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Optimisation of structural parameters of rotary tillage units to increase the stability of operation under the influence of variable loads

Abstract. The study was conducted to increase the stability of rotary tillage units by optimising their structural parameters considering variable loads. It was revealed that the stability of rotary tillage units under the influence of variable loads depends on such design parameters as the geometry and material of working bodies, the introduction of vibration-proof elements. It was determined that the optimal angle of attack (from 20 to 30 degrees) of the working bodies reduces the resistance of the ground, which, in turn, contributes to an even distribution of loads on the working elements of the unit. Changing the radius of curvature of the working elements reduces the stress concentration, which increases the durability of the working elements and reduces their wear during operation. Analysis of the mechanical properties of materials has shown that the use of special alloy steels containing chromium and manganese increases the wear resistance of the working bodies of units, reduces the frequency of maintenance, and extends the service life. The introduction of rubber shock absorbers in the design of attachment points helped to reduce the amplitude of vibrations and thus improve the stability of the unit during tillage. Analysis of the operation of the upgraded units showed an increase in productivity and a reduction in fuel consumption. Improving the quality of tillage was achieved by evenly distributing the depth of cultivation and reducing the level of soil compaction, which has a positive effect on the growing conditions of agricultural crops. Therefore,

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optimisation of the design parameters of rotary tillage units will increase their resistance to variable loads, reduce operating costs, increase operational efficiency, and ensure long-term and energy-efficient operation in complex geological processes

Keywords: blade geometry; alloy steels; wear resistance; damping elements; shock absorbers

INTRODUCTION

Dynamic loads that occur during the operation of tillage tools are a key factor that affects the efficiency and durability of their operation. Variable loads are caused by a number of reasons related to the characteristics of the soil, operating conditions, and design features of the units. The main causes of such loads include uneven soil, differences in the speed of movement of units, changes in the depth of cultivation, vibrations, fluctuations in the resistance force, and obstacles that affect the stability of working bodies. For example, different soil densities and structures create variable resistance to working elements, and surface irregularities or inclusions such as rocks or roots lead to sudden peak loads. Differences in the speed of movement of the aggregate associated with uneven ground surface or changes in the trajectory cause additional dynamic effects. Similarly, adjusting the depth of cultivation or fluctuation due to changes in field conditions also changes the force required for the units to operate. In addition, vibrations that occur during the operation of the units can reach resonant frequencies, which significantly increase the load on structural elements. Obstacles, such as uneven contact of the working elements with the ground or wear of parts, add unevenness to the operation of the system, causing additional loads. Changes in environmental conditions, such as temperature and humidity, also affect the mechanical properties of working body materials and soil, which creates additional difficulties in operation. Identification and analysis of these factors is a necessary condition for optimising the operation of tillage equipment: increasing its productivity, reducing maintenance costs, and improving the quality of tillage.

The problem of optimising the design parameters of rotary tillage units, in particular, increasing their resistance to variable loads, is relevant for ensuring the efficiency of agricultural machinery. One of the key aspects of optimising the operation of rotary tillage units is the analysis of the mechanical characteristics of the soil and their impact on the quality of cultivation. As noted by A. Panfilova *et al.* (2019), the correct selection of technological parameters of soil cultivation contributes to the reduction of its compaction and increased efficiency of agricultural machinery. The results obtained can be used to adjust the parameters of the working bodies of rotary tillage units in order to reduce loads on structural elements and improve the durability of their operation. D. Pandey *et al.* (2021) indicated that optimisation of the design parameters of the rotary cultivator blade significantly reduced specific energy costs. They developed a model of the blade and analysed the static force and fatigue of the material, which provided an improvement in its performance. As noted in the study by A. Dykha *et al.* (2020), the wear process depends on the mechanical properties of the materials and operating conditions, which confirms the feasibility of using alloy steels containing chromium and manganese to increase the durability of working elements.

Y. Zhang *et al.* (2024a) investigated the use of alloy steels with a high content of chromium and manganese for a guide shoe made of steel that supports the direction of movement of a coal combine and railway transport. They stressed the importance of choosing materials that can withstand high mechanical loads during intensive operation, which helped to increase wear resistance and reduce the frequency of maintenance of equipment. The wear resistance of the working parts of rotary tillage machines is an important factor determining their durability and operational efficiency. As shown in the study by O. Dubovoy *et al.* (2021), the use of electric arc spraying of cermet coatings can significantly increase resistance to abrasive wear. The study of materials based on 65G-TiC steel confirmed their high hardness and wear resistance, which makes such coatings promising for use in tillage machines operating under difficult conditions of variable load.

V. Budak *et al.* (2017) investigated the effect of changing the thickness of shells on the natural frequencies and modes of vibrations of non-cylindrical structures. This study can be useful for calculating and optimising the geometric parameters of rotating units operating under complex loading conditions. S. Mandal *et al*. (2021) investigated the optimisation of the blade design of rotary cutters to increase their service life. They focused on reducing the wear of the blades, which can withstand shock loads and high friction forces when interacting with the ground, which reduces unbalanced forces on the entire rotary cutter and ensures the durability of components. O. Grigorenko *et al.* (2021) investigate models of free vibrations of plate structures, which may be useful for the development of vibration-protective elements in the mounting nodes of rotary mechanisms. The introduction of such elements allows to reduce the amplitude of vibrations, which contributes to the uniform distribution of the load on the working bodies and increases the overall efficiency of soil cultivation.

A. Kumari & H. Raheman (2023) proposed a solution for operating the tractor and rotator at optimal speed, which reduces overall energy requirements and increases fuel efficiency. They examined the effects of throttle and transmission selection on energy requirements and power efficiency in various soil conditions. One of the important aspects of optimising the design parameters of rotary tillage units is to increase the reliability of rotor assemblies that are subjected to significant variable loads during operation. A. Panchenko *et al.* (2019) investigated the design features of orbital hydraulic motor rotors that are subjected to extreme loads and proposed methods for increasing their stability. The results obtained can be used to improve the rotary working bodies of tillage units, which will help reduce mechanical deformations and increase their durability. P. Zhao *et al*. (2024) proposed a fundamentally new soil treatment device with a wide seedbed, which includes a front pipe for applying fertilisers and an optimised design of rotary processing blades. For this purpose, a simulation model was developed and experiments were conducted to analyse the efficiency of straw cleaning, soil flushing, and energy consumption under different operating conditions.

