UDC: 631.3
DOI: 10.56407/bs.agrarian/2.2024.21

Ukrainian Black Sea Region Agrarian Science
Vol. 28, No. 2

The use of surface strengthening to increase the wear resistance of working bodies of agricultural machines

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Abstract. The research was aimed at investigating effective methods of surface strengthening of the working bodies of agricultural machines to increase their wear resistance and extend their service life. The study used surface hardening methods such as heat treatment, chemical and thermal processes, coatings, and mechanical methods. It has been shown that various methods of surface hardening significantly increase the wear resistance of working parts of agricultural machinery. The use of such heat treatment as induction hardening increased the resistance to wear due to localised heating and rapid cooling, which led to an increase in the hardness of the material. Chemical and heat treatment, including carburisation, nitrocementation and nitration, showed a significant improvement in surface layer hardness and increased corrosion resistance. Mechanical methods such as shot blasting and roller hardening have increased hardness and wear resistance by 30-50% due to plastic surface deformation. It has been

Article's History:
Received: 25.03.2024
Revised: 21.05.2024
Accepted: 11.06.2024

Suggested Citation:
Stavinskiy, A., Vakhonina, L., Martynenko, V., Mardziavko, V., & Rudenko, A. (2024). The use of surface strengthening to increase the wear resistance of working bodies of agricultural machines. *Ukrainian Black Sea Region Agrarian Science*, 28(2), 21-32. doi: 10.56407/bs.agrarian/2.2024.21.

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proven that the use of surfacing and coatings of physical vapour deposition/chemical vapour deposition increases the durability of parts by 20-40%, which reduces operating costs and increases the productivity of agricultural machinery. The study examined approaches to enhancing the wear resistance of agricultural machinery's working parts, highlighting a notable issue: Ukrainian agricultural machinery often exhibits a shorter service life (1.2-2 times less) compared to imported counterparts. The analysis focuses on the reasons behind the wear and deterioration of cultivator teeth, with particular emphasis on how wear affects the size and shape of the working parts, resulting in decreased efficiency. The surface strengthening methods under study can be directly implemented in production to increase the durability and reliability of working parts of agricultural machinery, which would help to increase their efficiency and reduce operating costs

Keywords: carburisation; induction hardening; heat treatment; titanium nitride; diamond-like carbon coatings

INTRODUCTION

Agricultural machinery plays a key role in tillage, harvesting, and overall mechanisation of farming processes. Ensuring reliability and efficiency is therefore essential for the sustainable development of the agricultural sector. Increasing the wear resistance of these components not only reduces downtime for repairs, but also lowers operating costs, which is crucial for ensuring efficiency in modern agricultural markets. A significant problem in this area is the lack of a comprehensive approach to choosing the optimal method of surface quenching of agricultural machinery, considering specific tasks and operating conditions.

Agricultural machinery is essential for tillage, harvesting, and general mechanisation in agriculture. The reliability and efficiency of these machines are critical for the sustainable development of the agricultural sector. Increasing the wear resistance of working bodies not only reduces machine downtime due to repairs, but also reduces operating costs, which is important for cost-effective farming in the modern market (Aramide *et al.*, 2021; Tekeste *et al.*, 2022). One of the main problems in the field under study is the lack of an integrated approach to choosing the optimal method of surface hardening of agricultural machinery, considering the specifics of work and operating conditions.

The study by S. Kumar *et al.* (2024) demonstrates the use of chemical and thermal methods to increase the corrosion resistance of working bodies. The study highlights the effectiveness of combining chemical and thermal processes to protect metal surfaces from corrosion in agriculture. H. Huang *et al.* (2022) focus on mechanical hardening techniques such as shot blasting and their impact on wear resistance. The study shows that the use of mechanical hardening methods can significantly increase the strength and service life of agricultural machinery and tools. The study by Y. Hu *et al.* (2021) is devoted to the investigation of the efficiency of induction hardening in increasing the hardness of metal surface layers. The study points to the potential of induction hardening to increase the strength and wear resistance of metal parts used in agriculture. R. Mallick *et al.* (2022) defines the use of PVD (physical vapour deposition)/CVD (chemical vapour deposition) coatings to protect working bodies from abrasive wear. Their study confirms the effectiveness of using thin coatings to increase the duration of operation of agricultural machinery in conditions of aggressive wear.

