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IMPROVEMENT OF THE ELECTROSLAG SURFACING TECHNOLOGY FOR THE WORKING PARTS OF THE SOIL TILLAGE MACHINES THROUGH COMPREHENSIVE MODIFICATION OF COATINGS

The object of research is wear-resistant electroslag coatings formed on the working bodies of the soil tillage machines in an electric-driven crystallizer.

The research conducted in the work focuses on eliminating the rapid wear of plowshares and cultivator paws, which is observed when they are exposed to abrasive abrasion and impact wear. Farmers have to replace their plowshares and cultivator paws frequently due to damage, which leads to higher costs for the farmer's own capital during his field work.

To increase the service life of plowshares and cultivator paws, 65G and 45 steel were used in various experiments, and various methods were also applied, including X-ray phase analysis and hardness measurement using HV10. The results show that the structure of the coating has changed. Laboratory tests have shown that the matrix has been crushed by 35–40%, with an increase in the amount of fine carbide by 25%. This change resulted in approximately a 20% increase in microhardness, which resulted in a significant reduction in wear intensity from the initial point of 0.73 to 0.79. Field reports show that the modified part lasts 40% longer than the serial part, and the best sample lasts 100% longer than the serial part. This result demonstrates that stability is provided by a fine-grained structure and uniform distribution of carbides, which prevents the delamination process.

The proposed approach combines thick-layer electroslag deposition with complex modification of the flux-cored wire. The technology can be used in agricultural repair enterprises and allows to reduce the total costs of repair and maintenance of machines by 35–40%.

The obtained results are recommended for the restoration of plowshares, cultivator paws and other working bodies of the soil tillage agricultural machines operating under conditions of intensive abrasive wear.

Keywords: electroslag surfacing, wear resistance, microhardness, carbides, microstructure, plowshares, abrasive wear, resource.

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1. Introduction

Increasing the durability of working bodies of the soil tillage machines is one of the important tasks of agricultural materials science and engineering practice [1, 2]. In agriculture, a significant part of operating costs is associated with the repair, restoration and replacement of the most loaded parts, primarily cutting and working elements of plows, cultivators, harrows and other soil tillage machines. The importance of this problem increases in the conditions of the transition to resource-saving, as well as minimal and zero tillage, when higher requirements are imposed on the working bodies in terms of preserving geometry, dimensional stability and performance over a long service life [2]. Existing technical solutions do not always allow to simultaneously ensure high durability, technological convenience of manufacturing or restoration and proper economic feasibility [1, 2].

Working bodies of the soil tillage machines are operated in difficult conditions, when several wear mechanisms act on their surface simul-

aneously. For black earth, heavy and stony soils, abrasive and impact-abrasive wear are most characteristic [1, 2]. Soil particles and solid mineral inclusions interact with the surface of the part as an abrasive medium, causing microcutting, plastic deformation of the surface layer and the nucleation of microcracks. In the presence of stones or dense solid inclusions in the soil, this process is complicated by local impact loads, which additionally accelerate the destruction of the working edge. As a result, the part gradually loses its initial profile, is more intensively used and decreases in mass, which negatively affects both the quality of the machine and its overall operational performance [1, 2].

Intensive wear also directly affects the energy performance of the units. Blunting of the working edges increases the resistance to soil cultivation, increases traction and fuel consumption. No less important is the fact that frequent replacement of worn parts causes simple equipment to fail precisely during the most intense field work. Therefore, increasing the resource of such elements should be considered not only as a materials science problem, but also as a production and economic problem [3, 4].

Known approaches to increasing wear resistance are conventionally divided into constructive and technological [1, 5]. Constructive ones include the choice of material, changing the geometry of the part, and the use of composite elements. Such solutions can be effective, but usually require either more expensive materials or a more complicated design, which is not always justified for mass parts of agricultural machinery [1, 5]. Technological approaches include thermal and chemical-thermal treatment, as well as the application of strengthening coatings [6, 7]. These methods make it possible to increase the hardness of the surface layer, but their effectiveness significantly depends on the processing modes, and the depth of strengthening is not always sufficient while maintaining the viscosity of the base [5, 6].

A separate group is made up of surfacing and spraying methods, which allow for the local formation of a wear-resistant layer with controlled thickness and composition [6, 8]. Electric arc processes are technologically accessible, but are accompanied by metal losses due to spattering, increased requirements for the qualification of the performer and a less stable thermal cycle [6, 9]. Gas-thermal and plasma methods provide a high level of coating properties, but require expensive equipment, which limits their widespread use in agricultural production [8, 9]. This indicates the feasibility of searching for technologies that would combine high productivity, stability of layer formation and acceptable cost of restoration. Such technologies include electroslag surfacing in a current-carrying crystallizer [10, 11]. This process allows for the formation of thick surfacing layers under a relatively stable thermal regime. Unlike arc methods, heat is released directly in the slag bath through which an electric current passes. This contributes to more efficient use of heat, reduced spatter and formation of a deposited layer with fewer defects. The current-fed crystallizer performs not only the shape-forming function, but also stabilizes the position of the bath and reduces deformation of the part [12, 13]. However, the process itself does not guarantee high wear resistance if the rational composition of the deposited metal is not ensured.