J. Zhang *et al*. (2024b) proposed a cooperative control method for unmanned hybrid tractors to improve trajectory tracking accuracy and improve energy efficiency during their operation. This allowed reducing energy losses and improving the overall efficiency of tractors. S. Zhang *et al*. (2025) focused on the dynamic characteristics of rotary blades and their behaviour under variable loads. This helped to improve the accuracy of setting up equipment and ensure a more uniform load on the working elements. Optimisation of the design parameters of the working bodies of rotary units has a direct impact on the quality of soil cultivation and the productivity of agrotechnical processes. X. Zhang *et al*. (2024c) investigated the prediction of energy consumption based on cutting parameters in rotary units, applying a modelling method to determine optimal operating parameters. Their study showed that optimising these parameters leads to a reduction in energy consumption, which contributes to energy savings during rotary tillage. I. Torotwa *et al*. (2023) investigated the torque and power of the rotating blades of a milling cutter designed according to the spalax claw geometry. As a result of field experiments, they proved that biomimetic rotary blades are energy efficient and can improve soil structure. X. Zhang *et al*. (2023) modelled the movement of soil under the action of rotary blades, examining the interaction between soil and working bodies, which helped to accurately estimate changes in energy, cutting resistance, and movement of soil particles at different depths. This allowed optimising the design and ensuring its durability. One of the promising areas for increasing the wear resistance of working parts of rotary tillage units is the use of wear-resistant coatings. As noted by D. Marchenko & V. Kurepin (2021), electric spark treatment contributes to the formation of wear-resistant layers on steel surfaces, which can significantly increase the service life of parts in difficult operating conditions. Thus, although some aspects of optimisation of rotary tillage units have already been studied, there are gaps in the aspects of integrating new materials, technologies, and improving mechanisms for increasing resistance to variable loads, in particular, in the context of the deformation characteristics of spring elements, which requires further study.

The purpose of the study was to determine the optimal values of the design parameters of rotary tillage units, which would ensure their maximum resistance to variable loads. Research objectives:

- to explore different geometry options for working bodies to reduce ground resistance and improve work efficiency;
- to evaluate the impact of working body materials on their wear resistance and durability;
- to analyse methods for reducing vibrations and dynamic loads to improve the stability of the units.

MATERIALS AND METHODS

The main design parameters of rotary tillage units, in particular, types of rotors, shapes, and angles of knife installation, mounting options for working bodies and damping systems, were studied to improve their stability under variable loads. The geometry of disks and blades, their shapes, materials and location were analysed, which contributed to effective contact with the soil. Attention was paid to mounting systems and transmission mechanisms to achieve maximum rigidity and minimise vibrations that can negatively affect the operation of the unit.

At the beginning of the study, static and dynamic loads acting on the working bodies of the units were analysed. The variability of soil resistance was also considered, depending on such factors as the depth of cultivation, humidity, and soil density, which provided a more accurate picture of the impact of these loads on the working bodies of units in variable operation. Further, the geometry of the working bodies of the units was analysed, since changing its parameters can significantly affect the stability of the unit, minimise ground resistance, reduce stress concentration, and improve the uniformity of force distribution. Optimisation of the geometry of the working bodies allows achieving better energy efficiency and reducing component wear.

Materials for manufacturing blades with high wear resistance and impact strength were studied. This helped to ensure the reliability and durability of working bodies in conditions of variable loads that occur during tillage. To adapt to different working conditions, medium-strength alloy steels (AISI 52100, AISI 4130, 20CrMnTi), composites (TiC-VC-WC/nanoWC-NiCr) and carbide-coated materials such as medium-strength stainless steel (AISI 5040), medium-strength high-carbon steel (AISI 1080) and ceramic composites (ZrB_2) were investigated.

The John Deere 8370R tractor (manufacturer: John Deere, USA), complete with a rotary cutter Kuhn EL 402 R (manufacturer: Kuhn, France), which can work in sandy loam-clay soil conditions at a humidity of 11 ± 0.89% was studied. The working bodies in this milling cutter used standard rotary blades, but they can be replaced with the version developed by the authors in the study (Xu *et al*., 2024). These blades had geometry of a spalax claw that was created using biomimetic principles. This solution helped to significantly reduce the torque on the rotary shaft and increase the overall efficiency of tillage. The use of these blades can also help to reduce the energy consumption of the unit, especially on heavy soils or in conditions of intensive use.

Various types of springs were considered in the study, in particular, compression, tension, conical, serpentine, torsion, and leaf springs. Each of these types of springs performs specific functions in the design of rotary tillage machines. These springs were used to dampen loads, maintain precise adjustment of working bodies, and ensure the stability and durability of rotary tillage units.

RESULTS

Analysis of structural elements and selection of materials

Optimisation of working bodies, attachment systems and transmission mechanisms are key to improving the efficiency and reliability of rotary tillage units. The geometry and material of the working bodies (disks, blades, ploughshares) has a decisive influence on the quality of tillage. Blades with curved profiles reduce the resistance of the ground and facilitate penetration into it, which reduces the load on the unit and increases work efficiency. High-alloy steels or carbide coatings significantly increase wear resistance, which allows extending the operational life of these elements. The optimal arrangement of blades and angles of attack contribute to uniform tillage, reduce vibration, which contributes to stable operation of the unit.

The system of fixing the working bodies is an important element that ensures the rigidity of the unit structure and minimises the level of vibrations during its operation. It includes not only the choice of materials, but also the optimal arrangement of fasteners, such as bolts, nuts, welded joints, which ensure the reliability, and stability of the structure. The use of high-strength materials in these joints, such as AISI 52100 alloy steel, which has high hardness and wear resistance, significantly improves the performance of the units. In addition, composite materials such as Tic-VC-WC (titanium, vanadium, and tungsten carbide) and nanoWC-NiCr (nanostructured tungsten carbide and nickel-chromium alloy) are often used to increase strength under high loads, which provide resistance to wear and shock loads. Based on the correct choice and design solutions, the mounting system allows ensuring stable operation of the units, reducing the likelihood of damage and wear during operation.

Transmission mechanisms play an important role in transmitting torque from the engine to the working parts of the unit. Optimisation of the gear ratio, in particular, the choice of the correct gears, allows reducing the energy costs of the unit. The choice of gears includes not only determining the gear ratio, but also considering the material of the teeth, design features (in particular, the elasticity of the teeth, the accuracy of their manufacture), and the type of gears. For example, the use of alloy steels (AISI 4130, 20CrMnTi) for teeth increases their wear resistance and ability to withstand high loads, which is especially important for tillage equipment where torque transmission occurs under high mechanical loads. In addition, the correct choice of gear type (cast iron, steel, hypoid or spiral-cylindrical) depends on the requirements for working efficiency and wear resistance. The use of gears with hypoid or spiral-cylindrical teeth reduces energy loss, as they reduce friction and noise during operation. Production technologies such as heat treatment and carburisation also affect the strength and durability of gears, which is an important factor in reducing maintenance costs and increasing the service life of units.

AISI 5040 alloy structural steel is corrosion-resistant, making it ideal for use in aggressive environments. High-carbon non-alloy steel AISI 1080, in particular, provides high compressive strength and wear resistance when processing hard soils. ZrB_2-based ceramic composites are characterised by high heat resistance and wear resistance, which makes them ideal for use in conditions of high temperatures and abrasive wear. Given that vibrations are the main source of wear and damage, the use of shock-absorbing systems, in particular, rubber or spring shock absorbers, is an important element for reducing dynamic loads. This reduces the impact of vibrations on the working elements and components of the unit, extending their service life by 20-30%, which helps to reduce the frequency of repair and replacement of blades (Stavinskiy *et al.*, 2024).

