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Design rationale for a milling drum used in layer-by-layer surface milling of peat deposits containing wood inclusions

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Abstract

This article addresses the technological foundations and design requirements for developing a machine intended for layer-by-layer surface milling of stump-containing peat deposits. The issue is particularly relevant for small-scale enterprises employing adaptive peat production technologies, where traditional stump removal methods are economically and technically impractical due to high preparatory costs and the need for bulky equipment. The study aims to substantiate the design parameters of a milling machine capable of simultaneously comminuting peat mass and embedded wood inclusions without their preliminary extraction. This approach is intended to enhance production efficiency, improve product quality, and reduce negative environmental impact. The research tasks included analysing milling regimes, interaction between cutting elements and wood inclusions, and developing proposals for a drive system with increased reliability under variable loads. A comprehensive methodology was applied: generalisation of data on physico-mechanical properties of peat and wood, analysis of literary and experimental sources, and theoretical substantiation of cutting parameters and milling drum design. A dual-motor hydraulic drive configuration was considered, wherein an auxiliary motor is activated upon increased cutting resistance, ensuring stable machine operation under deposit heterogeneity. As a result, optimal parameters of the milling drum were substantiated (working width 4.5 m, diameter 0.335 m, rotational speed 149 s^{-1} , peripheral velocity 25 m/s, feed per knife 0.015 m), providing peat crumbs with a particle size fraction of 10–25 mm and comminution of wood to dimensions suitable for subsequent separation, peat processing, and waste utilisation. The proposed approach facilitates accelerated drying of peat crumbs under natural conditions, reduced waste volumes, and rational resource utilisation. It is concluded that the proposed design demonstrates high efficiency for operation at small peat deposits with areas up to 100 ha. The obtained results will be applied in the design of a prototype and further development of adaptive peat production technology.

Keywords

adaptive technology, layer-by-layer surface milling, embedded wood, peat, particle size distribution, milling machines, production efficiency

For citation

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ГОРНЫЕ МАШИНЫ, ТРАНСПОРТ И МАШИНОСТРОЕНИЕ

Научная статья

Инженерное обоснование конструкции фрезерного барабана для поверхностно-послойного фрезерования торфяных залежей с древесными включениями

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Аннотация

Технологические основы и конструктивные требования к созданию машины для поверхностно-послойного фрезерования пнистых торфяных залежей особенно актуальны для малых предприятий, применяющих адаптивную технологию производства торфа, где традиционные методы корчевки



экономически и технологически нецелесообразны из-за высокой стоимости подготовительных работ и необходимости использования громоздкой техники. Цель работы – обоснование параметров конструкции фрезерной машины, способной одновременно измельчать торфяную массу и погребённые в ней древесные включения без предварительного извлечения последних. В работе применён комплексный подход: обобщение данных по физико-механическим характеристикам торфа и древесины, анализ литературных и экспериментальных источников, теоретическое обоснование параметров резания и конструкции фрезерного барабана. В результате обоснованы оптимальные параметры фрезерного барабана: ширина захвата 4,5 м, диаметр 0,335 м, частота вращения 149 с^{-1} , окружная скорость 25 м/с, подача на нож 0,015 м, обеспечивающие получение крошки фракции 10–25 мм и дробление древесины до размеров, пригодных после сепарации для последующей переработки торфа и утилизации отходов. Предложенный подход позволяет вести добычу торфа на залежах с древесными включениями без предварительной корчевки, что снижает затраты на подготовительные работы и расширяет ресурсную базу малых предприятий.

Ключевые слова

адаптивная технология, поверхностно-послойное фрезерование, погребенная древесина, торф, фракционный состав, фрезерующие машины, эффективность производства

Для цитирования

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Introduction

Most peat producers currently operate on a relatively small scale, with production geared primarily toward local consumption [1]. In this context, study [2] demonstrated the need to develop and implement an adaptive peat production technology at peat sites of up to 100 ha. This requires the development of multifunctional machinery, including equipment capable of simultaneously milling the peat deposit and the wood inclusions embedded within it.