In this aspect, the use of flux-cored wires is promising, which allow for the targeted introduction of not only alloying elements but also strengthening phases (modifiers) into the deposited metal [14]. Compared to solid electrodes, they expand the possibilities of controlling the structure and properties of the coating. However, the effectiveness of such an approach is determined not only by the composition of the filler, but also by the nature of the distribution of strengthening components in the deposited layer, their interaction with the matrix and their influence on the crystallization process [9, 15]. It is these factors that determine the structure of the carbide framework, the size of the matrix grain, the level of residual stresses and, ultimately, the wear resistance of the coating [16, 17]. Therefore, further improvement of electroslag deposition should be associated with the complex modification of the deposited metal.

In this work, an approach based on the complex modification of the deposited metal by the Cr-carbide – NbC – Al_2O_3 system is implemented. This approach is aimed at forming a finer-grained and structurally homogeneous deposited zone, as well as at increasing the resistance of the coating to abrasive and impact-abrasive wear. It is the assessment of the impact of this complex modification on the structure, microhardness, wear intensity and resource of the working bodies that constitutes the content of this research.

Each component of this system performs a specific function. Cr-carbides form a hard framework that directly perceives the abrasive load. Niobium carbide NbC, due to its high thermal stability, inhibits grain growth and promotes the formation of a fine-grained matrix. Aluminum oxide Al_2O_3 forms additional crystallization centers. As a result, a more uniform distribution of solid phases in the coating structure is ensured [9, 18, 19]. It is expected that the complex action of the components of this system will provide increased wear resistance without excessive increase in brittleness [20].

Despite the availability of publications devoted to electroslag surfacing, wear-resistant coatings and restoration of working bodies of the soil tillage machinery, a number of issues remain insufficiently clarified.

The cited scientific sources do not sufficiently fully disclose the regularities of the influence of complex modification of the surfacing metal by the Cr-carbide – NbC – Al_2O_3 system on the formation of the microstructure and phase composition of thick-layer electroslag coatings. The influence of such modification on the distribution of microhardness over the layer thickness, abrasive wear indicators and crack resistance of coatings requires further clarification. The relationship between the structural characteristics of the coating, its laboratory tribological indicators and the actual resource of plowshares and cultivator arrow-shaped paws in real operating conditions is also limited. The issue of the technical and economic feasibility of using complexly modified flux-cored wires for the restoration of such parts in repair production conditions remains insufficiently investigated. These are the issues considered in this work.

The object of research is wear-resistant electroslag coatings formed on the working bodies of the soil tillage machines in a current-fed crystallizer.

The aim of research is to improve the technology of electroslag deposition in a current-fed crystallizer by comprehensive modification of the deposited metal with the Cr-carbide – NbC – Al_2O_3 system to increase the wear resistance and service life of the working bodies of the soil tillage machines.

To achieve the set aim, it is necessary to solve the following objectives:

1. To determine the influence of comprehensive modification of the flux-cored wire on the formation of the microstructure and phase composition of the deposited metal.
2. To evaluate the change in microhardness and abrasive wear indicators depending on the composition of the modifying components.
3. To check the effectiveness of the restored parts during field tests in terms of service life and stability of operation.
4. To establish the technical and economic feasibility of applying the developed technology in the conditions of repair enterprises of the agricultural profile.

2. Materials and Methods

The work investigated the working bodies that most fully reflect the conditions of abrasive and impact-abrasive wear, namely plowshares made of 65G steel and cultivator arrow-shaped paws made of 45 steel. To ensure the possibility of multiple sampling for structural, hardness, tribological and resource studies, model samples on a substrate made of 45 steel with a diameter of 60 mm were used. The thickness of the substrate was 35 mm, and the thickness of the deposited layer was 20–25 mm. This geometry was chosen as a compromise between approaching real parts and the convenience of dividing the sample into separate sections for further research. To systematize the factors that determine the wear resistance and resource of restored working bodies, a cause-and-effect diagram of Ishikawa was developed. In Fig. 1 shows the author's cause-and-effect diagram of factors that determine the wear resistance and resource of working bodies of the soil tillage machines.

Analysis of the diagram in Fig. 1 shows that in the conditions of a repair enterprise, the most controllable and technologically accessible factors are the composition of the deposited metal and the parameters of the electroslag process. In contrast, soil and climatic conditions, the nature of operational loads and agrotechnical requirements belong to external factors that set the operating conditions of parts. That is why the work consistently investigated the influence of the composition of flux-cored wires on the formation of the structure of the deposited metal, the distribution of microhardness over the layer thickness, abrasive wear indicators, the resource of working bodies in field conditions and generalized technical and economic indicators. Special attention was paid to quantitative morphometric analysis and the establishment of dependencies of the type "structure – microhardness – wear resistance – resource". This made it possible to substantiate practical criteria for choosing the composition of deposited coatings for repair enterprises of the agricultural profile.