Thus, optimisation of the structural elements of rotary tillage units allows increasing productivity, reducing energy costs, and extending the service life of equipment. The correct choice of materials, improvement of the shape of working bodies, and improvement of the fastening system and transmission mechanisms are necessary to achieve optimal results in agricultural engineering.

Load modelling and optimisation of working body geometry

Modelling loads on the working bodies of rotary tillage units is an important stage in the development and improvement of equipment. This allows optimising the design of the unit, reducing the risk of breakdowns and increasing its efficiency and durability. Given the complexity of the operating conditions, it is necessary to analyse both static and dynamic loads for different types of soil. In the design of the John Deere 8370R tractor complete with the Kuhn EL 402 R rotary cutter, static and dynamic loads play a key role in determining the efficiency of the unit and the durability of its components. Static loads occur when the tractor and milling cutter operate in stable conditions, without sudden changes in speed or irregularities on the ground surface. These loads include the weight pressure of the cutter transmitted through the attachment points to the tractor frame, and the uniform resistance of the soil to the working bodies during processing of a given depth. Dynamic loads, on the contrary, are variable in nature and occur due to uneven terrain, changes in the speed of the tractor, or when the working elements of the cutter come into contact with solid inclusions, such as stones. Such loads cause vibrations that are transmitted to the working elements and attachment system of the cutter, and pulse shocks that increase the risk of deformation or breakage. Given the complexity of the operating conditions, it is necessary to analyse both static and dynamic loads for different types of soil. Sandy soils with low resistance reduce horizontal loads, but can cause uneven vertical loads. Clay soils with high resistance increase horizontal and dynamic loads. Stony soils cause sudden shock loads (Sun *et al.*, 2022). Analysis of such variables allows optimising the design of aggregates and increase their efficiency. Virtual modelling of the working and structural parameters of a rotary cutter using Discrete Element Method (EDEM) software allows assessing the impact of various factors on its performance and durability. This approach makes it possible to analyse the interaction of the soil and the working elements of the cutter, considering such parameters as the angle of attack, knife geometry, rotation speed, and the physical and mechanical properties of the soil. Using virtual modelling tools, it is possible to determine the optimal parameters for reducing energy consumption, reducing wear on the working elements, and ensuring stable operation of the unit in various conditions. It also allows pre-testing new design solutions without the need to create physical prototypes, which significantly reduces development time and costs (Bossy, 2021).

Dynamic models are an important tool for analysing variable loads that occur during the operation of aggregates on different types of soils (Zhai *et al.*, 2022). They consider the physical and mechanical properties of the soil, such as its humidity, density and depth of cultivation, which directly affect the soil resistance and efficiency of the unit. Changes in soil moisture are one of the most significant factors affecting the operation of tillage units. Higher humidity can lead to increased soil resistance, which increases the load on the working elements. Dynamic models built with EDEM can anticipate these changes and optimise the machine's performance by adjusting the speed or rotation of the working members to avoid overloading. It also allows optimising fuel consumption, because energy savings can be achieved by reducing congestion. Considering variables such as soil density and structure helps to reduce the risk of premature wear of aggregates and ensure their stable operation under various conditions.

The efficient geometry of the working bodies of rotary tillage units is a key factor in ensuring their stable and long-term operation, reducing energy costs. Optimisation of geometric parameters allows reducing ground resistance, stresses in materials, and achieving an even distribution of forces during operation (Table 1).

Table 1. Influence of the geometry of the working bodies of rotary units on soil resistance and work efficiency

Working body geometry option	Angle of attack	Radius of curvature (mm)	Ground resistance level (N/m^2)	Productivity (ha/h)	Intended use
Direct disks	15°	50	2,000	1.2	Suitable for light soils or surface treatments with minimal energy costs
Curved discs	20°	70	1,800	1.5	Optimal for medium cultivation conditions, where an increase in soil resistance is required for better penetration into the deeper layers of the soil
Double angle blades	25°	60	1,700	1.8	They are used for heavy soils or to reduce fuel consumption by improving load distribution.
Combined disks (high radius)	30°	90	1,500	2	They are effective for working with heavy soils where maximum resistance reduction is required to achieve the highest productivity, especially for deep treatments.

Source: compiled by the author based on I. Shevchenko *et al.* (2024)

Optimisation of the geometry of the working bodies, including the shape of the blades (discs, claws, straight blades), is of great importance for the stable operation of rotary tillage units. Choosing the correct shape of the blades, along with the parameters of the angle of attack, the location of the blades, and the radius of curvature, helps to reduce ground resistance and reduce energy costs. Discs and claws provide different levels of soil penetration and processing efficiency, depending on their shape and angle of attack, which can reduce engine loads and increase productivity. The choice of working body geometry also affects the durability of the units, since reducing friction and optimal load distribution reduces the wear of the elements. Such changes help to reduce soil resistance and increase work efficiency. For example, if the soil resistance level is 2,000 N/m^2 the capacity is 1.2 ha/h, and when the resistance is reduced to 1,500 N/m^2 productivity increases to 2 ha/h. It also reduces stress in materials and promotes even load distribution during operation, which is important for efficient and economical tillage.

The angle of attack is one of the most important parameters for optimising the operation of working bodies. Correct adjustment of the angle of attack allows achieving an optimal balance between processing efficiency and energy costs. Too small an angle (less than 15°) leads to inefficient processing due to the sliding of the working body on the ground, which reduces the quality of processing. On the other hand, an excessively large angle increases the resistance of the soil, which leads to increased energy costs and overload of the unit. The ideal angle of attack usually varies from 20 to 30 degrees, depending on the type of soil and the depth of cultivation, which allows achieving an optimal level of productivity and reduce energy costs (Kalimullin *et al.*, 2021).

In the case of using working bodies with a double angle of attack, the angle can vary depending on the processing area, which ensures more effective penetration into the soil. The double angle of attack combines two angles for different parts of the working body: one angle, which is sharper, provides deep penetration, and the second, which is less sharp, reduces resistance and increases the stability of the unit. This approach allows reducing soil resistance at different stages of processing and improving the quality of processing on different types of soils, while reducing energy costs. Similar solutions are used in blades and discs for heavy tillage equipment, where the efficiency of each stage of processing is critical. As for combined disks with a high radius, it is worth noting that a high radius means an increased diameter of the working body, which reduces soil resistance and improves processing efficiency. This allows evenly distributing the load over a large area and reducing energy loss during processing. This geometry is used for heavy soils, where conventional disks can create excessive resistance.