The research conducted by Y. Wang *et al.* (2022) emphasizes the impact of different parameters in the carburization process on the structure and properties of the surface layer. The study provides important information for optimising carburisation processes to improve the wear resistance of tools in agriculture. The study by R. Dalcin *et al.* (2022) evaluates the effectiveness of nitration in increasing the hardness and improving the wear resistance of metal parts. The work demonstrates that nitration can be an important method for strengthening the surface layers of materials in agriculture. T.-T. Nguyen & T.-M. Le (2021) investigate the effect of roller hardening parameters on the mechanical properties of the surface. The study shows that optimising the parameters of roller hardening can significantly increase the strength and wear resistance of materials used in the production of agricultural machinery.

A. Kostin & V. Martynenko (2017) describe the development of new materials for surfacing coatings that improve the wear resistance of agricultural machinery. The study confirms the importance of developing new technologies in production aimed at increasing the service life of equipment in agriculture. The study by Z. Sydow *et al.* (2021) provides data on the impact of various surface hardening methods on the performance of agricultural technologies. The paper highlights the need for a systematic approach to the selection of strengthening methods to achieve optimal results in improving the efficiency and duration of equipment in the agricultural sector. There is a need to further investigate the impact of a combination of different strengthening methods on the economic efficiency and durability of agricultural machinery in different climatic and geographical conditions. But there is a need to further investigate the impact of a combination of different strengthening methods on the economic efficiency and durability of agricultural machinery in different climatic and geographical conditions.

The purpose of the study was to investigate effective methods of surface hardening of the working bodies of agricultural machines to significantly increase their wear resistance and extend their service life. Objectives of the study:

1. Evaluation of the impact of various heat treatment methods, such as induction hardening and tempering, on the mechanical characteristics of the surface layers of agricultural machinery parts.

2. Investigation of the effect of chemical heat treatment, such as carburisation and nitriding, on improving the wear and corrosion resistance of working parts.

3.Comparison of different approaches to mechanical surface quenching, such as shot blasting and roller quenching.

MATERIALS AND METHODS

This study thoroughly investigated the effect of various heat treatment methods on the surface layers of components used in agricultural machinery. The study focused on quenching, tempering, and induction hardening processes.

The quenching process involved heating the metal to high temperatures, followed by rapid cooling, which significantly increased the hardness and wear resistance of the material. After that, tempering was used to relieve internal stresses that occurred as a result of quenching and further affect the mechanical properties of the surface layer. Induction hardening used high-frequency currents to heat certain areas of metal, selectively hardening those that were exposed to the highest mechanical stresses during operation.

Analysis of various methods of chemical and heat treatment, such as carburisation, nitrocementation, and nitriding, showed their effect on the properties of metal parts of agricultural machinery. Carburisation carried out at high temperatures saturated the surface layer with carbon, which significantly increased the hardness and wear resistance of the material. Soft nitriding and nitriding processes saturated the surface layer with nitrogen, increasing corrosion resistance and creating a hard surface that can withstand the harsh operating conditions of agricultural machinery.

The study also discussed various methods of coating the surface of agricultural machinery. Special attention was paid to thermal sputtering, as well as physical vapour deposition and chemical vapour deposition methods. Thermal spraying was used to create a layer of wear-resistant material on the working surfaces of agricultural machinery. This allowed increasing their durability and reducing wear under abrasive operating conditions. PVD and CVD coatings were used to form thin but very strong films. For example, titanium nitride and diamond-like carbon coatings have been used to protect against mechanical wear and effectively protect surfaces from corrosion. These measures significantly extended the service life of agricultural machinery, providing increased reliability and efficiency in various operating conditions.

All the figures used in the study were taken from the work of L. Tulaganova *et al.* (2022) and were used to visualize changes in the size and shape of the working parts of agricultural machines under the influence of various methods of surface hardening. The study focused on the selection and substantiation of methods aimed at improving the wear resistance and durability of components of tillage units, considering factors such as design, technology, and materials science. These improvements were aimed at increasing wear resistance and performance while reducing the production costs associated with machine components. The study was conducted at the Institute of Agricultural Machinery named after I. Petrov in Ukraine. Various models of tillage machines were used, including the Titan-300 model from Agrotechnica, Italy, and the Agroforce-500 model from Agroforce, Poland. The study was conducted in 2023 on an area of about 500 hectares. Conditions included high soil moisture, uneven structure, and large differences in the composition of soil masses. The significant wear and tear these machines were subjected to highlighted the important factors contributing to wear. Subsequently, these factors gradually changed the size and shape of the tillage unit, which eventually led to its functional deterioration (Figs. 1, 2).