One of the main ways to reduce the cost of developing small peat sites is to develop mechanized equipment [3] capable of milling peat together with wood inclusions without prior stump removal. This approach opens up new opportunities for layer-by-layer surface milling of peat deposits to produce milled peat of a specified quality and ensure the efficient use of biogenic resources [4].

Milling establishes the process conditions for all subsequent production stages, including drying, harvesting, and processing of the milled peat [5]. Various types of peat milling machines are used for this purpose [6]. These machines are designed to operate under harsh conditions [7]. Innovative solutions in this area are technically feasible and economically viable and can support the sustainable development of small peat producers [8].

The aim of this study was to justify the design parameters of a milling drum capable of minimizing energy consumption while producing milled peat with a specified particle size distribution suitable for subsequent production and processing operations.

The objectives of the study were as follows:

1. To analyze published and experimental data on the physical and mechanical properties of peat and wood.

2. To justify the cutting parameters required to obtain milled peat particles in the 10–25 mm size range, which is considered optimal for subsequent production stages.

3. To develop design proposals for the milling drum and consider a dual-motor hydraulic drive configuration to improve reliability under variable loads.

The proposed approach builds on the research reported in [2] and will be applied in the design of a milling drum for operation in peat deposits with a high stump content under challenging peat extraction conditions.

Study rationale

The development of small peat deposits covering up to 100 ha requires economically viable solutions, since conventional stump grubbing is not justified because of its high cost and labor intensity [2]. Practical experience [9] shows that the use of high-capacity machinery at small deposits with limited working areas is inefficient: its full production capacity cannot be utilized, while the associated capital costs substantially increase the unit cost of production.

Simultaneous milling of peat and stumps embedded in the deposit eliminates the need for additional operations and avoids the cost of purchasing and operating numerous specialized machines. It also allows the same set of machinery to be used under different operating conditions, in accordance with the concept of adaptive technology [2].

The concept of continuous milling of a peat deposit together with wood inclusions was first considered in the mid-twentieth century [10]. However, it was not widely adopted because of technical limitations and the insufficient power of the tractors available at the time. Modern engineering solutions,



including a dual-motor hydraulic drive and optimization of the cutting-element parameters, allow this concept to be revisited and implemented under current operating conditions.

Layer-by-layer surface milling is a key operation on which all subsequent stages of the production process depend, including drying, spreading, harvesting, and utilization [5]. Milling quality directly affects the particle size distribution of the milled peat, the drying process, and the condition of the deposit surface after machine operation [3]. It is therefore essential to select cutting elements and milling parameters [4, 11] that produce a uniform milled peat spread and ensure effective comminution of the peat while simultaneously reducing the stumps to fragments no smaller than 10 mm, allowing them to be efficiently removed using standard separators.

Studies have shown that the specific energy consumption of wood milling is substantially higher than that of peat milling [4, 12]. A key optimization objective is therefore to reduce failures and overloads, which can be achieved using the dual-motor hydraulic drive proposed in [13]. The proposed machine should be mobile, cost-effective, and suitable for commercial production, as supported by studies on machinery design for small peat deposits [14]. It must also be suitable for peat extraction conditions, including operation under variable loads and in high-moisture environments. The interaction between the cutting elements and the heterogeneous medium is stochastic and therefore requires an adequate mathematical description of the cutting forces [15].

Current conditions therefore call for new engineering solutions that allow milling to be performed without prior preparation of the peat deposit. Such operations require robust and reliable equipment capable of withstanding variable loads while producing material in the specified particle size range.

Methodology

The study was based on an integrated analysis of the literature and synthesis of reliable data on the physical and mechanical properties of peat and wood. The available data were considered sufficient to justify the design parameters without the need for additional experimental studies.