The uniform arrangement of the blades of the working bodies is also important for optimising loads and reducing vibrations. An asymmetric arrangement of the blades can occur in the event of improper installation or uneven wear of the elements, which leads to uneven distribution of forces. This causes additional vibrations that reduce the stability of the machine and can lead to rapid wear or even breakage of the blades. Damage to the blades can occur due to heavy use or insufficient maintenance, which is quite common in agricultural practice. On average, the blades break down after 300-400 hours of use without proper maintenance, which indicates the need for regular monitoring and maintenance to ensure efficient operation of the units (Acernese *et al.*, 2021).

The optimal arrangement of the blades ensures constant contact with the soil, which contributes to uniform loosening and reduces energy costs. For example, for a rotary cutter, it is optimal to position the blades at a certain angle to the axis of rotation, which allows ensuring effective grinding of the soil without excessive resistance. In the case of a harrow, the blades must be positioned in such a way as to ensure an even load distribution over the entire width of the unit, which prevents uneven tillage and reduces wear on individual elements. This arrangement allows evenly distributing workloads, increasing the efficiency of the unit.

The radius of curvature of the working bodies plays a key role in reducing the stress concentration in the material (Havrylenko *et al.*, 2021). Too small a radius of curvature (less than 50 mm) can lead to local overloads and cracks in the material, which reduces the service life of the working elements. Increasing the radius of curvature helps to reduce the stress concentration and the likelihood of cracks. The optimal radius of curvature is determined by mathematical modelling, considering the material of the working bodies and the operating conditions of the unit. This method allows analysing the mechanical properties of materials such as hardness, wear resistance and strength, and working conditions, including soil type, processing speed, and loads that occur during operation. Consideration of these parameters can significantly increase the durability of working elements and reduce the risk of their wear (Sanaei & Fatemi, 2021).

The choice of materials for the working bodies of rotary tillage units plays a crucial role in ensuring their durability, productivity, and resistance to variable loads. High-quality materials with high wear resistance and impact strength can ensure stable operation of the units even under difficult operating conditions (Table 2).

Table 2. Influence of materials on the wear resistance and durability of working bodies

Material	Steel/composite grade	Hardness (HRC)	Wear resistance (mm/h)	Durability (hours)
Alloy steel	AISI 52100	45	0.15	1,500
Composite materials	TiC-VC-WC/nanoWC-NiCr	55	0.10	1,800
Stainless steel	AISI 5040	50	0.12	1,700
High carbon steel	AISI 1080	60	0.08	2,000
Ceramic composites	ZrB_2	70	0.06	2,500

Source: compiled by the author based on Y. Wang *et al.* (2023)

The hardness of materials and their wear resistance significantly affect the durability of the working bodies of agricultural machinery. Alloy steel (AISI 52100) with a hardness of 45 HRC has a wear resistance of 0.15 mm/h and a durability of 1,500 hours, which is suitable for cultivator blades, gears, but the wear resistance is not the highest. Composite materials such as TiC-VC-WC/nanoWC-NiCr (hardness 55 HRC) have a wear resistance of 0.1 mm/h and a durability of 1,800 hours, making them effective for the manufacture of ploughs and ploughshares.

Stainless steel (AISI 5040) with a hardness of 50 HRC has a wear resistance of 0.12 mm/h and a durability of 1,700 hours, which is suitable for protective elements (equipment frames, protective covers). High-carbon steel (AISI 1080) with a hardness of 60 HRC is the most wear-resistant with an indicator of 0.08 mm/h and a durability of 2,000 hours, which makes it ideal for ploughshares, harrow discs. Zrb_2-based ceramic composites with a hardness of 70 HRC, have excellent wear resistance and durability of up to 2,500 hours, making them the best for use in plough heads, harrows. The choice of material depends on the operating conditions and the required characteristics of wear resistance and durability.

Wear resistance is the main criterion when choosing materials for working bodies, since constant contact with abrasive soil particles causes intense wear. Alloy steels 40X or 65G are often used in the construction of housings, shafts, and teeth of working bodies of tillage equipment, such as ploughs, cultivators, and harrows. These steels are high in carbon and alloying elements such as chromium, manganese, and silicon, which ensures their wear resistance. In addition, composite materials with carbide coatings can significantly increase the service life of working bodies, increasing their wear resistance to a level that is not achieved with conventional steels. Heat treatment technologies, in particular, quenching and carburisation, also significantly improve the wear resistance of steel, which reduces wear by 30-40% and increases the service life of working bodies by 50-60% (Tulaganova *et al.*, 2022). The choice of material depends on the type of soil that the unit works with and the required service life.

Impact strength is an important characteristic for materials exposed to dynamic loads, such as when handling uneven or dense soil. High impact strength (more than 50 J/cm^2) allows the material to absorb mechanical impacts without cracking or destroying elements, even under intense dynamic load. Materials enriched with nickel or molybdenum can withstand high shock loads without loss of strength, which is critical for stable operation of units in conditions of variable dynamic impacts, such as collisions with dense areas of soil or rocks. To ensure the reliability of materials, it is important to control technological processes, since the presence of defects, such as pores or microcracks, can significantly reduce the mechanical properties of the material. This requires the use of modern methods of monitoring the quality and processing of materials.

The combination of alloy steels (65-70%) and composite materials such as reinforced polymers (30-35%) provides an optimal balance between wear resistance and the ability to absorb shock loads. This is achieved through casting or mechanical integration of materials, in which steel components are connected to composite materials using welding, forging technologies or special adhesives that ensure a strong and long-lasting connection. Alloy steels give the structure high strength and durability, while composite materials help to effectively dampen vibrations and reduce shock load, which is especially important in conditions of intensive operation. The use of such materials allows achieving high indicators of durability and productivity of units, reducing the weight of working bodies by 20-25% and extending their service life by an average of 30-40% (Jaiswal & Barve, 2022). This has a positive effect on the energy efficiency of the units, since reducing the weight leads to a reduction in energy costs during operation. Material optimisation improves the performance of rotary tillage units by reducing wear, improving operational stability, and reducing overall maintenance and replacement costs. Thus, the correct choice of materials for working bodies is a key element for ensuring reliable and long-lasting operation of rotary tillage units, while maintaining high productivity and economy.

Springs in rotary tillage machines such as the John Deere 8370R tractor complete with the Kuhn EL 402 R rotary cutter are commonly used in parts of working bodies such as protective mechanisms and shock absorbers. They can be located in spring elements that provide repulsion of the working bodies when pressed or in contact with obstacles in the ground. Such springs help to protect the cutter teeth from overloads, reducing mechanical damage and extending the service life of the working parts of the unit. Spring elements can be installed directly in the system of fixing working bodies or in mechanisms that regulate the depth of cultivation, helping to adapt the equipment to different soil conditions (Fig. 1).

