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EXPERIMENTAL AND THEORETICAL METHOD OF DETERMINATION OF LOADS FOR CUTTING UNITS

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ABSTRACT

The paper presents assumptions which allow determination of energy demand of a machine which uses a simple guillotine cutting of a specific material of low elasticity e.g. soft wood. A simple manner of experimental determination of cutting resistance and a coefficient which characterizes properties of material and a cutting device has been suggested. A numerical value of coefficient was determined based on the principle of maintaining mechanical energy and the principle of labour and mechanical energy balance. Based on the determined coefficient, average load and the power of a cutting unit of a shredder for energy willow were determined.

Introduction

From the beginning of its existence, a man had to deal with cutting biological material (plants and animals). Cutting was used during construction of houses, hunting, preparation of food and waging wars. Having no knowledge on theory of cutting, a man constructed various tools designated for cutting a material. Supposedly, a stone knife was the first tool. By means of intuition and experiments he determined that cutting ability depends on the degree of sharpening a tool and its efficiency on the blade speed. Speed of movement of the blade could be enhanced by placing it at the end of a lever. Thus, tools, which are still used nowadays, were constructed: a scythe, a poleaxe, a chopper, an axe. Cold steel – e.g. swords and sabres, is a variety of these tools. Light blades e.g. scythes, light swords, sabres were used for cutting relatively soft materials, and for cutting hard materials heavy blades were necessary, e.g. axes, halberds, heavy swords which were able to cut the warrior's armour. Today, one may say that it was practically and theoretically justifiable. Rotating blades in today's chaff-cutters, buzz-saws, milling machines or blades mowing with translational motion in bandsawing machines and chain saws use the oldest known property, according to which efficiency of cutting depends on the speed of cutting. Energy is necessary to perform any work. In case of cutting soft materials, high resistance of a blade was unnecessary. The required energy of cutting was obtained by placing a blade in high speed, which in case of small mass was possible (e.g. swords). Whereas, in case of cutting hard materials, resistance of a blade needed to be higher, therefore, more massive and heavier tools placed on longer handles were used in order to place a tool in appropriate speed (e.g. axes, halberds). Practice proves that efficiency of a light axe is low. In other words, kinetic energy of movement of a cutting tool decides on the efficiency of cutting, which depends on the square of the tool speed and its mass.

Cutting biological materials is the most frequently performed activity in direct food production – e.g. cutting fruit, vegetables, meat and indirect – e.g. grass, straw. Although, this activity is popular, no general theory of cutting plant materials, which would allow determination of basic geometrical, kinematic and dynamic parameters, e.g. such as; dimensions of a tool, speed of the tool's motion, values of forces related to cutting depending on kinematic parameters have been yet developed. In many works, attempts to describe mathematical phenomenon of cutting limited to a selected cut material (meat, stalk of a plant) and a cutting tool were made (Diakun, 1985; Dowgiałło, 2002; Żuk, 2007). As soon as at the stage of determining the forces necessary to cut a specific material, problems with determination of parameters which influence its value, occurred. Mutually exclusive theories and opinions were formulated, with which it is hard to agree, e.g. in Kanafojski's work (Kanafojski, 1980) a statement was made that at cutting plants, cutting resistance and the value of work do not depend on the size of the obtained area of cross-section. Based on the so-called Goriaczkin's formula, which determines a unit pressure of the blade length p made on material as a function of speed of perpendicular cutting v_{on} and contact cutting v_{ot} one may assume that the force of infinite value is needed.

Any of the known computational models of cutting resistance is not enough precise to be applied in the process of designing a processing machine (Dowgiałło, 2002). It seems that construction of a general model of cutting is impossible since the phenomenon itself is difficult to be mathematically described on account of depending on many parameters and factors. Impact on energy demand depends on the type and variety of the cut material which has a wide range of properties such as hardness, elasticity, viscosity, anisotropic properties and the type of a cutting tool, its geometry of the cross-section of a blade and geometry of the blade line.

Description of the phenomenon which depends on many parameters is very difficult and frequently even impossible. Then, simplified and experimental methods are used.