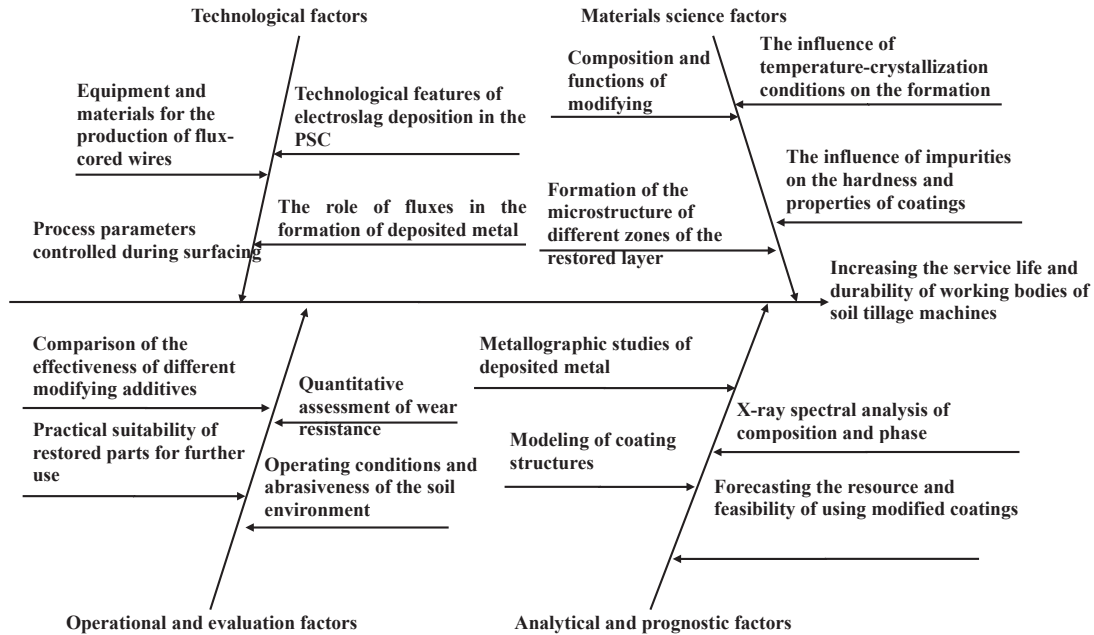


Fig. 1. Ishikawa diagram, reflecting a systematic approach to increasing the resource and durability of working bodies of the soil tillage machines (developed by the authors)

Fig. 2 shows a diagram of the electroslag deposition (ESD) process in a current-fed crystallizer, adapted from the data of work [12]. The powder electrode (position 1) is a consumable electrode-wire, which is continuously fed into the process zone and melts in the slag bath due to the release of heat during the passage of current through the conductive slag [12]. The molten electrode metal in the form of drops passes through the slag into the metal bath, after which crystallization occurs in a water-cooled crystallizer and a deposited layer of a given thickness is formed [12].

Modifying impurities (position 9) are introduced together with the powder filler of the electrode wire, in particular in the form of carbides, oxides and other dispersed components according to the data in Table 1. After entering the liquid metal bath, these components participate in the formation of the coating structure. They simultaneously affect the nucleation of crystals and play the role of strengthening components. As a result, the deposited layer acquires a finer and more homogeneous structure, which positively affects its wear resistance.

The deposition modes were selected taking into account the thermal state of the process and the need for stable formation of the slag bath. The welding current was maintained within 800–1000 A, the voltage was 30–40 V. The flux-cored wire feed speed was 1.5–2.5 m/min, and the speed of movement of the crystallizer relative to the part

was 3–6 mm/s. With such parameters, the process proceeded stably, without violating the tightness of the slag bath, and ensured the formation of a coating 20–25 mm thick in one pass [12].

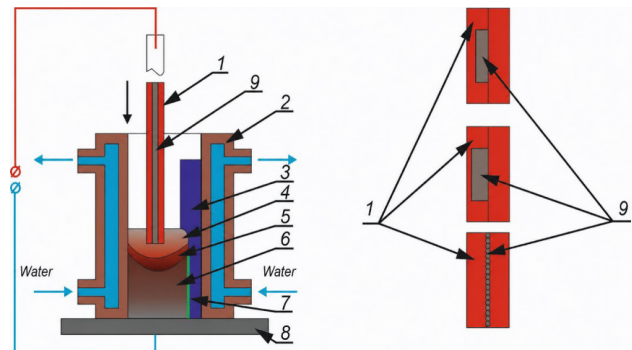


Fig. 2. Scheme of the process of electroslag deposition of working bodies in a current-carrying crystallizer (adapted from [12]): 1 – composite plate electrode; 2 – water-cooled crystallizer; 3 – product to be restored; 4, 5 – slag and metal baths; 6 – deposited metal; 7 – fusion line; 8 – pallet; 9 – charge material