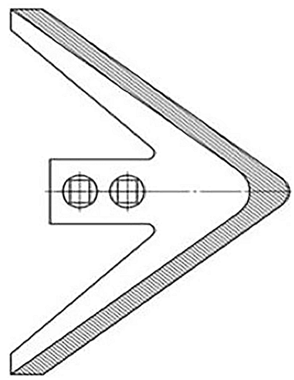


Figure 1. *Profile changes due to wear and tear*
Source: *L. Tulaganova et al. (2022)*

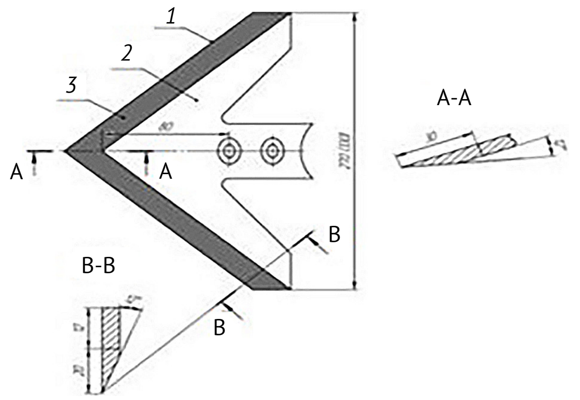


Figure 2. *Schematic representation of the process of restoring the sweep blade of a cultivator*
Notes: *1 – surface area for weld overlay; 2 – component requiring restoration; 3 – position of the corner plate*
Source: *L. Tulaganova et al. (2022)*

The study of profile changes due to wear determined the best methods for restoring or replacing components to ensure a long service life and maximum productivity in working conditions. A schematic representation of the process of restoring the sweep blade of the cultivator clearly showed what steps or techniques are used to restore the working surface of the blade to ensure that it once again performs at its optimum.

RESULTS

The use of surface hardening to improve the wear resistance of working parts of agricultural machinery is a critical factor. Increased wear resistance can extend the service life of components, reduce maintenance and repair costs, and improve the overall efficiency of agricultural machinery. Heat treatment is the main method of surface hardening of metal parts and is widely used in various industries. One of the most common methods is quenching followed by tempering. During quenching, the material is heated to a high temperature, causing structural changes that increase its hardness and wear resistance. This process is then followed by rapid cooling to achieve the desired microstructure of the surface layer. Induction hardening uses high-frequency currents to locally heat the surface of the component. This technology allows hardening only the target surface, minimising the impact on the rest of the material. The effectiveness of induction hardening lies in its ability to achieve high hardness and wear resistance exactly where it is most needed. This makes the method particularly attractive to tool and component manufacturers who place high demands on accuracy and reliability. Heat treatment, which includes quenching and induction hardening, is a highly effective method for improving the mechanical properties of the surfaces of parts, improving wear resistance and overall durability. This approach is of great importance in modern industry (Aswad *et al.*, 2021).

Chemical heat treatment is the most important method of strengthening the surfaces of metal parts and is widely used in industry due to its ability to improve their mechanical and protective properties. The key method in this category is carburisation. During the carburisation process, the metal surface is saturated with carbon at high temperatures in the presence of carbon-rich substances. This process forms a high-carbon layer, which significantly increases the hardness and wear resistance of the surface layer. Nitrocementation is a more complex process that involves saturating the surface with carbon and nitrogen simultaneously. This method allows creating a surface layer with high hardness and improved corrosion resistance, which makes it particularly valuable for parts used in aggressive environments. Nitriding, in turn, is the directed saturation of the surface with nitrogen without adding carbon. This process forms a hard and wear-resistant surface layer, which ensures the durability and reliability of metal parts in conditions of intensive operation. Chemical and heat treatment, including carburisation, nitrocementation, and nitriding, are effective surface hardening methods that can significantly improve the functional properties of metal parts. These treatments increase wear resistance and protect against external influences, which makes them indispensable in modern industry (Kantoríková *et al.*, 2021).

Coatings play a crucial role in the surface hardening of metal parts designed to work in heavy wear and harsh environments. One of the methods is to apply a wear-resistant layer to the surface of the part by welding. This technology significantly improves mechanical properties such as hardness and wear resistance by using materials rich in chromium and hard carbides. Another important approach is to apply PVD and CVD coatings. These approaches allow applying thin, strong, and wear-resistant coatings to the surface of parts. For example, titanium nitride and diamond-like carbon coatings provide excellent protection against mechanical wear and corrosion, making them ideal for applications where high strength and efficient equipment functionality are required. Coatings such as surface coating and PVD/CVD techniques are an effective strategy for improving the performance of metal parts, increasing their durability, and reducing maintenance costs in various industries.