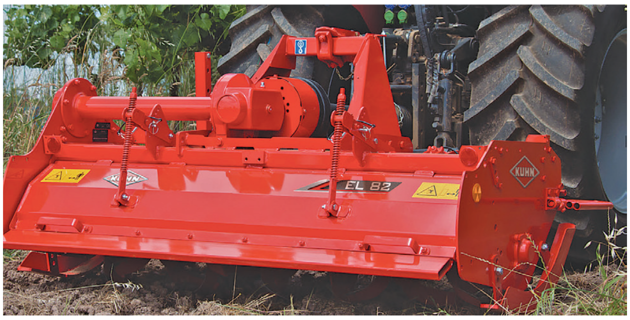

Figure 1. Rear hood with spring to optimise the seedbed where additional reinforcement and alignment is required
Source: Power Tillers EL Series (2023)

To increase durability and strength, the springs are made of alloy steels that have high strength and wear resistance, for example, steel with the addition of chromium, vanadium, or molybdenum. Alloy steels provide not only high elasticity, but also resistance to corrosion and high temperatures. This allows significantly extending the service life of the springs, even in harsh operating conditions, such as frequent collisions with rocks or dense areas of soil. The choice of spring material and design is important to ensure reliable operation of the units, since the correct selection of the spring helps to reduce the cost of repair and maintenance of equipment.

Compression springs are widely used to absorb vertical loads and impacts in various mechanisms of rotary tillage machines (Fig. 2). They can effectively reduce the impact of compressive loads and vibrations when working bodies come into contact with soil or obstacles. In rotary cutters, these springs are often placed in the suspension and shock absorber areas, where they protect the machine structure from damage when working on various types of soil. Such springs can also be used to control mechanical vibrations, reducing the level of vibrations and improving the stability of the unit.

Figure 2. Compression spring
Source: Types of spring (2022)

Stretching springs, on the other hand, are used in systems where it is necessary to maintain constant tension or stretching of elements (Fig. 3). They are used in tensioning mechanisms, such as dynamometers or belt tensioners, and for tensioning the working bodies of rotary tillage machines. Stretching springs ensure stable operation of the mechanisms and allow adapting the forces required to adjust the depth of tillage, which helps to increase the efficiency of the equipment.

Figure 3. Stretch spring
Source: Types of spring (2022)

Cone Springs with variable coil diameters are able to adapt stiffness at different stages of operation. They are often used in shock absorbers, where variable stiffness helps to more precisely adjust the operation of units for different conditions (Fig. 4). In rotary cutters, conical springs are used to reduce vibrations and shock loads, ensuring softer and more uniform operation of mechanisms under variable ground conditions.

Figure 4. Cone spring
Source: Types of spring (2022)

Serpentine springs, due to their ability to absorb vibrations, effectively reduce noise and vibrations in systems where flexibility is required (Fig. 5). They can be installed in various parts of rotary tillage machines, such as suspensions and shock absorbers. Their shape allows them to be used in such mechanisms where adaptation to variable loads is important.

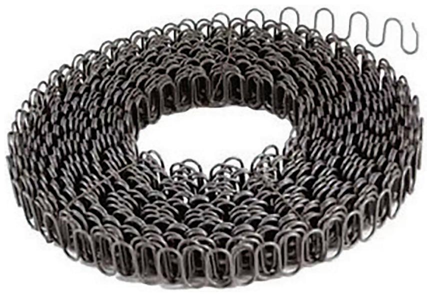

Figure 5. Serpentine spring
Source: Types of spring (2022)

Torsion springs are used to provide resistance to rotation in those mechanisms where protection against mechanical overloads or unpredictable rotational movements is required (Fig. 6). They are installed in the units responsible for the rotation of the working bodies or suspension mechanisms, helping to reduce the load on the machine structure when working on difficult and uneven areas.

Figure 6. Torsion spring
Source: Types of spring (2022)

The leaf type of springs is usually used to absorb heavy loads and ensure stable operation of mechanisms during intensive operation (Fig. 7). They are often installed in suspensions and other mechanisms of rotary tillage machines, where it is necessary to provide shock absorption and reduce vibration loads. The leaf type of springs allows reducing wear and improving the stability of equipment during operation.

Figure 7. Leaf type spring
Source: Types of spring (2022)

Poppet springs are used to create significant forces with minimal deformations (Fig. 8). In rotary cutters, they are used to precisely adjust the tension of the working bodies or adjust the pressure on the ground. This allows maintaining a stable processing depth and reducing the wear of mechanisms, improving work efficiency.

Figure 8. Poppet spring
Source: Types of spring (2022)

Machined springs made by mechanical processing allow creating complex shapes and precise mechanisms for rotary tillage machines (Fig. 9). These springs are used in systems where high accuracy and reliability are required, such as shock absorbers or suspensions. They can provide optimal vibration absorption and reduce noise during the operation of equipment, which increases operator comfort and reduces the need for maintenance.

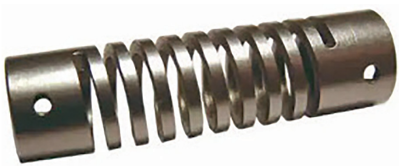

Figure 9. Machined spring
Source: Types of spring (2022)

As a result of considering the different types of springs used in rotary tillage machines, it can be concluded that each type of spring has its own unique functions that ensure efficient and stable operation of equipment in difficult conditions. Compression, tension, conical, serpentine, torsion, and leaf springs perform a variety of tasks, from shock absorption of loads to maintaining precise adjustment of working bodies. The use of such springs reduces the wear of mechanisms, improves productivity, and increases the service life of machines, which is critical for efficient operation in the agricultural sector.

Damping elements and deformation characteristics of spring elements in tillage tools under the influence of dynamic loads

One of the most important ways to increase the stability of rotary tillage units is to use damping elements to reduce the negative impact of dynamic vibrations. Oscillations that occur during the operation of the units cause vibrations, increased wear of parts, and a decrease in the quality of tillage. The use of damping technologies can not only minimise these impacts, but also improve the performance and durability of equipment (Table 3).

Analysing the data in Table 3, conclusions can be drawn about the effectiveness of various methods of reducing vibrations and dynamic loads. The energy absorption indicated in Joules reflects the amount of energy that each element can absorb during operation. This indicator is key, as it determines the ability of the system to reduce vibrations and their negative impact on the stability of the unit. The more energy an element can absorb, the better it copes with reducing vibrations and shock loads. The effect on stability indicates the effectiveness of the elements in maintaining stable operation of the unit. For example, rubber shock absorbers and dynamic dampers show a high and very high level of stability, respectively, which makes them the most effective in reducing vibrations and protecting the structure from wear or breakage.

