Energy efficiency of rotary brush cutters

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Abstract. The paper is devoted to emergent issues of reduction of power consumption and increase of efficiency of machinery and equipment used to remove shrub weeds and trees as well as recycle cutting residues left in the course of clearing the area intended for future buildings, clearings, roadside zones. The paper deals with methods to determine the cutting resistance forces for typical cutting parts of rotary brush cutters widely used around the world. The paper also presents the results of experimental research of the functioning of some cutting parts and the analysis of their efficiency.

1. Introduction

The main task for mulchers, variously designed brush cutters, stump and branch shredders is to remove shrubs, trees, stumps, and cutting residues. In all cases, the operation of these machines is accompanied by large unit costs of energy and fuel. At the same time, it is not always optimal due to large energy losses because the working body is not designed to cut and mulch efficiently. This is why it is important to do the right decision when choosing the design of cutting parts — it increases the efficiency of the machinery. The analytical and experimental methods of research into cutting various wood materials can be used to solve this problem.

Wood with natural humidity is a complex anisotropic natural composite with cellular structure of the fibers [1]. The strength properties of wood during cutting are represented by the complex nature of compaction of a part of the material, shear and stretching of fibers, as well as processes of brittle fracture and plastic deformation [2]. To justify the parameters of rotary machinery, a mathematical model is required. This model should be based on a sufficiently accurate calculation of cutting resistance forces depending on the orientation of the wood fibers, its type, geometry, and the speed of the cutting parts.

There are three main focus areas aimed to study the process of cutting the wood-based materials. The results of these studies, in general or each one specifically, can give an idea of the loads on the working body of the rotary machine.

The first focus area includes studies on improving the quality of cutting wood and wood-based composites. Typically, to solve this problem, a high-speed cutting mode is used at relatively small tool feed values [3].

The second group includes studies of tool wear processes. Prediction of lifetime for cutting parts made of high-speed steel [4], carbide [5] is relevant not only for a woodworking tool but also for cutting parts of rotary machines designed to remove vegetation. Various service life-extending coatings of cutting parts are of particular interest in this area. Durability of cutting parts is just as
important when designing a machine as the load on them. Operational efficiency of the future machine depends on the highly balanced decisions.

The third group of papers studies how to determine cutting resistance forces and cutting energy efficiency for wood-based materials. The proposed calculated dependencies to determine cutting resistance forces [7] reflected the energy efficiency of cutting in the middle of the last century. Later, there appeared the refined formulas for determining cutting parameters [8] of wood, which were aimed mainly at the design of woodworking equipment.

Analytical determination of the energy efficiency of the wood destruction process while more complex models are created with the growth of computational possibilities allows to fully reveal the contact stresses in different areas of the cutter tooth and stresses in the material [9], but the developers prefer experimental methods because it is impossible to properly justify the parameters of the mathematical model.

Experimental study of loads on the cutting part is very important in practice, but it is impossible to conduct a full-factor study of cutting while keeping in mind anisotropic properties of wood, how the type of wood, humidity, geometric and speed values affect it. This is the reason why these studies can only describe the phenomena in a specific local region.

For example, it is interesting to examine the study results of the work process [10] the cutting resistance forces of which were determined while cutting the maple with a different chip thickness. These led to the graphs in polar coordinates. These graphs link the cutting forces with the direction of the wood fibers. A good visual assessment of cutting resistance could be done based on that. The cutting forces that appear during tool operation depend on the position of fibers in the material. The authors of [11] managed to obtain numerical values of these forces for ash, basswood and sugar maple at about 8% humidity. The studies were conducted on a cutter tooth with a 40 degrees rake angle.

The attempt to generalize the laws of cutting resistance forces in [12] depending on the thickness of chips to be cut, cutting angles, and type of wood also resulted in a number of useful dependencies. In [13], the influence of cutting resistance forces not only on the orientation of the fibers but also on cutting speeds.

The combined effect of cutting velocity and cutting angles was investigated in [14]. It shows the results of studying of transverse, longitudinal, and end woodcutting. The cutting resistance forces are significantly affected by speed, and by increasing cutting speed from 1 to 12 m/s, the cutting forces decrease. For all cases of cutting, the components of cutting resistance forces increase with the increase of the sharpening angle.

[15], which also has a certain practical value, presents the results of measuring the torque on the cutting machine shaft when using knives with different sharpening angles for shredding wood samples. The presented graphs allow to determine loads on the working device for three main material cutting planes. It has been determined that the torque on the machine shaft is linearly dependent on the feed rate.

As shown in [16], not only the angles in the cross-section of the cutting edge but also the shape of the blades can influence the value of cutting resistance forces. For example, using a parabolic knife instead of a cylindrical knife reduces cutting forces by 4 - 5 %.

Relatively simple methods can be used to estimate the energy efficiency of cutting various types of wood. The method proposed in [17] provides an opportunity to obtain energy characteristics of the cutting process on inexpensive equipment. The paper also shows the effects of different attack angles on forces and power during the milling. For the same purpose, to analyze the cutting resistance, the author of [18] suggests using the depth of penetration of a spherical indenter as an evaluation indicator.

The extensive experience gained by scientists in the field of woodcutting cannot be fully used for the design of rotary brush cutters. Given the complexity of the cutting and the specific design of the cutting parts of rotary brush cutters, it is advisable to experiment locally. These experiments should determine the components of the cutting resistance force when using cutter teeth of a given design.
2. Methodology of experiments

The main requirement for experimental equipment when preparing for the experiment is the most complete compliance with the actual working process. In addition, the equipment must be safe, easy to operate, and inexpensive.