Mechanical methods of surface hardening play a key role in improving the wear resistance and durability of metal parts used in conditions of intensive operation and high mechanical loads. One of these methods is shot blasting, which consists in a directed action on the surface of the shot jet. This process leads to intense plastic deformation of the material, which helps to improve its mechanical properties, including increasing hardness and wear resistance. Shot blasting is effectively used to prepare the surface before applying coatings or to improve the adhesion between parts. In addition, roller hardening is the process of plastic deformation of the metal surface when rolling with special rollers. This method improves the mechanical properties of the surface layer, such as hardness and wear resistance, making it particularly useful for parts exposed to abrasive materials and high mechanical loads. Mechanical hardening techniques, such as shot blasting and roller hardening, play an important role in modern industry, providing increased durability and reliability of metal parts, which ultimately helps to reduce maintenance costs and improve process efficiency (Unal *et al.*, 2022).

Surface quenching is a highly efficient technology that can significantly improve the properties of metal parts used in agricultural machinery. By increasing the wear resistance and hardness of working elements such as ploughshares and cultivator blades, this method can significantly extend their service life, reduce the frequency of replacements and repairs, and reduce operating costs. Increased reliability and durability of parts contribute to more stable and productive operation of agricultural machines, minimising downtime and ensuring continuity of tillage and harvesting processes. Thus, the introduction of surface hardening methods is a key aspect of optimising production processes in the agricultural sector, which contributes to improving the efficiency and economic profitability of agricultural production. Surface hardening plays a key role in agricultural machinery, where high wear resistance and reliability of working bodies are critical for efficient operation (Yadav *et al.*, 2023). For example, when strengthening ploughshares and blades of ploughs and cultivators, their service life is significantly increased, which reduces the time for replacement and repair, and increases the productivity of tillage. In the case of seed drills and harvesters, reinforcing the coulters and blades helps to ensure more precise and even sowing and harvesting, which is important for ensuring high quality agricultural products. Combine harvesters also benefit from strengthening elements in contact with soil and plant material, such as drums and threshing mechanisms, which improves their performance and durability in heavy-duty environments. The introduction of the above-mentioned surface quenching methods can significantly improve the performance of agricultural machinery parts, which ultimately leads to an increase in the efficiency and reliability of agricultural production.

In the course of the study, the wear patterns observed on the working components of the cultivator were studied and evaluated. The blades work at a depth of 6 to 15 cm, colliding with weeds that stick to the blades during processing. The blade tip is subjected to the most significant wear, resulting in a reduction in strength along the blade edge. Once the linear wear at the tip reaches 30 mm, both the blades and bolts experience wear, leading to heightened traction resistance and uneven working depth (Lorenzi *et al.*, 2023). The wear of the hoe blades primarily depends on several key factors. One of the critical factors is the distribution of soil particle size, which determines its abrasive nature. Changes in soil composition can significantly affect this characteristic and therefore affect the rate of blade wear during processing. Another important factor is the soil density. A higher soil density increases the pressure exerted on the blade during operation. This increased pressure accelerates wear around the edges of the blade, thereby compromising their long-term durability and operational efficiency. The choice of materials for cultivator blades significantly affects their physical and mechanical properties (Neill *et al.*, 2022). Blades made of materials with high hardness and exceptional wear resistance usually have a longer service life and greater abrasion resistance. In contrast, blades made of softer or less durable materials tend to wear out faster, resulting in higher maintenance costs and lower tillage efficiency. Therefore, understanding and effectively addressing these factors is crucial to optimise the durability and performance of hoe blades for agricultural purposes.

When restoring these components, it's crucial to enhance the hardness and wear resistance of both the tip and the blade. This improvement significantly extends the service life of the working components of agricultural machinery used for tillage. Various methods are used to achieve this hardening. Heat treatment is a common technology that can change the properties of a material to increase hardness and wear resistance. Another approach is to use bimetallic compounds, such as plating or double-layer steels, which create a layered structure that combines the strength of one material with the wear resistance of another. In addition, spraying wear-resistant coatings effectively adds a protective layer to the surface of parts, providing protection against abrasive wear. Solid alloy plating involves welding or gluing solid materials to the surface of parts to increase their hardness and wear resistance. Ultimately, the vibration hardening of the blades in the cutting elements uses mechanical vibrations to increase the surface hardness of the material, improving its ability to resist wear and extend its service life in agricultural conditions. These hardening methods are crucial for maintaining and improving the efficiency and reliability of agricultural tillage equipment by extending the service life and improving the productivity of the main working components.