Table 3. Experimental data of the prototype sample of the SEMC

Vibration reduction method	Element type	Energy absorption (J)	Impact on stability
Rubber shock absorbers	Attachment points	5	High (ensure the stability of the unit as a whole)
Springs	Suspension system	7	Medium (reduce vibrations and contribute to the stability of the position of the working bodies)
Polymer inserts	Working bodies	4	Medium (absorb vibrations and ensure stability of the working body position)
Dynamic dampers	Unit chassis	6	Very high (effectively reduce vibrations and ensure the stability of the unit as a whole)

Source: compiled by the author based on R. Liu *et al*. (2022)

Among the considered methods, rubber shock absorbers absorb 5 Joules of energy and provide a high level of stability, which makes them a universal solution for complex vibration reduction in the unit. Springs that absorb 7 J have an average level of stability, but effectively compensate for dynamic loads that occur when working bodies interact with hard ground or stones. Polymer inserts absorb 4 J of energy and provide average stability, mainly used to reduce vibrations without significant mechanical load on the working elements. Dynamic dampers that absorb 6 J of energy have a very high impact on stability, which makes them ideal for providing effective vibration control and stable operation of the unit as a whole.

Optimal energy absorption depends on the operating conditions of the unit. It should be sufficient to reduce vibrations and dynamic loads, but without creating additional structural complications, such as being overweight. In this context, dynamic dampers and rubber shock absorbers are the most effective methods, as they provide a high level of stability of the unit, reduce wear on structural elements, and help to increase their service life. Rubber and rubber-metal vibration isolators are widely used vibration isolation systems in marine equipment and can withstand pulse loads, including from underwater explosions (Kluczyk *et al.*, 2022). In tillage equipment, rubber shock absorbers can absorb shocks and vibrations that occur in the attachment points. It is possible to use shock absorbers in disk units, where loads often have a pulsating character. They are resistant to soil moisture and abrasive particles, making them a practical choice for the field.

Polymer materials, in particular, polyurethane or high-strength plastic, are also widely used as damping elements. They combine high wear resistance with the ability to absorb shock loads. Polymer inserts can be integrated into attachment points or used as intermediate layers between metal parts. Their advantage is to reduce the weight of the structure and high resistance to chemical influences. The use of damping elements, in particular, shock absorbers and special rubber dampers on the joints, reduces vibrations and noise during operation of the units by 25-30% (Singh *et al.*, 2023). This not only extends the service life of individual components and the structure as a whole, but also provides more comfortable working conditions for equipment operators. In addition, reducing fluctuations contributes to the uniformity of tillage, which is an important factor for increasing yields. Thus, the introduction of damping elements is one of the key areas for improving rotary tillage units, which allows achieving better results due to stable operation and durability of equipment.

Variable loads are loads that change in their parameters (magnitude, direction, point of application) over time (Pylypaka *et al.*, 2024). In the context of the operation of rotary tillage machines, variable loads occur due to uneven soil, obstacles (stones, roots) and constant dynamic interaction of working bodies with the environment. Under these conditions, the key load characteristics are the modulus of force, the direction of the load vector, the point of application of force, and the arm of force, which determine the level of deformation and stress in the structural elements.

For example, during the operation of the Kuhn EL 402 R rotary cutter, the impact force modulus depends on the weight of the obstacle, the speed of the rotor, and the hardness of the ground. To determine the value of these parameters, dynamic models are used that consider the angular velocity of the rotor, the weight of the working body, and the interaction geometry. The force vector changes direction depending on the angle of interaction of the knife with the ground surface or obstacle, which creates complex combinations of loads, including vertical, horizontal and rotational components. The arm of force, which determines the load moment, is important for analysing the deformations of spring elements. For example, knife attachment mechanisms use torsion springs that respond to variable torques caused by shock loads. The deformation of such springs depends on the angular acceleration and moment of inertia of the working body, which provides protection against excessive load.

Cylindrical compression springs, which are installed in the suspension units, absorb vertical vibrations caused by the interaction of the rotor with the ground. Their work consists in changing the length under the influence of variable forces that occur during the movement of the machine. In such springs, it is important to ensure that elasticity is maintained after multiple deformation cycles. For this purpose, special materials with a high elastic limit are used, such as alloy steel.

Conical springs are often used to dampen vibrations with a gradual decrease in amplitude. Their design allows smoothly changing the stiffness depending on the applied load, which is useful for absorbing peak impacts. The operation of spring elements under the influence of variable loads also includes the study of oscillatory processes. For example, damping with polymer-metal shock absorbers allows absorbing both vertical and horizontal components of vibrations. The combination of rubber and metal in such elements reduces vibrations, which reduces noise and increases operator comfort.

Optimal values of design parameters of rotary tillage units

Optimal design parameters of rotary tillage units are key to ensuring efficient operation, high productivity and minimising wear. The overall dimensions of the unit determine its performance and manoeuvrability. For example, the working width usually varies from 1.5 to 4 metres for medium-sized machines, which allows processing large areas without excessive time spent. The length and height should be optimised for easy transport and stability in the field. Working elements, such as blades, must be made of high-strength materials that ensure wear resistance and long service life. Their number and location are selected in such a way as to ensure high-quality tillage, and the depth of tillage is regulated depending on the type of soil and agrotechnical requirements in the range of 10-30 cm. The speed of rotation of the rotor is a critical parameter. Optimal values are in the range of 200-350 rpm, which avoids excessive destruction of the soil structure. The rotor diameter, usually 50-80 cm, affects the energy consumption and quality of soil mixing (Du *et al.*, 2022).

Spring elements and dampers play an important role in reducing the impact of dynamic loads. The spring stiffness must be adjusted to compensate for peak loads without plastic deformation. For this purpose, high-strength steels such as AISI 52100, AISI 4130, 20CrMnTi are used. Polymer dampers provide vibration absorption, reduce noise and contribute to the durability of the unit. The weight of the aggregate should be sufficient to ensure stability, but not excessive to avoid compaction of the soil. For medium models, this parameter is about 800-1,500 kg. The working speed of the unit is usually 6-12 km/h, which provides an optimal balance between productivity and processing quality (Zhang *et al.*, 2022). The energy consumption of the unit depends on its design and working width. For example, vehicles with a width of 3 metres require a tractor with a capacity of 80-120 kW. All these parameters must be considered when designing and operating rotary tillage machines to ensure their efficiency, reliability, and durability.

DISCUSSION

The geometry and materials of the working bodies of the rotary tillage unit determined its resistance to variable loads. Determining the optimal angle of attack and radius of curvature of the elements contributed to a uniform distribution of stresses in the materials, which reduced the risk of premature wear and destruction. In addition, these parameters reduced dynamic loads, ensuring stable operation in difficult field conditions.

This issue was also investigated by K. Ravshanov *et al*. (2021). Their results confirmed that the geometry and relative position of the working bodies of rotary units reduce wear due to improved load uniformity and reduced friction. The use of optimal shapes, such as specially designed blades or discs, extends the service life of working bodies and increases the productivity of units, reducing energy costs. The most efficient design for non-dump tillage is a combination of a dumpless housing with flatteners, a battery with cut-out spherical disks, and a roller, which ensures high-quality processing with minimal energy costs.