Table 1
Characteristics of basic and modified flux cored wires for electroslag surfacing

Wire option	Main components of the charge	Cr-carbide content in the charge, wt. %	NbC content in the charge, wt. %	Al ₂ O ₃ content in the charge, wt. %	Expected effect
Basic flux cored wire	Steel strip 0.5 × 12 mm; charge: ferrochrome about 28.8%, diamond-clay mixture about 3.2%; the rest is ferroalloy base	0	0	0	A wear-resistant coating is formed for parts operating under conditions of increased friction. Hardness increases, but resistance to abrasive wear remains limited
Modified flux cored wire with NbC	Steel strip; charge: Cr about 20%, Ni about 10%, NbC about 10%; the rest is base charge	0	10	0	Wear resistance and corrosion resistance increase due to the formation of finely dispersed strengthening phases based on niobium; the coating works better under shock and abrasive loading conditions
Modified flux cored wire with CrC and Al ₂ O ₃	Steel strip; charge: CrC about 20%, graphite about 1.5%, crystalline Si about 1.5%, Al ₂ O ₃ about 3%; the rest is base charge	20	0	3	A hard carbide phase based on CrC and a refractory oxide phase Al ₂ O ₃ are formed in the coating structure, which increases microhardness, heat resistance and resistance to abrasive wear

For the research, samples from steel 45 and serial working bodies of the soil tillage machines made of steel 65G (plough shares and arrow-shaped cultivator paws) were used. For surfacing, flux-cored wires with a low-carbon steel sheath were used, the filler of which contained iron powder, ferrochrome, ferromanganese, as well as modifiers Cr-carbides, NbC and Al_2O_3 according to the data in Table 1.

Metallographic studies were performed on samples cut from the central part of the surfacing plates perpendicular to the surfacing direction, after standard preparation of the sections. Electroslag surfacing was performed on the A-1401 installation in a current-carrying water-cooled crystallizer (E. O. Paton Institute of Electrotechnical Engineering, Ukraine), and the microstructure was studied using an IE200M metallographic microscope (SeekScope, China).

The phase composition was specified by X-ray phase analysis with identification of the martensite matrix, chromium carbides of various types, NbC and oxide phases [21, 22].

For a more detailed analysis of the shape of the strengthening phases, their sizes, the nature of the distribution of elements and possible stress concentration zones, scanning electron microscopy was used. A JEOL JSM-6510LV electron microscope (Jeol Ltd., Japan) and an Oxford Instruments X-MaxN X-ray spectrometer (Oxford Instruments, Great Britain) were used. The phase composition was determined by X-ray structural analysis on a DRON-4M diffractometer (PA Burevisnik, Ukraine, Kyiv), and the results were processed in the Mach!4 program (Crystallimpact GmbH, Germany) using the open COD database. An optical-mathematical approach was used for morphometric analysis of digital microimages.

One of the features of the research is the use of optical-mathematical morphometric analysis. Digital microimages of the structure were converted into binary masks with a clear separation of the "matrix – carbides" phases. Using specialized software Mach!4, segmentation was performed to determine the area of individual grains and inclusions, their equivalent diameter, shape factor, and clustering indices. Based on the processing of statistically representative samples, particle size distributions were constructed and the planar fraction of finely dispersed carbides was calculated for each coating variant [23].

The HV10 microhardness was determined by the standard Vickers method on transverse sections. For each sample, a series of measurements were performed in the near-surface zone, the central part of the coating, and in the fusion zone with the base. The results of microhardness determination are given in section 3.2.

To assess abrasive wear resistance, a bench-top installation was used that implements the "sample – abrasive" friction scheme. Quartz sand of standard fraction was used as the abrasive medium. The normal load, sliding speed, and test duration were kept constant for all variants. The results of laboratory tests are given in section 3.2.

3. Results and Discussion

3.1. The influence of complex modification of flux-cored wires on the microstructure and phase composition of the deposited metal

Metallographic analysis showed that the basic electroslag coating obtained from serial flux-cored wires without special modification has a rather coarse martensitic structure and an uneven distribution of the carbide phase [21]. Local accumulations of large carbides are observed in its structure, between which relatively large matrix grains are located. Such heterogeneity contributes to the occurrence of local stresses. Under conditions of impact-abrasive loading, this increases the probability of microcrack nucleation and subsequent chipping of the material, which is clearly visible in the microstructural images shown in Fig. 3.

The introduction of Cr-carbides and aluminum oxide Al_2O_3 into the composition of flux-cored wires noticeably affects the course of crystallization of the deposited metal [21, 22]. As a result, the number of centers for the nucleation of solid phases increases, which contributes

to a decrease in the average size of the matrix grains. The carbide phase is formed smaller and is distributed more evenly in the volume of the coating. Such changes are most clearly manifested in the complex modification of the Cr-carbide – NbC – Al_2O_3 system. NbC particles, due to their high thermal stability and slow dissolution, play the role of effective crystallization centers and at the same time restrain grain growth. As a result, a more homogeneous fine-grained structure of the deposited layer is formed, which is also confirmed by the data shown in Fig. 3.