In this paper a simple way of experimental determination of a coefficient was used, which characterizes resistance of cutting of the selected material with a specific cutting tool. The principle of maintaining mechanical energy and the principle of equivalence of work and mechanical energy was applied. A simple guillotine cut (perpendicular) was assumed. Then, based on the determined coefficient, the course of loads for an exemplary cutting unit of a shredder for energy willow was determined.

Experimental determination of the cutting resistance coefficient

Oppositely to shear strength, the determined size was called a coefficient of cutting resistance because it describes stresses, which are formed during cutting a material with a specific cutting tool. Coefficient of cutting resistance is determined on a simple research position which operates similarly to a known Charpy's single-blow impact testing machine, differing only with the material of the pendulum arm, which is made of a light material. A knife is mounted at the end of an arm – figure 1. Due to the fact that the mass of a pendulum is focused at the end of an arm is considered as mathematical. The knife blade line is horizontal and at the same time perpendicularly to the motion plane of the pendulum that is a simple guillotine cut is performed. A sample of the tested material of a rectangular cross-section is mounted immobile at the place of placing a balance for a pendulum. Following a hit from a given angle, a depth g_w and width b_w of the knife cut into a tested sample is measured.

The research position is assumed to be designated for determination of an approximate cutting resistance of a specific material with a knife used in a specific machine which cuts layers of materials of a given thickness g_w. Then, deflection of a pendulum increases gradually as to the moment of cutting the whole layer. In case, when the kinetic energy is too low at the moment of hit for the maximum deflection (horizontal location of an arm), the increase of potential energy is possible by adding an additional mass at the end of the pendulum.

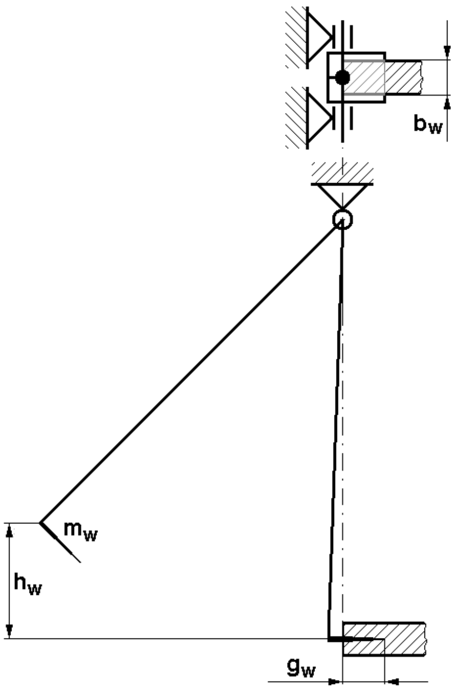

Figure 1. Schematic representation for determination of the cutting resistance coefficient

Theoretical bases

It is known that the force necessary for cutting a material depends directly proportionally on the cut cross-sectional area. To cut the material, the condition must be met (Wolny, 2002)

$$\tau_t = \frac{F_w}{s_{mt}} \geq k_{mt} \tag{1}$$

where:
F_w – force necessary to cut material, in the section plane (N),
k_{mt} – resistance of material to shear (MPa),
s_{mt} – area of the cut cross-section (m^2),
τ_t – shear stress at shearing (MPa).

The above condition assumes that in the moment of shear, the whole area of the cut cross-section is moved at the same time, i.e. the whole cross-sectional area is displaced. During cutting material with a knife the whole cut cross-section is dislocated. In case of a static pressure of a knife on the loose cut material, movement of a knife through a material will start at the moment of exceeding admissible pressures of the cut material through an area of a pressing knife, which is difficult to be determined, that is a cut material is subject to surface pressure. It may be assumed that after exceeding the strength to surface pressure, a knife will "flow" through the cut cross-section but also in this case the force necessary for cutting will increase along with the thickness of the cut layer of a material – figure 2.