In the course of the study, the dynamics of wear of the blades and tips of boom blades under various hardening methods were considered, which is described in detail in Table 1. Based on the outcomes of these hardening techniques, the restoration approach involving welded 45 G steel corner plates with surfacing and vibration-point hardening demonstrated minimal wear while operating the cultivator across 500 hectares. In addition, an analysis of total blade wear was performed, which showed that adhesive wear is 25% of total wear, surface fatigue is 8%, corrosion wear is 2%, and abrasive wear is 20%. It is noted that as the teeth wear out, traction resistance increases, which, in turn, reduces the efficiency of the machine and leads to an increase in fuel consumption by 15-20%.

Table 1. *Signs of wear detected on the edges and tips of the sweep blade*

Choice of tines to use	Cultivator hours worked, ha	Average wear of blades, mm	Average wear of the sweep, mm
New teeth made of 65 G grade steel	500	7.345	22.467
New vibration-reinforced teeth made of 65 G grade steel	500	3.875	14.712
Repaired by welding angle plates made of 45 G steel with enamel surfacing	500	4.652	16.391
Rehabilitated through welding angle plates of 45 G steel with enamel surfacing and vibration hardening	500	2.784	10.126

Source: *compiled by the authors*

Heat treatment increases the strength of the part, but usually does not reach a sufficient quenching depth (0.4-1.2 mm), which leads to relatively low wear resistance (total wear 4.16-11.4 mm). Technological processes utilizing vibration entail subjecting the tool surface to numerous micro-impacts. This method enhances the material of the part, thereby boosting its fatigue strength and resistance to wear. The process of restoring sweep blades and ploughshares includes a structured sequence of technological operations. It starts with cleaning the surface to remove dirt and preparing parts for inspection and sorting, identifying areas that require attention. Next, the worn sections are removed, and depending on whether the part is a cultivator tooth or a ploughshare, corner plates or slats for restoring structural integrity are attached to it. Then the grooves are turned and a surfacing material is applied to increase durability. The cutting edge is carefully sharpened to restore optimal functionality. An important step is vibration hardening, in which the part is treated with micro-shocks to improve its hardness and resistance to fatigue and wear. Ultimately, strict quality control measures are applied to ensure that restored parts meet performance standards before they are returned to service. This thorough process is aimed at extending the service life and improving the efficiency of agricultural machinery components.

After processing 500 hectares, the blade exhibited wear rates of 0.0174 mm/ha for the initial type and 0.0074 mm/ha for the fourth improved type. Likewise, the tine experienced wear rates of 0.0549 mm/ha for the initial type and 0.0227 mm/ha for the improved fourth type. Most failures in agricultural machinery (up to 80%) are caused by mechanical wear caused by abrasion and corrosion, while fatigue failures account for 20-30% of component problems. Corrosion occurs due to the interaction of mechanical components between materials and their environment, which leads to undesirable deterioration of the surface. Abrasive wear is regarded as one of the most hazardous and destructive forms of wear, frequently resulting in catastrophic failures of components. The rate of wear largely depends on the hardness of the abrasive material, and the size and shape of the abrasive particles. Total material loss due to wear can be classified as follows: 15% of wear, 15% of cracks, 55% of surface damage, 15% of material cost loss, and 15% of corrosion. The overall wear distribution consists of 25% adhesive wear, 8% surface fatigue, 2% corrosion wear, and 20% abrasive wear. However, approximately half of all wear issues are attributed to abrasion. Figures 3 and 4 present the results of statistical analysis on the wear resistance and durability of assembled parts and components.