Fig. 3 shows the characteristic microstructures of the coatings obtained by the authors during metallographic studies. The results of morphometric analysis also confirmed the advantages of the optimally modified composition [23]. It was found that the average equivalent diameter of the grains of the martensite matrix decreases by approximately 35–40% compared to the base coating, and the planar fraction of finely dispersed carbide inclusions increases to 15–20%. A decrease in clustering coefficients indicates a lower tendency of carbides to form large clusters and a more uniform distribution of them in the deposited layer. Such a structure contributes to a more uniform perception of the load and reduces local stress concentration.

The phase composition of the coatings was specified by X-ray diffraction analysis. The results obtained confirmed the presence of a martensitic matrix, chromium carbides of various types, niobium carbide NbC, as well as oxide phases in the structure of the coatings [21, 22].

The totality of the results of metallographic, morphometric and X-ray phase analysis indicates that the complex modification of flux cored wires provides a directed change in the mechanism of structure formation. As a result, a more dispersed, uniform and structurally stable system is formed, which is a prerequisite for increasing the hardness, wear resistance and durability of deposited coatings.

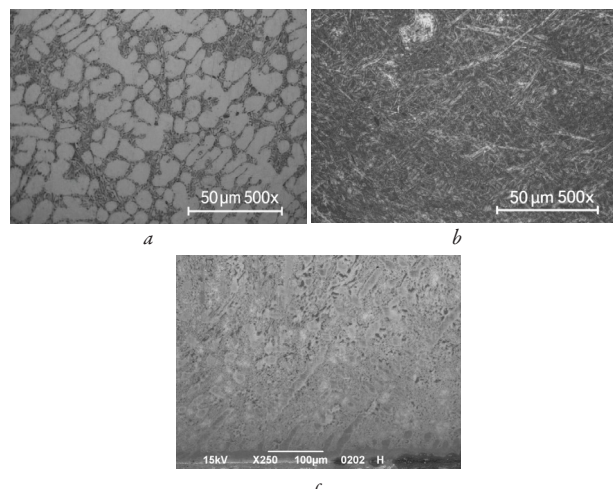


Fig. 3. Characteristic microstructures of electroslag coatings obtained by the authors during metallographic studies: *a* – base coating obtained using serial flux-cored wire; *b* – coating modified by the Cr-carbide – Al_2O_3 system; *c* – coating with complex modification by the Cr-carbide – NbC – Al_2O_3 system

3.2. The influence of modifiers on the microhardness and abrasive wear resistance of deposited coatings

Evaluation of the microhardness of deposited coatings showed that the composition of flux cored wire significantly affects the hardness of structural components and the average microhardness of the deposited layer. According to the data in Table 2, for the base coating the average microhardness is 466 HV10. For modified compositions this figure increases to 489 HV10 for wire No. 2 and to 524 HV10 for wire No. 3. The increase in microhardness is consistent with an increase in the proportion of hard inclusions and the grinding of the structural components of the coating. In Table 2, all values of the microhardness of the structural components are given in units of HV10.

Table 2

Indices of the microhardness of the structural components of electrosag coatings depending on the composition of the flux-cored wire

Wire No.	Matrix microhardness, HV10	Carbides microhardness, HV10	Matrix microhardness, HV10	Carbides eutectic phase microhardness, HV10	Average coating microhardness, HV10
1	361	571	361	571	466
2	361	617	361	617	489
3	492	556	492	556	524

It is important that for modified coatings the hardness distribution along the thickness of the deposited layer is characterized by a less sharp transition in the fusion zone. This provides better deformation compatibility of the coating with the base metal and reduces the risk of local stress accumulation. The highest microhardness values were recorded for the carbide-oxide composition with CrC and Al₂O₃, which is shown in a generalized form in Fig. 4. Therefore, by changing the composition of the flux-cored wire, it is possible to purposefully increase the hardness of the coating without significantly complicating its structure and without a noticeable increase in heterogeneity.

Fig. 4 shows the hardness HRC for a serial working soil tillage tool as a separate indicator of the surface hardness of the part, while for deposited coatings the microhardness HV10 is given. The results of laboratory tests on abrasive wear also confirmed the higher resistance of the modified coatings compared to the base version. As can be seen from the data in Table 3, for wire No. 2, the relative weight intensity of wear is 0.79, which corresponds to a relative wear resistance of 1.26 conventional units. For wire No. 3, this indicator decreases to 0.73, while the relative wear resistance increases to 1.37 conventional units. Thus, the introduction of modifiers provides a constant decrease in the intensity of abrasive wear, and the best result was obtained for a coating with a carbide-oxide composition.