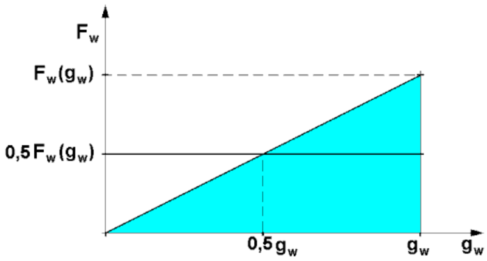

Figure 2. The course of the cutting force as a function of the thickness of the cut layer

The following dependence expresses the performed work of cutting a layer of a rectangular cross-section

$$W_w = 0.5 F_w g_w \tag{2}$$

where:
g_w – thickness of the cut layer (m),
W_w – work necessary to cut material (J).

that is after including dependence (1) we will obtain

$$W_w = 0.5 k_{mt} s_{mt} g_w = 0.5 k_{mt} b_w g_w^2 \tag{3}$$

where:
b_w – active length of a knife (width of a sample) (m).

From the principle of the performed work and energy the following is obtained

$$W_w = E_w = g m_w h_w \tag{4}$$

where
E_w – energy of cutting (J),
g – gravitational acceleration (m·s^{-2}).

thus, a coefficient of strength of shear with a specific knife may be determined according to the dependence.

$$k_{mt} = \frac{2 g m_w h_w}{b_w g_w^2} \tag{5}$$

The force necessary to cut material based on (1) may be determined according to the dependence.

$$F_w = k_{mt} b_w g_w \, . \tag{6}$$

Determination of machine loads

Material for shredding energy willow is fed by two rotating shafts (3) between a counter-cutting edge (2) and mobile blades placed along the element of the rotating shaft (1) – figure 3 driven by an electric motor.

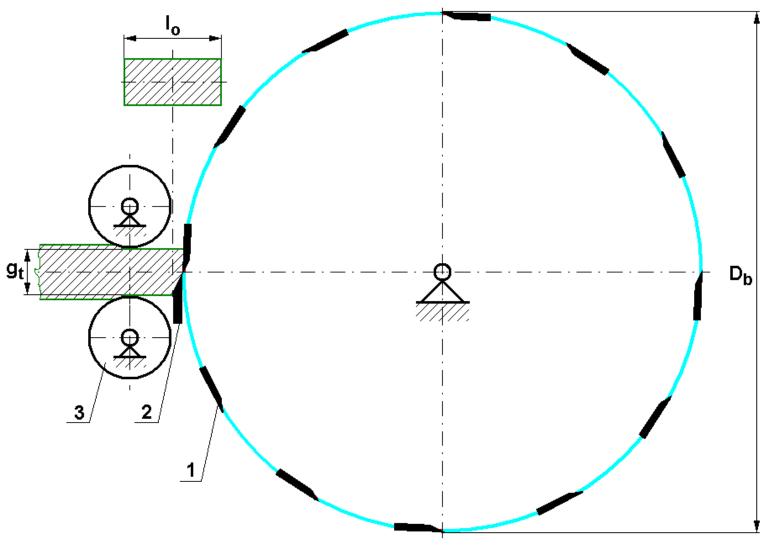

Figure 3. Schematic representation of a shredder for energy willow

Total work of cutting forces of blades placed at the circumference of a drum including a counter-cutting edge

$$W_{to} = \pi D_b F_{ts} = 0.125 k_{mt} l_o g_t^{\,2} z \tag{7}$$

where:
- D_b – diameter of a drum (m),
- F_{ts} – average cutting force (N),
- g_t – thickness of the cut layer (m),
- l_o – length of the active blade (m),
- W_{to} – work of cutting forces at the circumference of a drum (J),
- z – number of blades at the circumference.

thus, the value of average cutting force may be expressed with the dependence

$$F_{ts} = \frac{k_{mt} l_o g_t^{\,2} z}{8\pi D_b} \tag{8}$$

whereas, the moment of forces loading a driveline

$$M_t = 0.5 F_{ts} D_b = \frac{k_{mt} l_o g_t^{\,2} z}{16\pi} \tag{9}$$

Required minimum power of the driving motor

$$N_t = F_{ts} v_t = \frac{k_{mt} l_o g_t^{\,2} z \omega_s}{16\pi} \tag{10}$$

or

$$N_t = F_{ts} v_t = \frac{k_{mt} l_o g_t^{\,2} z n_s}{480} \tag{11}$$

where:
- M_t – moment of forces loading the driveline (N·m),
- N_t – power of the driving motor (W),
- n_s – rotational speed of a drum (rot·min^{-1}),
- v_t – peripheral speed of a drum (m·s^{-1}),
- ω_s – angular velocity of a drum (rad·s^{-1}).