Analysis of the results of the study indicates that the geometry of the working bodies of rotary units has a significant impact on reducing wear and improving the efficiency of tillage. Reducing the mechanical load on the working elements allows not only to extend their service life, but also to improve the productivity of equipment (Melnyk, 2024). In addition, the correct adjustment of parameters, such as the clamping force of the springs and the geometry of the working elements, reduces load fluctuations, which, in turn, reduces the risk of overload and damage to the components of the unit. Considering the type of soil and appropriate adjustment of the working bodies is important for achieving high efficiency and reliability of equipment in various operating conditions.

Y. Gao *et al*. (2024) also showed that the efficiency of rotary tillage largely depends on the interaction of the tractor, the three-point suspension mechanism, and the rotary mechanism. The study showed that as the speed of the unit increases, the vibration acceleration of all components increases, and the greatest changes were observed in the three-point suspension. To optimise the design of tractors and rotary cutters, it is important to consider resonant frequencies to minimise vibration, improve productivity, and reduce the negative impact on operator health.

Optimisation of the geometry of the working bodies of rotary units is a difficult task, since it requires considering not only technical characteristics, but also specific operating conditions (Bulgakov *et al*., 2019). Parameters such as the material of manufacture, shape and size of the working elements must be adapted to different types of soil and variable loads during operation. Incorrectly selected geometry can lead to rapid wear of the working elements and reduced productivity, which, in turn, increases maintenance costs and reduces the service life of the units.

It was found that structures with asymmetrically arranged working bodies often showed an increased tendency to vibrations, which negatively affected the overall performance of the units. Instead, the use of a uniform arrangement of the blades reduced vibrations and contributed to more efficient use of energy. It was found that optimisation of these parameters helped to reduce the energy costs of tillage compared to the basic structures, which are characterised by less efficient blade geometry, lack of vibration damping systems, and less adaptability to changing soil conditions.

B. Aramide *et al*. (2021) concluded that tools wear out quickly on arid agricultural land, which leads to high replacement costs and reduced operational efficiency. This wears out due to corrosion and tribocorrosion, which degrades the quality of tillage and increases fuel costs. To solve this problem, engineers are developing new technologies and materials to increase the durability of tools, which helps to reduce costs and increase productivity. The results obtained confirm the conclusions of B. Aramide *et al*. that optimisation of the geometry of the working bodies of rotary units significantly improves the efficiency of tillage. In particular, reducing friction and improving load uniformity leads to a reduction in the wear of working elements, which, in turn, helps to reduce energy costs and increase overall productivity. In addition, the results confirm that improving the design of aggregates, such as suspension mechanisms and clamping forces, also plays an important role in ensuring the stability of equipment and reducing negative environmental impacts.

The study by M. Askari *et al*. (2022) found that the energy efficiency of structures in optimising the distribution of loads on the working bodies of tillage units is a key factor, since the correct balance of loads can reduce fuel consumption and wear of working bodies. Improving this parameter is important not only to reduce operating costs, but also to reduce the negative impact on the environment (Shvedchykova *et al*., 2024). With this approach, geologists can achieve not only economic, but also environmental benefits. These findings of M. Askari *et al*. confirm the results of the study, as they demonstrate that the uniform arrangement of the blades of the working bodies significantly reduces the level of dynamic loads and vibrations affecting the unit. This allows not only improving the stability of the equipment, but also increasing its service life by reducing the wear of working bodies. In addition, an even distribution of loads helps to reduce energy costs, which also increases the overall efficiency of tillage.

The results also highlighted the importance of material selection. Alloy steels and composite materials with high wear resistance have ensured a longer service life of the working bodies. Heat treatment technologies, such as quenching and carburisation, increased the hardness of materials, which reduced their tendency to wear under the influence of an abrasive medium (Khlivnyi & Bazilo, 2023). This is especially true for the operation of aggregates on heavy soils, where abrasion is a significant factor.

This result is consistent with conclusions of I. Vidaković *et al.* (2021), who proved that the use of high-strength steels subjected to quenching and boron for the manufacture of working bodies of tillage units effectively increases their wear resistance. These machined steels have increased resistance to mechanical wear and corrosion, which reduces the frequency of replacement of parts and reduces maintenance costs. This is especially important for equipment operating in difficult environments, where durability and efficiency are key factors.

In turn, S. Locs *et al.* (2017) investigated tool steel reinforced with laser plating and concluded that heat treatment is an important process for reducing wear and extending the service life of tillage elements. It allows changing the internal structure of the metal, increasing its strength and resistance to wear. Based on the correct choice of temperature and processing time, an optimal balance between hardness and ductility can be achieved, which minimises the possibility of cracks or deformations during operation and reduces the frequency of repairs, improving the reliability of the equipment.

These data correspond to the theses given in the previous section, since they confirm that the use of high-strength alloy steels and heat treatment significantly increase the wear resistance and durability of the working bodies of tillage units. The high level of strength and resistance to external influences that tool steel provides reduces maintenance costs and the frequency of component replacement. However, given the higher cost of tool steel compared to carbon and alloy steels, there is a contradiction between its high performance characteristics and the economic feasibility of such use in agriculture (Adamchuk *et al.*, 2016). Therefore, the use of such materials can be cost-effective only if the cost of their manufacture is reduced or due to significant savings on maintenance and repair of equipment in the long term.

The agreement between geometric parameters and materials showed a significant synergistic effect. The use of working elements with an optimal angle of attack in combination with high-carbon steel helped to significantly reduce local overloads, which often cause structural failure. This not only increased stability but also improved the quality of tillage. Y. Yang *et al.* (2021) developed biomimetic rotary tillage blades to reduce torque and power consumption based on the geometric characteristics of the spalax's five front claws. Their study considered the contour curves of the claw tips and the structural characteristics of the multi-claw combination. The optimal blade was chosen considering three factors: the ratio of the claw width to the lateral position, the angle of inclination of the multi-claw combination, and the speed of rotation, which was tested by testing with a ground hopper. The results of the study are consistent with the results of Y. Yang *et al.* in the fact that optimising the geometry of working bodies, in particular the shape and angle of attack, has a significant impact on reducing energy costs and improving the efficiency of tillage. The correct choice of materials and structural elements reduces wear and increases the durability of equipment, which is confirmed by positive test results and practical application of new technologies.

X. Zhao *et al.* (2025) also found that optimisation of the geometry of rotary blades of tillage units, in particular, in terms of specific strength and specific stiffness of structural efficiency, reduces local overloads, and lowers the risk of damage to machinery elements. They evaluated the developed model based on key performance indicators such as blade neck strength, maximum stress, fatigue life, and ultimate fracture stress. This optimisation ensures a more even distribution of forces, which reduces the concentration of loads on individual elements and increases the efficiency and reliability of equipment.