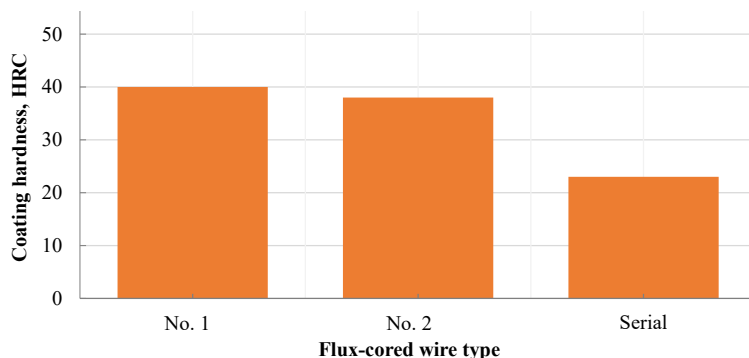


Fig. 4. Comparative diagram of the hardness of electrosag coatings and a serial working body: for deposited coatings, the microhardness is HV10, for a serial working body, the hardness is HRC

To illustrate the relationship between microhardness and wear resistance, a generalized dependence "hardness – wear resistance" was constructed, shown in Fig. 5. Analysis of this dependence shows its nonlinear nature. In the initial area, an increase in hardness is accompanied by an increase in wear resistance. At the same time, an excessive increase in hardness without proper structural optimization can lead to an increase in brittleness and a tendency to chipping. The most favorable area is the one in which increased hardness is combined with a fine-grained structure and a uniform distribution of dispersed carbides, which is consistent with the literature data [9].

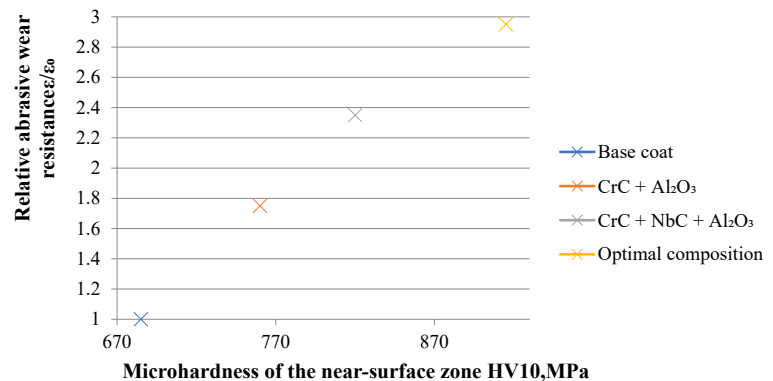


Fig. 5. Generalized dependence of the hardness of electrosag coatings and their relative abrasive wear resistance on the composition of flux cored wires

Summing up the results obtained, it is possible to conclude that the complex modification of flux cored wires provides a simultaneous increase in the microhardness and abrasive wear resistance of electrosag coatings. The highest efficiency was shown by the composition of wire No. 3, for which the maximum average microhardness and the best resistance to abrasive wear were recorded. This allows to consider such a composition as the most promising for the restoration of working bodies of the soil tillage machines.

3.3. Field tests of restored working bodies and assessment of their resource

Field tests of restored working bodies were carried out on tillage units operating in heavy, in particular rocky, soils [24]. Batches of serial unrestored parts, as well as working bodies restored by electrosag surfacing using basic and modified flux cored wires, were installed on the same units. During operation, the area of the cultivated field before reaching the limit state, the change in the mass and geometric parameters of the parts, the number of their replacements, as well as the time spent on dismantling, installing and adjusting the equipment were recorded.

As can be seen from the data in Table 4, the use of electrosag surfacing with complexly modified flux-cored

Table 3
Weight intensity of abrasive wear and relative wear resistance of electrosag coatings

Wire No.	Coating option	Mass loss Δm, g	Relative weight intensity of wear	Relative wear resistance, conventional units
1	Basic	0.0024	1.00	1.00
2	Complex modified (NbC)	0.0019	0.79	1.26
3	Carbide-oxide (CrC + Al ₂ O ₃)	0.00175	0.73	1.37

wires provides not only an increase in the resource of the working soil tillage tools, but also a decrease in the number of their replacements and total costs per 1000 hectares of cultivation.

Analysis of the obtained data showed that serial working bodies without special strengthening provide a resource of about 35–40 hectares. Parts restored by electroslag surfacing using a basic flux-cored wire worked longer and provided a service life of 55–60 hectares. The highest indicators were obtained for working bodies restored using complex modified wires of the NbC – CrC – Al₂O₃ system. For this variant, the resource was approximately 65–80 hectares, which on average corresponds to an increase of 35–40% compared to serial parts, and for the optimal coating composition – up to 85–100%. This confirms the high efficiency of complex modification of the surfacing layer in real operating conditions.

The dependence of the mass loss of working bodies on the area of cultivation is shown in Fig. 6. The graphs were constructed by the

authors based on the results of field tests. For parts with complexly modified coatings, wear curves are flatter than for serial parts.