Since the destruction process of wood material is largely determined by high energy losses, it is most expedient to use energy loss measurement during cutting with a single cutter tooth. A pendulum stand shows good results for studying cutting processes [19]. In addition, because this method is reliable, it is possible to use the pendulum stands for many other methods, including standard ones [20].

The pendulum stand developed for the experimental tasks (Fig. 1) is a frame structure on which a pendulum is suspended. An inertial element is installed at the end of the pendulum to change the impact energy. The cutting part is installed at the end of the pendulum to change the impact energy. The material is rigidly mounted on the bottom of the frame. One can change the cutting depth by changing the length of the pendulum.

When the pendulum passes through the cutting zone, a shield at an angle to the cutting plane enters the detection area of the laser sensor. This makes it possible to measure the cutting speed.

An accelerometer is also attached to the mount area of the cutting part to register the acceleration (deceleration) of the pendulum.

The operation of the stand is based on the law of energy conservation. In this case, the work of the cutting resistance forces \( A \) is equal to the change in the kinetic and potential energy of the pendulum:

\[
A = m_p \cdot g \cdot (h - h_0);
\]

where \( h_1 \) is the drop height at the extreme point;
\( h_0 \) is the maximum displacement height at the extreme point after impact;
\( m_p \) is the reduced pendulum mass;
\( g \) is the gravity acceleration.

Since the mass of the pendulum is not concentrated in the cutting zone of the material, it is necessary to determine the equivalent of the given mass. This equivalent is the reduced mass. The reduced mass is determined by the formula:

![Figure 1. Pendulum stand diagram.](image-url)
Where \( T \) is the pendulum period;
\( M \) is the first moment of the pendulum;
\( L_4 \) is the distance from pendulum hanging point to cutting zone.
\( T \) and \( M \) are determined experimentally, after the cutting unit has been installed and the cutting depth has been adjusted.

In the course of the experiment, cutting forces were obtained by exposing the cutter teeth to a sample of pinewood with a height of its section of 100 mm and a width of 40 mm (Fig. 2). Transverse and longitudinal cutting processes were studied. The pendulum was dropped from a height that provided an initial cutting speed of 7 m/s.

The teeth traditionally used in rotary bush cutters were used for the research, in particular, a cutter tooth with two titanium carbide and tungsten carbide inserts, a similar cutter tooth with one insert, and a disc cutting element (Fig. 3).
The main geometrical parameters of the cutting elements (tooth width, main front corner, rear corner) are presented in Table 1. The first two types of cutting elements are widely used in rotary brush cutters. The third type is considered promising because it does not require frequent sharpening, and the reduced front angle reduces the energy intensity of milling.

| No. | Type of cutting element | Cutting element width, mm | Cutting angles, deg |
|-----|-------------------------|----------------------------|---------------------|
| 1   | with two carbide inserts | 46                         | 85                  |
| 2   | with one carbide insert  | 22                         | 81                  |
| 3   | disc                    | 45                         | 40                  |

The experiments were repeated three times at each point. They were used to determine the horizontal component of the cutting resistance force at a depth of 2, 7, and 15 mm for the end and transverse cutting method.

3. Results

The diagrams (Fig. 4) show the results of the work of the tangential component of the cutting resistance forces for the transverse and end cutting of the material with the cutting element.

It shows that the cutting forces are zero when the thickness of the chips to be cut is also zero. The graphs show the corresponding points.

The results obtained indicate a nonlinear increase in cutting resistance forces and, consequently, in cutting forces as a function of chip thickness for all types of cutting elements. However, the values of these forces differ significantly from each other. In all cases, the energy intensity of end cutting of wood is more than twice the corresponding value for crosscutting.
Due to the fact that the cutting forces of a brush cutter are significantly impacted by the width of the tooth, which increases the amount of recycled material, it is necessary to compare the cutting performance of the cutting elements on specific indicators. This can include the ratio of the tangents of the cutting forces to the width of the cutting element:

\[ a = \frac{A}{b} \]  

Where \( b \) is the cutting element width.

The obtained results are shown in Figure 5, where the values do not differ so significantly.

4. Conclusions
The experiment established the energy characteristics of the working process of cutting wood material for different types of cutting parts. In terms of specific characteristics, the best result is achieved by using a disc cutting element.

The disc element of this design with small front angles is only made of different steel grades. This significantly limits their service life and will require frequent replacement. Knives made of high-speed grades of steel are used in practice in some rotary brush cutters, but the most common are cutter teeth made of titanium, tungsten, and cobalt carbides with significantly higher wear resistance.

In this case, a cutting element with one carbide insert can be recommended. The specific work for this tooth is higher than for a disc cutter tooth, but the high wear resistance gives way for more efficient use of the equipment during the work shift.

![Figure 5](image)

**Figure 5.** Specific work of cutting resistance forces at transverse (a) and end (b) cutting.

Cutting elements with two carbide plates, in spite of their wide application, proved to be the least effective in this experiment.

The special features of rotary brush cutters include the fact that the wood chips and fragments formed during the cutting are not only the result of it, but also the result of cracking and breaking. Such destruction is possible if the impact energy is high enough. Perhaps this is the reason why large cutting elements with two or more carbide inserts are used.

The obtained results can be used to predict loads on the cutting elements and, while using them in an adequate mathematical model, it should be possible to determine the drive power, calculate the structural elements for strength, reasonably predict the performance of equipment.
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