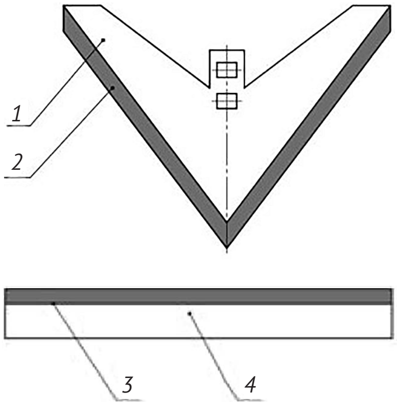


Figure 3. *Cultivator rack diagram*
Notes: *1 – rear surface of the working area; 2 – blade region; 3 – hardened area with enhanced blade hardness towards the rear; 4 – factory-standard hardness zone*
Source: *L. Tulaganova et al. (2022)*

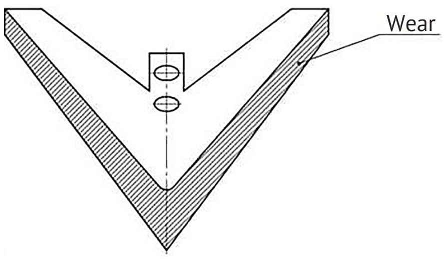
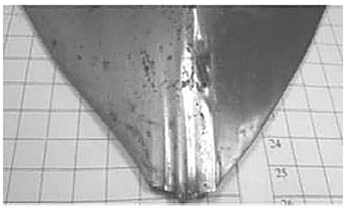


Figure 4. *Example of a geometric imbalance of a tool*
Source: *L. Tulaganova et al. (2022)*

As the workpieces wear out, their cutting edges become less sharp. Blunting results in the formation of reverse chamfers on the cutting edge and drawbar, impacting the consistency of digging depth, drawbar shape, and blade width adversely. Dulling the blade increases traction resistance, decreases performance, and correlates with a 15-20% rise in fuel consumption (Fig. 5).

a)


b)


Figure 5. *The wear of the sweep blade encompasses*
Notes: *a) – altering the sweep's shape; b) – modifying the shape and width of the prong blade*
Source: *L. Tulaganova et al. (2022)*

In 2023, tillage tools were typically made of 65 G carbon steel, which was heat-treated to achieve a hardness of 45-50 HRC (Rockwell C Scale Hardness) (Liao *et al.*, 2022). This process ensures the impact strength of the tools. Techniques such as induction surface treatment, plasma spraying, flame surface treatment, and coating are commonly used to increase the durability of these tillage tools. These methods effectively improve the wear resistance of components exposed to abrasive impacts and wear.

DISCUSSION

Enhancing the wear resistance of agricultural machinery's working components is essential for ensuring the equipment operates efficiently and remains durable over time. In agriculture, the working bodies of machines are subjected to intense loads and abrasive wear when interacting with soil and plant residues. The use of surface hardening methods can significantly improve the performance of parts, reduce maintenance and repair costs, and increase the overall productivity of equipment.

The study conducted by A. Gulyarenko & M. Bembenek (2022) also discussed this aspect, concluding that enhancing the wear resistance of agricultural machinery's working components is crucial for maintaining efficient and durable performance in agricultural settings. These working bodies are subjected to significant loads and abrasive wear when interacting with soil, stones, plant residues, and other materials in the field. As a result of this impact, their surfaces can wear out quickly, which reduces their productivity and requires frequent maintenance or replacement. Also in the study conducted by C.E. Okafor *et al.* (2023), it was noted that the use of surface hardening techniques plays a crucial role in improving the performance of working bodies. These methods may include heat treatment to increase the hardness and wear resistance of the material, spraying or surfacing of special coatings to protect the surface from abrasive effects, and induction hardening or vibration hardening to improve the mechanical properties of the material, which is consistent with the results of this study.

The working parts of agricultural machines, such as ploughshares, seed drills, cultivator tines and harrow discs, are in constant contact with abrasive soil particles and crop residues. Due to intensive wear, their efficiency decreases, which requires frequent replacement or repair. This leads to downtime of equipment and increased operating costs. Increasing the wear resistance of these elements reduces costs and increases productivity. A study conducted by A. Sobirjonov *et al.* (2021) further explored this topic, affirming that enhancing the wear resistance of agricultural machinery's working components is pivotal in agriculture, given their constant exposure to abrasive elements such as soil, rocks, and plant residues. Working elements such as ploughshares, seed drills, cultivator tines and harrow discs are the main elements that determine the efficiency and productivity of agricultural machinery. Their wear and tear and the need for regular replacement or repair significantly increase operating costs and can lead to equipment downtime, which negatively affects the production processes and profitability of agricultural enterprises.