This indicates a lower wear intensity of such parts throughout the entire testing period. It is important that during field studies no cases of delamination or chipping of the deposited layer were recorded. The absence of sharp jumps in the mass loss curves indicates sufficient crack resistance of the coatings and stable operation of the deposited layer under abrasive and impact-abrasive loading.

Thus, the results of field tests confirmed the effectiveness and practical feasibility of restoring plowshares and cultivator arrow-shaped paws by the method of electroslag deposition with complex modification of coatings.

In real operating conditions, this technology provides an increase in the resource of parts, a decrease in the frequency of their replacements and an increase in the operational stability of the soil tillage units. This allows to consider modified electroslag coatings as a feasible solution for practical application at repair enterprises of the agricultural profile.

Table 4

Comparison of the resource and economic effect when using serial and restored working tools

Working element variant	Coating characteristics	Time to limit state, ha	Number of replacements of working elements per 1000 ha	Total costs per 1000 ha, share of the baseline	Relative costs, %	Cost savings compared to the baseline, %
Standard	No special modifiers (typical serial plowshares and paws)	~35–40	40	1.0	100	–
Renewed by electroslag deposition using basic flux cored wire	Base wire without carbonitride and oxide modifiers	~55–60	25–28	≈0.7	~70	≈20
Renewed by electroslag deposition using modified flux cored wires (NbC, CrC, Al ₂ O ₃)	Surfaced with wires with modifying impurities NbC, CrC and Al ₂ O ₃ ; fine-grained structure; increased wear resistance	~65–80	20–22	≈0.5–0.6	~50	≈40

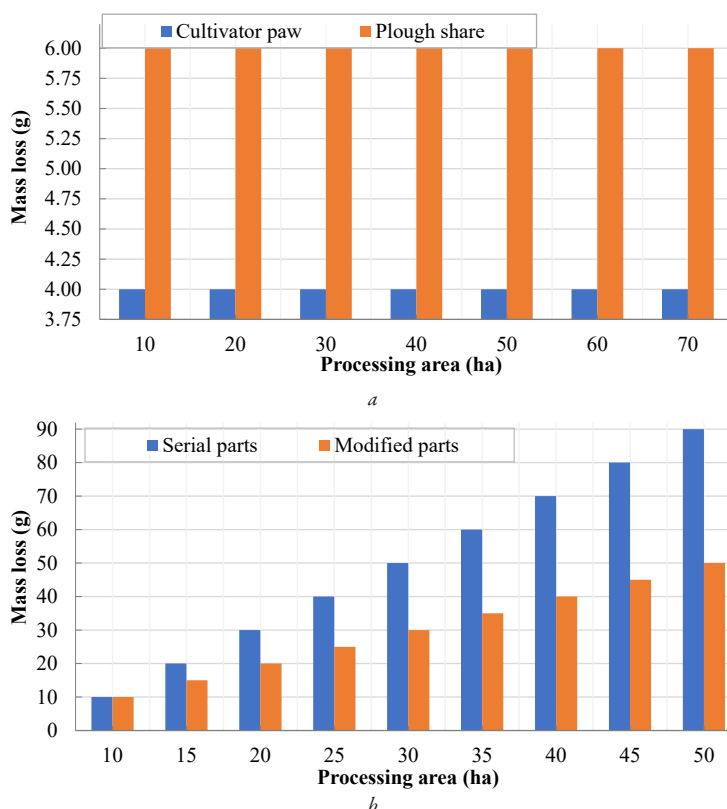


Fig. 6. Dependence of mass loss of working bodies of the soil tillage machines on the cultivation area, constructed according to the results of field tests: a – serial unrestored parts; b – parts with complexly modified coatings

3.4. Technical and economic feasibility of applying the developed restoration technology

The technical and economic feasibility of applying electroslag surfacing with complexly modified flux-cored wires was assessed taking into account the resource of working bodies, the frequency of their replacements during operation, as well as the costs associated with dismantling, installation, equipment adjustment and machine downtime during technological operations [25].

The results obtained showed that the use of restored working bodies allows for a significant reduction in operating costs compared to serial parts. The economic effect is achieved primarily by increasing the resource of parts and reducing the frequency of their replacements. For the basic restoration option, the total costs are reduced to approximately 70% of the level of serial parts. For electroslag surfacing with complex modified coatings, this indicator decreases to approximately 50–60% of the base level. Accordingly, the cost savings compared to serial parts are about 20% for the base wire and about 40% for modified compositions. This indicates the high feasibility of using complex modified flux cored wires in repair production conditions.

The practical efficiency of the developed technology is also confirmed by the results of economic calculations performed within the framework of this research. In particular, the introduction of modified coatings for cultivator paws provides an economic effect of 350 USD, and the reduction in costs for their repair is 390 USD. Restoration of plowshares using electroslag surfacing with modifiers provides savings of 440 USD. The total economic efficiency of the implementation of the developed surfacing technology and strengthening of agricultural machinery parts when cultivating 1000 hectares is over 1,180 USD.