A particle size range of 10–25 mm for the milled peat was adopted as the optimization criterion for the cutting conditions, since this range facilitates faster drying and efficient separation [16]. The resulting wood fraction can also be used as fuel [17]. Machines based on a similar operating principle – forestry mulchers – have demonstrated high efficiency in comminuting woody residues and stumps [18].

Mathematical modeling was used to determine the drum parameters from the following kinematic equations:

$$v_{per} = \frac{\pi D n}{60}, \quad s = \frac{v_f}{nz},$$

where v_{per} is the peripheral speed, m/s; D is the drum diameter, m; n is the drum rotational speed, rpm; s is the feed per knife, m; v_f is the forward speed, m/s; z is the number of knives.

To obtain the specified particle size range, the milling depth, feed per knife, drum peripheral speed, and the number and geometry of the cutting elements were calculated. The resulting values formed the basis for the milling drum design, which was intended to ensure consistent comminution of both the peat and the wood inclusions.

Results and discussion

The exploitation of small peat deposits of up to 100 ha is becoming increasingly important in many regions of Russia, as it helps meet local demand for peat used both as fuel and for agricultural purposes. The diversification of peat applications, primarily toward further processing that preserves some of its natural properties, has necessitated the development of new peat production machinery and technologies capable of producing material with the required particle size characteristics [2].

Layer-by-layer surface milling of a peat deposit is the first and key operation in the milled peat production cycle [2]. The quality of this operation largely determines the performance of the entire cycle, including drying time, peat yield per cycle, moisture content, and other properties of peat produced under natural field conditions [5]. The milling operation must therefore create a layer of milled peat that dries as rapidly as possible under the prevailing weather conditions. This is the primary technical requirement for the milling operation.

Milling quality is assessed by the particle size distribution of the resulting milled peat and its drying behavior during the production cycle [16]. Another important criterion is the condition of the production field surface after milling [19]. The particle size distribution of the milled peat is also influenced by the milling depth, peat deposit properties, and the peripheral speed of the cutter, which corresponds to the cutting speed [7]. An optimal peripheral speed of 25 m/s was established, providing stable fragmentation of the wood without excessive comminution of the peat.

The analysis showed that the 10–25 mm size fraction provides an optimal balance between drying rate and the efficiency of separating wood inclusions.

Particles of this size, spread in a layer 1–1.5 particles deep, exhibit the highest rate of moisture loss while offering minimal resistance to airflow [3, 5, 16]. Larger peat particles were found to dry more rapidly (Fig. 1), thereby reducing the time required to reach the harvesting moisture content.

A layer of fine particles dries more slowly than a layer of coarser particles because its smaller pores reduce the rate of moisture evaporation. Fine particles at the surface form a dense layer with low thermal conductivity, limiting the penetration of solar radiation into the underlying material and slowing the drying of the lower layers. The 10–25 mm size fraction therefore substantially improves drying efficiency and the reliability of the milled peat production process.

A properly formed milled peat spread is characterized by a uniform depth of the milled layer and

a homogeneous particle size distribution dominated by coarser peat particles [20]. For milled peat intended for agricultural use, a direct relationship has also been established between particle size and substrate properties, including air capacity and water retention [21]. The cutter design and knife geometry should therefore be selected to produce a particle size distribution favorable for drying in the spread layer while minimizing the spread nonuniformity coefficient.

Feed per knife is one of the principal parameters determining both the milling process and the design of the cutter elements [6, 7]. The proportion of the 10–25 mm fraction, (F_{10-25}), varies nonlinearly with feed per knife (Fig. 2). The maximum value of (F_{10-25}), reaching 58.3%, was obtained using straight knives of triangular cross-section at a feed per knife of 0.015 m [11, 20].