Y. Saygili & B. Cakmak (2023) also investigated that the use of modern surface hardening techniques can significantly improve the characteristics of these working bodies. For example, heat treatment to increase the hardness of the material, spraying special coatings or using bimetallic compounds help to increase wear resistance and extend the service life of components. This not only reduces the frequency of replacements and repairs, but also reduces operating costs, which is an important aspect in the context of modern agriculture, focused on improving efficiency and resilience to economic challenges. Therefore, dedicating resources to enhance the wear resistance of agricultural machinery's working components is a critical measure to streamline production processes and boost overall profitability in the agricultural sector. It is worth noting that the use of methods to increase wear resistance plays an important role in agriculture, helping to reduce costs and increase the efficiency of agricultural machinery.

Wear-resistant coating spraying uses materials such as carbides, nitrides, and oxides to create coatings that are resistant to abrasive wear by thermal and vacuum spraying. This aspect has attracted the attention of many researchers, including J. Liu *et al.* (2021), who emphasise that surface hardening techniques play an important role in improving the durability and efficiency of metal parts subject to intense wear. One of the main methods is heat treatment, which includes quenching, carburisation, and nitrocementation. Quenching increases the hardness of the metal by rapidly cooling after heating, making it more resistant to wear. However, this process can make the material more brittle, which requires a balance between hardness and ductility.

B. Białobrzeska *et al.* (2021) concluded that laser hardening is a more modern method that allows local changes in the properties of the metal surface without changing its basic structure. This process is particularly effective for strengthening critical areas where high wear resistance is required. Plasma surfacing creates a wear-resistant coating by applying a layer of solid material to the surface of the part, which increases its resistance to abrasive wear and improves the adhesion of the coating to the base material. These results support the above study, as these methods not only increase the service life of parts, but also reduce operating costs by reducing the frequency of replacements and repairs, which is important for the economic efficiency of agricultural and industrial enterprises.

The advantages of surface hardening are increased service life of parts, which reduces the frequency of their replacement and repair and reduced operating costs, as less wear and tear on parts leads to lower maintenance and replacement costs, which is especially important for farmers and agricultural enterprises. Increased productivity: reliable and wear-resistant working elements ensure smooth operation of machinery, which contributes to increasing the overall productivity of agricultural operations. E. Benami *et al.* (2021) investigated this phenomenon, noting that surface hardening plays a key role in agriculture, where the working bodies of agricultural machinery are subjected to significant mechanical and abrasive loads. The use of methods such as quenching, plasma spraying and chrome plating significantly increases the service life of parts. This is especially important for farmers and agricultural enterprises, where the reliability and durability of agricultural machinery directly affect production efficiency.

Moreover, P. Chen *et al.* (2021) investigated that less wear on the working bodies of agricultural machinery leads to a decrease in the frequency of replacements and repairs, which reduces operating costs and improves the overall economic efficiency of agricultural production. The longer service life of parts also helps to increase the productivity of agricultural operations, ensuring smooth operation of machinery in the field and increasing overall agricultural output. Data on surface hardening and its impact on agricultural machinery confirm the main points outlined in the previous section. Strengthening the surface of the working bodies significantly increases their wear resistance, which leads to a decrease in the frequency of replacements and repairs. This reduces operating costs and increases the overall productivity of agricultural production. Thus, the use of surface hardening methods is a key factor for ensuring efficient and long-lasting operation of agricultural machinery.

The study by H. Pekşen & A. Kalyon (2021), which also showed that increased wear resistance of working bodies reduces the likelihood of downtime and increases the productivity of agricultural operations. Farmers and agricultural enterprises can save on operating costs, as less wear and tear on parts requires fewer resources to replace and repair them. This is especially important in conditions when the efficiency of using agricultural machinery directly affects the competitiveness and sustainability of the agricultural sector, contributing to its development and modern modernisation. Comparing the data obtained in the course of research, the use of surface hardening methods significantly reduces the rate of wear of the working bodies of agricultural machinery. This increases the interval between replacement of parts, saving on maintenance and increasing the reliability of the equipment. Improved wear resistance also helps to improve the production characteristics of machines, reducing friction and increasing the overall productivity of the agricultural process.

Enhancing the wear resistance of agricultural machinery's working components through surface hardening is essential for achieving efficient and durable performance. Under conditions of heavy loads and abrasive wear, methods such as heat treatment, laser hardening, plasma surfacing, chrome plating and spraying of wear-resistant coatings significantly improve the performance of parts. This leads to an increase in the service life of working bodies, a reduction in operating costs, and an increase in the overall productivity of agricultural machinery. The introduction of surface hardening technologies contributes to increasing the competitiveness and sustainability of the agricultural sector, ensuring the cost-effectiveness and reliability of the use of agricultural machinery.