Comparing the data obtained in the course of the study, it can be concluded that optimisation of the geometry and materials of the working bodies of tillage units provides a significant increase in their reliability. It was revealed that the combination of an improved shape of working elements using high-strength materials allows not only reducing wear, but also increasing the resistance of units to mechanical damage under heavy loads. This helps to reduce the frequency of repairs and the overall operating costs.

However, further studies of variable loads that occur during the treatment of various types of soils, in particular static and dynamic loads, are necessary. Static loads usually occur due to the constant interaction of working bodies with the soil, while dynamic loads are associated with vibrations and shock impacts during the operation of aggregates. Understanding these loads will help to more accurately assess their impact on tool wear and durability. This is especially true for the development of universal structures that can adapt to different operating conditions. In particular, tests have shown that soil density significantly affects the efficiency of aggregates, so consideration of these factors in structural parameters is an important area of future research.

J. Shang *et al.* (2024) investigated the effect of the downforce of springs in seed drills on the stability of machinery during the treatment of various types of soils. They concluded that uneven loading can significantly reduce the efficiency of machinery, especially in conditions of heavy soils, such as clay or rocky. In such conditions, the units experience significant load fluctuations, which can lead to overload of the working bodies and their damage. To ensure stable operation, it is necessary to consider the type of soil and adjust the parameters of the units, in particular, the downforce of the springs, to reduce these vibrations. Conclusions of J. Shang *et al.* are consistent with the results of the study, as they confirm the need to adapt the structures of tillage equipment to the conditions of a particular soil. In particular, adjusting the pressure force of the springs is of great importance for ensuring stable operation of the units, especially in heavy soil conditions, where uneven loads can significantly reduce the efficiency of processing and accelerate the wear of working bodies. Consideration of these factors will not only reduce operating costs but also increase the durability of equipment and its productivity.

Z. Long *et al*. (2023) found that the development of universal designs that allow the tillage components of seed drills to adapt to different operating conditions is a key aspect for improving their efficiency and reliability. Such structures must be able to adapt to different types of soils, variable loads and atmospheric conditions, which allows maintaining the stability of the units in different conditions. Innovative solutions may include the use of replaceable working bodies or adaptive control systems that optimise the operation of equipment depending on external factors.

From the results of the study, it is clear that variable loads caused by different types of soils significantly affect the stability of tillage units. In particular, heavy soils, such as clay or stony ones, can lead to large load fluctuations, which increases the risk of overloading the working elements and their premature wear. This requires adapting the design of the units to ensure their stability and reliable operation in such conditions, which, in turn, confirms the need to improve the technologies and designs of tillage equipment. Optimisation of the design parameters of rotary tillage units not only increases their resistance to variable loads, but also reduces energy consumption and improves durability. This is of great importance for the development of energy-efficient and reliable agricultural machinery that can work stably even in difficult operating conditions.

CONCLUSIONS

The study confirmed the importance of choosing materials for working bodies with high wear resistance and impact strength. Medium-strength alloy steels, such as AISI 52100, AISI 4130, 20CrMnTi, and composite materials, in particular TiC-VC-WC/nanoWC-NiCr, demonstrate high efficiency in working with abrasive soils, reducing wear and increasing the overall durability of units. Carbide-coated materials such as medium-strength stainless steel (AISI 5040), high-carbon steel (AISI 1080), and ceramic composites (ZrB_2), showed excellent results in improving wear resistance. The use of heat treatment, in particular quenching and carburisation, allows achieving optimal material characteristics, which ensures reliability under dynamic loads.

To improve productivity and reduce energy costs, it is important to properly adjust the design of the units depending on the type of soil and working conditions. This allows ensuring stable operation and reduce the likelihood of overloading individual components of the units. Technical innovations aimed at improving these parameters can reduce the cost of operation and maintenance of equipment, which is an important factor in preparing the soil for further geological research or development of deposits.

Compression springs, tension springs, conical springs, coil springs, torsion springs, and leaf springs are all important in ensuring the reliable and efficient operation of rotary tillage machines. Each type of spring performs specific functions, including shock absorption of loads, maintaining precise adjustment of working bodies and reducing mechanical impacts on the design of equipment. Their use helps to improve productivity, reduce energy costs, and extend the service life of machines, which, in turn, ensures the efficiency of agricultural production.

Optimal parameters of rotary tillage units include a working width of 1.5 to 4 m, a processing depth of 10-30 cm, a rotor rotation speed of 200-350 rpm, and a diameter of 50-80 cm. The spring stiffness is selected using AISI 52100, AISI 4130, 20CrMnTi steels to compensate for peak loads. The weight of the unit is 800-1,500 kg, and the working speed is 6-12 km/h. The power of the tractor for a 3-metre-wide unit should be 80-120 kW, which ensures efficiency and reliability of operation. To further improve rotary tillage units, it is necessary to study the impact of the latest materials and technologies, such as nano-coating and alloying, on wear resistance and resistance to mechanical loads in long-term operation.

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CONFLICT OF INTEREST

None.

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Оптимізація конструкційних параметрів ротаційних ґрунтообробних агрегатів для підвищення стійкості роботи під дією змінних навантажень

Анотація. Дослідження проведено для підвищення стійкості ротаційних ґрунтообробних агрегатів шляхом оптимізації їх конструкційних параметрів з урахуванням змінних навантажень. Виявлено, що стійкість ротаційних ґрунтообробних агрегатів під дією змінних навантажень залежить від таких конструктивних параметрів, як геометрія та матеріал робочих органів, впровадження віброзахисних елементів. Визначено, що оптимальний кут атаки (від 20 до 30 градусів) робочих органів дозволяє знижувати опір ґрунту, що, своєю чергою, сприяє рівномірному розподілу навантажень по робочим елементам агрегату. Зміна радіусу кривизни робочих органів дозволяє знизити концентрацію напружень, що підвищує довговічність робочих елементів і зменшує їх зношення під час експлуатації. Аналіз механічних властивостей матеріалів показав, що використання спеціальних легованих сталей, що містять хром та марганець, підвищує зносостійкість робочих органів агрегатів, дозволяє зменшити частоту обслуговування, подовжити термін служби. Впровадження гумових амортизаторів у конструкцію вузлів кріплення допомогло зменшити амплітуду вібрацій і таким чином покращити стабільність роботи агрегату в процесі обробітку ґрунту. Аналіз роботи модернізованих агрегатів показав підвищення продуктивності та зменшення витрат пального. Покращення якості обробітку ґрунту досягнуто завдяки рівномірному розподілу глибини культивації та зменшенню рівня ущільнення ґрунту, що позитивно впливає на умови вирощування сільськогосподарських культур. Отже, оптимізація конструкційних параметрів ротаційних ґрунтообробних агрегатів дозволить підвищити їх стійкість до змінних навантажень, знизити експлуатаційні витрати, збільшити ефективність роботи та забезпечити довговічну й енергоефективну експлуатацію в умовах складних геологічних процесів

Ключові слова: геометрія лез; леговані сталі; зносостійкість; демпфуючі елементи; амортизатори