Therefore, the use of electroslag surfacing with complex modified coatings is technically and economically feasible for the restoration of working bodies of the soil tillage machines. This approach provides an increase in the resource of parts, a decrease in the number of their replacements, a reduction in repair and maintenance costs, as well as an increase in the stability of the equipment under conditions of intensive abrasive and impact-abrasive wear.

3.5. Limitations and directions of research development

The practical significance of the results obtained is that the developed technology of electroslag surfacing with complex modification of flux-cored wires can be used at repair enterprises of the agricultural profile for the restoration of plowshares and cultivator arrow-shaped paws. The use of this technology makes it possible to increase the resource of working bodies, reduce the intensity of abrasive wear, reduce the frequency of replacement of parts during operation and, accordingly, reduce the costs of repair and maintenance of equipment. Field tests have shown that such coatings work reliably in difficult conditions, in particular on heavy and rocky soils. Economic calculations have also confirmed the feasibility of their practical application.

The conducted research has certain limitations, despite the results obtained. Experimental testing was carried out only for certain types of working elements of the soil tillage machines, a small number of flux-cored wire compositions and specific operating modes. In this regard, it is strongly recommended to further improve the ideal deposition regimes, determine the nature of modifying additives and assess the stability of coating properties on parts of different sizes with different grades of base metal and under different operating conditions before the conclusions can be applied in general practice. Special attention should be paid to studying the prospects for adapting the technology to production conditions at various repair enterprises.

Future research should be aimed at increasing the number of modifying additives, determining their optimal content in the composition of flux-cored wires and studying in more detail the relationship between the microstructure, phase composition, crack resistance and

durability of deposited coatings. One of the directions is the research of new refractory elements, such as silicon carbide, which may be a suitable candidate for increasing the hardness, thermal stability and resistance of coatings to abrasive wear. In addition, it is advisable to expand the field test program to include other types of agricultural machinery working bodies and various soil and climatic operating conditions.

4. Conclusions

1. The research studied the effect of combined modification of flux-cored wire on the process of structure formation of the deposited metal. The use of the system (Cr-carbide – NbC – Al₂O₃) was found to contribute to the formation of both a finer and more uniform matrix and better dispersion of carbide phase particles. Tandem deformation of wire rods leads to a decrease in the average grain size by 35–40% and an increase in the number of finely dispersed carbide inclusions by 15–20%. The data obtained indicate the possibility of controlled regulation of the process of structure formation of the deposited layer, which allows the production of coatings with better operational properties. The practical achievement lies in the rational assessment of the composition of flux-cored wire, which should be selected depending on the operating conditions of the restored parts related to the soil tillage machines.

2. The effect of the composition of modifying additives on the microhardness and wear resistance of coatings was studied. The average microhardness value of the base coating is 466 HV10. This value increases to 489 HV10 in the case of NbC modification and to 524 HV10 in the case of CrC + Al₂O₃ carbide (carbide-oxide composition). At the same time, the relative weight intensity of abrasive wear decreases to 0.79 and 0.73, and the relative wear resistance increases to 1.26 and 1.37 conventional units, respectively. This shows that the best effect is due not only to the increase in hardness, but primarily to the combination of higher microhardness, fine-grained matrix structure and uniform distribution of carbide phases. The practical significance of this result lies in the possibility of choosing the optimal coating composition based on the ratio of hardness and wear resistance.

3. The effectiveness of the restored parts in real field conditions has been confirmed. It was established that the resource of serial unrecovered working bodies is approximately 35–40 ha, parts restored with basic flux-cored wire – 55–60 ha, and parts with complexly modified coatings – 65–80 ha. On average, the resource of such working bodies increases by 40%, and for the optimal composition of the coating – by 85–100% compared to serial parts. It is important that during operation no delamination or chipping of the deposited layer was recorded. This indicates sufficient reliability and stability of the coatings even when working on heavy and rocky soils and confirms the possibility of their practical use in real conditions of operation of the soil tillage equipment.

4. The technical and economic feasibility of using the developed technology at repair enterprises of the agricultural sector has been proven. The use of restored parts with multilayer modified coatings reduces the total costs of repair and maintenance of machines by 35–40%. The economic effect is 150 USD, and the reduction in repairs is 390 USD for parts that work actively, such as tines. The savings for plowshares are 440 USD. The total economic effect of using this technology to process 1000 hectares exceeds 1180 USD. The complex modification of flux-cored wires is not only technically effective, but also a cost-effective solution for the restoration of working parts of the soil tillage equipment.

Conflict of interest

The authors declare that they have no conflict of interest regarding this research, including financial, personal, authorship or other nature, which could affect the research and its results presented in this paper.

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The research was conducted without financial support.

Data availability

Data will be provided upon reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the presented paper.

Authors' contributions

Ivan Rybalko: Conceptualization, Methodology, Supervision, Writing – review and editing; **Andrii Zakharov:** Investigation, Data curation, Formal analysis, Visualization, Writing – original draft; **Oleksandr Tihonov:** Methodology, Validation, Resources, Writing – review and editing.

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