CONCLUSIONS

Surface hardening plays a crucial role in contemporary agriculture, particularly in enhancing the durability of operational parts within agricultural machinery. This method covers various methods, such as quenching, plasma spraying, and laser quenching, which significantly improve the physical and mechanical properties of component surfaces. Increasing the wear resistance of working parts reduces the frequency of maintenance and lowers the economic costs associated with agricultural machinery by increasing the intervals between replacement of parts. This is especially important in intensive use scenarios where reliable and durable equipment is essential for processing large areas. Surface hardening technology also helps to increase the overall productivity of agricultural work. Increased wear resistance allows the working elements to operate efficiently for a longer time, thereby reducing downtime and improving the quality of tillage processes. Increased wear resistance helps to mitigate the adverse impact on the environment. By reducing the need for replacement and repair of agricultural machinery components, resource consumption is reduced, which, in turn, reduces the overall carbon footprint and environmental impact of agricultural operations.

The paper considered modern technological processes of repair of working bodies of cultivators and identified the main factors that limit their wear resistance and prevent extending their service life. Improving the wear resistance of cultivator parts is crucial both to reduce metal consumption and improve maintenance of agricultural machinery, but also to effectively meet operational requirements. Studies show that the most significant wear occurs on the nose and blade of the cultivator teeth, which directly affects productivity. Key technological methods are aimed at surface hardening without changing the design of these working elements. Thus, the inclusion of surface reinforcement technology in the production and maintenance of agricultural machinery is essential to increase productivity, reduce costs, and improve the overall sustainability of the agricultural sector.

This study, however, include a limited number of examples of the use of specific technologies in different climatic and soil conditions, which may limit the overall applicability of the results obtained. Further research should be aimed at investigating the impact of various surface hardening methods on the energy efficiency and economic profitability of agricultural machinery operation. It is important to assess the costs of using and operating these methods, and their impact on energy consumption and component life. This will help develop recommendations for manufacturers on choosing the most efficient and cost-effective methods to improve the performance of work surfaces.

ACKNOWLEDGEMENTS

None.

CONFLICT OF INTEREST

None.

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Використання поверхневого зміцнення для підвищення зносостійкості робочих органів сільськогосподарських машин

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Анотація. Дослідження було спрямоване на вивчення ефективних методів поверхневого зміцнення робочих органів сільськогосподарських машин для підвищення їхньої зносостійкості та продовження терміну служби. У ході дослідження використовувалися методи поверхневого зміцнення, такі як термічна обробка, хіміко-термічні процеси, покриття та механічні методи. Було показано, що різні методи зміцнення поверхні значно підвищують зносостійкість робочих частин сільськогосподарської техніки. Використання такої термічної обробки як індукційне загартування дозволило підвищити стійкість до зношування завдяки локалізованому нагріву і швидкому охолодженню, що призвело до збільшення твердості матеріалу. Хіміко-термічна обробка, включаючи цементацію, нітроцементацію та нітрування, продемонструвала значне покращення твердості поверхневого шару та підвищення корозійної стійкості. Механічні методи, такі як дробоструминна обробка та коткове зміцнення, збільшили твердість та зносостійкість на 30-50 % за рахунок пластичного деформування поверхні. Було доведено, що застосування наплавлення та покриттів фізичного осадження з парової фази/хімічного осадження з парової фази збільшує довговічність деталей на 20-40 %, що знижує експлуатаційні витрати та підвищує продуктивність сільськогосподарської техніки. У дослідженні розглядалися методи підвищення зносостійкості робочих частин сільськогосподарської техніки, при цьому наголошувалося на значній проблемі, пов'язаній з тим, що українські сільськогосподарські машини часто мали більш короткий термін служби (в 1,2-2 рази) порівняно з імпортними аналогами. Проаналізовано причини зносу та погіршення стану зубів культиватора, приділяючи особливу увагу впливу зносу на розмір та форму робочих частин, що призводило до зниження їх ефективності. Вивчені методи зміцнення поверхні можуть бути безпосередньо впроваджені у виробництво для збільшення довговічності та надійності робочих частин сільськогосподарської техніки, що сприятиме підвищенню їхньої ефективності та зниженню експлуатаційних витрат

Ключові слова: цементація; індукційне загартування; термічна обробка; нітрид титану; алмазоподібні вуглецеві покриття