Numerical example

A pressed layer of shoots of energy willow of a rectangular cross-section and dimensions $b_w \times g_w$ = 0.1 m × 0.03 m was cut with a knife of similar geometry used in a machine for shredding energy willow. Total mass of a knife along with a load m_w=5 kg was placed at the end of the pendulum deflected to the value of h_w=1.5 m.

Based on dependence (5), the value of coefficient of the cutting resistance

$$k_{mt} = \frac{2gm_w h_w}{b_w g_w^2} = \frac{2 \cdot 9.81 \cdot 5 \cdot 1,5}{0.1 \cdot 0.03^2} = 1.64 \text{ MPa}$$

A shredder for energy willow, with knives in the number of z=12 placed at the circumference of the rotating drum of a diameter of D_b=0.5 m rotating with a rotational speed of n_s=500 rot·min^{-1}, cuts the layer of $l_o \times g_t$ = 0.2 m × 0.06 m.

Value of average cutting force based on dependence (8)

$$F_{ts} = \frac{k_{mt} l_o g_t^{\,2} z}{8\pi D_b} = \frac{1.64 \cdot 10^6 \cdot 0.2 \cdot 0.06^2 \cdot 12}{8\pi \cdot 0.5} = 1128\text{N}$$

The moment of forces loading the driveline based on the dependence (9)

$$M_t = 0.5 F_{ts} D_b = 0.5 \cdot 1{,}128 \cdot 0.5 = 282\text{Nm}$$

whereas the required minimum power of the driveline based on the dependence (11)

$$N_t = \frac{k_{mt}}{480} l_o g_t^2 n_s z = \frac{1.64 \cdot 10^6}{480} 0.2 \cdot 0.06^2 \cdot 500 \cdot 12 = 14.8 \text{ kW}$$

Conclusion

The value of the coefficient of cutting resistance physically describes relation between the energy of movement of the specific cutting tool and the obtained cross-sectional area. The coefficient may be described as a dynamic coefficient of cutting resistance since it was determined during dynamic (impact) cutting attempt. Depends on the type of cut material and geometry of a cutting tool, that is, it should not be compared to shear strength. The suggested method allows only approximate determination of average load and the power of the driveline of the cutting device. It may be used for initial determination of parameters of the machine at the design stage, because periodical changes of load, which occur during machine work, movement resistance in the driveline and dynamics of the movement of the knife drum were not included. The determined value of power is comparable to the power of engines used in this type of devices of similar dimensions and efficiency.

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DOŚWIADCZALNO-TEORETYCZNA METODA WYZNACZANIA OBCIĄŻEŃ ZESPOŁÓW TNĄCYCH

Streszczenie. W pracy przedstawiono założenia pozwalające na określenie zapotrzebownia energetycznego maszyny wykorzystującej proste cięcie gilotynowe określonego materiału o małej sprężystości, np. miękkiego drewna. Zaproponowano prosty sposób doświadczalnego wyznaczania oporów cięcia oraz współczynnika charakteryzującego właściwości materiału i narzędzia tnącego. Liczbową wartość współczynnika wyznaczono na podstawie zasady zachowania energii mechanicznej oraz zasady równoważności pracy i energii mechanicznej. Na podstawie wyznaczonego współczynnika, określono średnie obciążenie i moc zespołu tnącego rozdrabniarki do wierzby energetycznej.

Słowa kluczowe: cięcie gilotynowe, współczynnik oporu cięcia, praca cięcia, zespół tnący