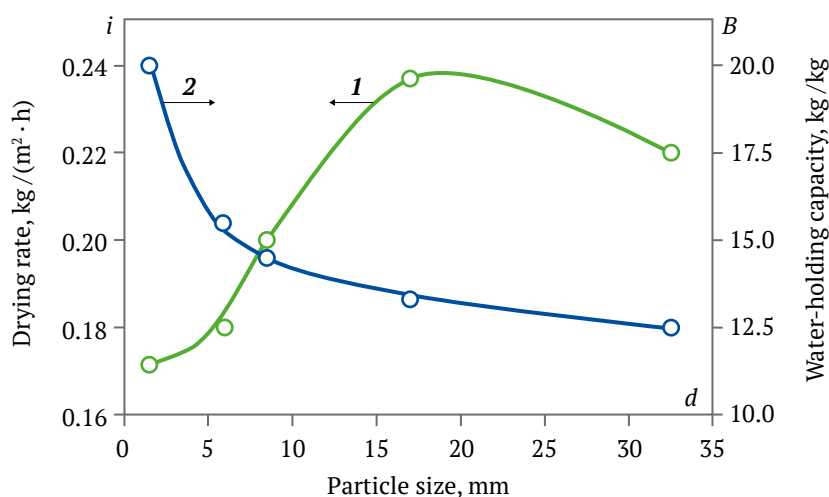


Fig. 1. Dependence of drying rate (i) and water-holding capacity (B) on milled peat particle size (d) [5, 20]

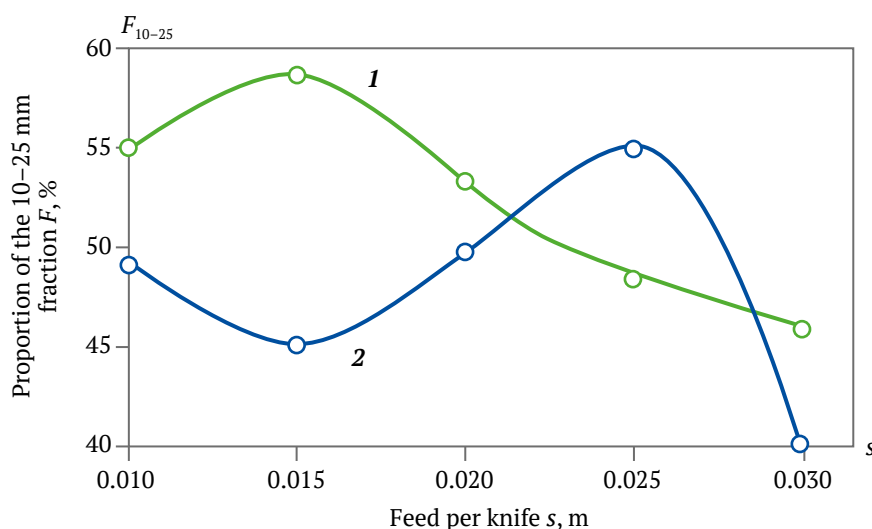


Fig. 2. Dependence of the proportion of the 10–25 mm fraction F_{10-25} in milled raised-bog peat on feed per knife s for milling drums fitted with straight knives of triangular cross-section (1) and longitudinal knives (2) [11, 20]



The difference in performance between straight and through knives is attributable to the physical processes involved in chip formation and in drawing the detached material through the gap between the cutter and the peat deposit. The quality of the milled peat spread depends on the type of milling equipment and the cutting elements fitted to it.

The specific energy consumption for peat milling ranges from 0.14 to 1.1 MJ/m³, whereas that for milling green wood is considerably higher, ranging from 12.6 to 14.4 MJ/m³ [4, 17, 22]. The mean specific energy consumption for milling peat together with stumps is 5.76 MJ/m³ [13], indicating that this process can be implemented without a substantial increase in energy demand. The separated wood fraction can be used as fuel. Thermal conversion of blended fuels based on peat and comminuted wood can yield biochar with favorable fuel properties [23]. In Europe, the replacement of peat with locally available biomass, including comminuted wood, is also being considered [24].

