 Orlicz]. The literature announces the values of specific surface cutting resistances for three main directions (fig. 1): transversal $k_{\neq}$, longitudinal $k_{\shortparallel}$ and perpendicular $k_\perp$.
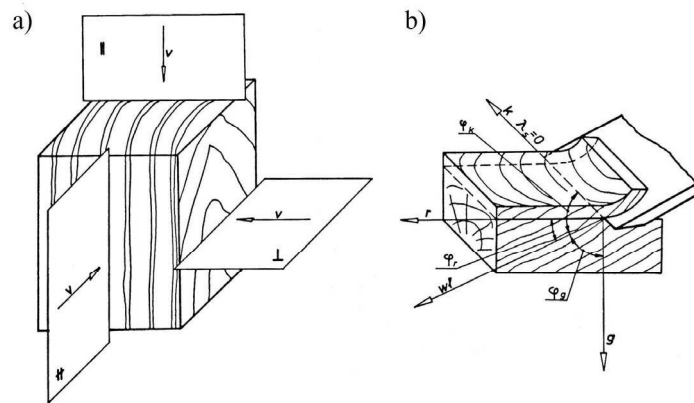

Fig. 1. The main directions of cutting edge (a) and the directional angles defined its position (b) [2 Orlicz].

In order to determine the value of specific surface machining resistance in any direction of cutting edge it is necessary to use the equation [2 Orlicz]:

$$k_\varphi = k_\neq \cdot cos^2\varphi_r + k_\shortparallel \cdot cos^2\varphi_k + k_\perp \cdot cos^2\varphi_g \tag{2}$$

The cutting force per one saw's cutting edge is determined as:

$$F_c = k_c \cdot A_D \tag{3}$$

The presented method is fully tabled and was successfully applied by Gorski (2001), who studied the woodcutting process with the chain electric saw.

The way to determine cutting forces elaborated by Orlicz (1988) takes into consideration only phenomena on the primary cutting edge. However, during woodcutting also seconadary cutting edges take part in the process, what is especially noticeable during machining by using thin saws. The preliminary researches carried out by Orlowski (2003) recommended taking in this case the new model of specific cutting resistance, so-called surface-friction cutting resistance. The specific surface cutting resistance on the primary cutting edge k_{cS} and the specific surface cutting resistance on the secondary cutting edges $2k'_{cS'}$ are its components. They are closely connected with the length of the cutting edge, so a relationship on specific surface-friction machining resistance has the form:

$$k_{c\mu} = k'_{cS} \cdot S_t + 2k''_{cS'} \cdot f_z \tag{4}$$

Presented in Eq. (4) specific resistances per the unit length of the primary cutting edge (k'_{cS}) and the secondary cutting edge ($k''_{cS'}$) are engaged in sawing process in defined changeability range of analyzed factors [1 Orlowski].

AN APPROACH WITH FRACTURE TOUGHNESS APPLICATION

Many years of experimental research in cutting both wood and other materials carried out by Atkins'a (2003, 2005, 2009), gave a rise to the conclusion that the forces occurring in the process of cutting depend not only on the blade geometry and basic material properties, but at a large extent on the processes related to fracture mechanics. Fracture toughness R [J/m2] is a property which represents the fracture mechanics in this approach [3, 6 Atkins]. Fracture toughness is also known as - the energy needed to produce a unit crack surface during cutting (the critical energy release rate) [7 Ashby and Jones].
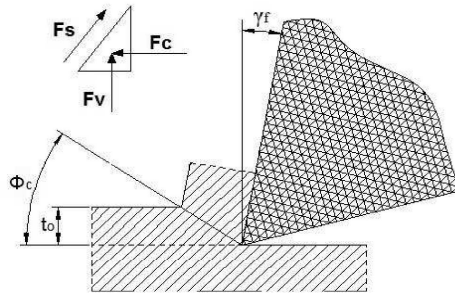

Fig. 2 Simplified geometric model of the cutting zone (Atkins, 2009).

Atkins (2003) using the original equation of Ernst-Merchant (describing the angle of shear), based on the results of their research, and additionally assuming a rectangular arrangement of the cutting tool (fig. 2) developed an equation of forces acting in the cutting process [3, 5, 6 Atkins]. The usefulness of this new model in the application to narrow-kerf saw blades in the case of wood sawing was studied by Orlowski and Atkins (2007). Cutting force can be in this approach described as follows:

$$F_c = \frac{\tau_y \cdot \gamma \cdot S_t \cdot t_0}{Q} + \frac{R \cdot S_t}{Q} \tag{5}$$

where Q is the correction factor of friction conditions, described by the relationship:

$$Q = \left[1 - \frac{\sin \beta_\mu \cdot \sin \Phi_c}{\cos(\beta_\mu - \gamma_f) \cdot \cos(\Phi_c - \gamma_f)} \right] \tag{6}$$

And γ - shear strain along the shear plane, is:

$$\gamma = \frac{\cos \gamma_f}{\cos(\Phi_c - \gamma_f) \cdot \sin \Phi_c} \tag{7}$$

And eventually Φ_c is the angle of shear plane with respect to cut surface, which could be determined in the simplified approach with the Ernst-Merchant equation:

$$\Phi_c = \left(\frac{\pi}{4} \right) - \frac{1}{2} \cdot \left(\beta_\mu - \gamma_f \right) \tag{8}$$

However, in fact Φ_c is a complex function in which also raw material properties such as fracture toughness R and shear yield stress along primary shear plane τ_y are involved [3, 6 Atkins], and may be calculated only numerically [9 Orlowski and Ochrymiuk].

CONCLUSIONS

The methods for determining the cutting forces presented in this paper have shown the gradual development of this issue. Nevertheless up till now a classical approach to determining cutting forces is still the most popular method. On the other hand, both Orlowski (2003) and Atkins (2003) by developing their models based on the results of experimental studies, developed the basic relationships, by widening the group of properties having a significant impact upon the process of cutting force estimation, in the case of Atkins also to other machining processes. The new models are not as popular as the classic ones, but with the emerging research findings further confirming its validity, could be an effective tool to determine the energetic effects of the wood cutting process.

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Streszczenie: *Sposoby określania sił przy przecinaniu drewna.* W artykule przedstawiono podstawowe metody określania sił przy przecinaniu drewna, które ulegały modyfikacjom wraz z postępem wynikającym z badań nad tym procesem. Przedstawione metody podzielono na dwie grupy: podejście klasyczne oraz nowatorskie podejście z zastosowaniem mechaniki pękania, które uwzględniają różne własności mające wpływ na proces przecinania. Podejście klasyczne reprezentują metody opierające się na właściwym powierzchniowym oporze skrawania, podczas gdy w nowym ujęciu opartym na mechanice pękania uwzględnia się wpływ wiązkości materiału obrabianego.

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