The most promising technical solution for layer-by-layer surface milling of a peat deposit together with stumps was proposed by M.I. Sarmatov [13] based on laboratory and theoretical studies. This work provided a justification for the cutter geometry and kinematic parameters and introduced a calculation model for determining the power required to drive the drum knives [25, 26]. Further developments were reported in [27, 28], which presented analytical relationships for calculating the increase in resisting torque when the cutter encounters a stump and for determining the active width of the cutter. These relationships were used to establish the optimal number and arrangement of knives on the drum and to justify the advantages of a continuous cutting edge.

Milling units with a larger working width are known to be less maneuverable, more material-intensive, and more labor-intensive to maintain [6, 29]. A working width of 4.5 m was therefore selected for the cutter. This width permits a whole number of passes across the production field, providing high productivity while maintaining sufficient machine maneuverability.

According to [30], the knife design, the material from which the knives are made, and their arrangement on the drum are critical to the efficient operation of the milling unit. The knives must be made of high-strength, wear-resistant materials suitable for the intended operating conditions [31]. This is particularly important when milling wood inclusions, which substantially increase cutting resistance.

The peripheral speed required to fragment the wood can be achieved either by increasing the drum rotational speed [32], which is subject to technical limitations, or by increasing the cutter diameter, which is a more practicable solution. Because the cutter mass is inversely proportional to the square of the peripheral speed, reducing its mass at a constant rotational speed requires an increase in cutter diameter [33]. Based on the design proposed in [13], the cutter diameter measured over the knife tips was set at 0.335 m.

The proposed machine is expected to employ a dual-motor hydraulic drive in which the second motor is automatically engaged when cutting resistance increases, for example when the cutter encounters a large stump [13]. This configuration is expected to improve operational reliability and reduce the risk of equipment failure.

The following key parameters should be adopted in designing a milling drum for layer-by-layer surface milling of peat deposits with a high stump content to obtain milled peat in the required 10–25 mm size range:

- working length of the drum, 4.5 m;
- cutter diameter measured over the knife tips, 0.335 m;
- drum rotational frequency, 149 s⁻¹;
- peripheral speed at the cutting edges, 25 m/s;
- feed per knife, 0.015 m;
- knife working height (milling depth), 0.020 m;
- knife working width, 0.025 m;
- number of cutting elements per cutting plane, 6;
- machine travel speed, 2.14 m/s;
- number of hydraulic drive motors, 2.

Promising directions for further development include the introduction of systems for monitoring and automated control of cutter operating parameters [34]. Further research should also investigate the use of composite materials for cutting elements capable of withstanding higher loads with minimal wear.

Conclusion

The engineering solutions presented in this article are aligned with current trends in mining technology aimed at improving the efficiency and environmental safety of mineral deposit development.

The study demonstrated the feasibility of developing a specialized milling machine for layer-by-layer surface milling of peat deposits with a high stump content. The identified design parameters and features of the milling unit will enable simultaneous comminution of the peat and wood inclusions, pro-



duction of milled peat in the 10–25 mm size range, and reliable equipment operation.

The key engineering solutions include a milling drum with the following optimal parameters: a working width of 4.5 m, a diameter of 0.335 m, a rotational frequency of 149 s^{-1} , a peripheral speed of 25 m/s, and a feed per knife of 0.015 m. These parameters ensure the required quality of the milled peat. The dual-motor hydraulic drive is expected to improve machine reliability and reduce the risk of equipment failure when the cutter encounters large stumps.

The study findings are of practical value and will be used to design a prototype for operation under actual field conditions at peat extraction sites. By

eliminating preliminary stump grubbing, the proposed design can reduce production costs and improve the environmental performance of the peat production process. Future work will focus on developing a prototype fitted with heavy-duty cutting elements made of composite materials and integrating load-monitoring systems to optimize operating parameters. The peat and comminuted wood produced during milling can be separated and subsequently used as feedstock for biochar production by pyrolysis, thereby broadening the options for waste utilization. The findings provide a basis for developing an adaptive peat production technology that accommodates different scenarios for the commercial use of the available resources.

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