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Research on the technological process of restoration with electrodiffusion strengthening of the working surfaces of the segments of the headers of combine harvesters

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Abstract

The paper presents a study of the technological process of restoring the working surfaces of combine harvester header segments using electrodiffusion strengthening (EDS). The EDS of restored Duracut Knife Sections was experimentally investigated. It was found that after EDS, the microhardness of the working surfaces of the Duracut Knife Sections increased 1.03 - 2.09 times to a depth of 200 - 500 microns. With a current density range from 0.022 - 0.095 A/cm², the ratio between the hardness of the front and rear surfaces of the blade was observed to range from 1.26 - 1.30, ensuring a self-sharpening effect. The relative wear resistance of the restored segments with EDS hardening was on average 1.3 times higher than that of new segments. Quantitative microanalysis of the chemical composition across the cross-section of the EDS-treated segments revealed an increase in the concentration of alloy-forming components in the hardened surface by 1.1 - 2.4 times compared to the core. As a result of diffusion segregation, the concentration of elements increased in the following ranges: carbon 1.6 - 1.8 times, chromium 2.2 - 2.4 times, silicon 1.7 - 2.1 times, and manganese 1.1 - 1.3 times. Larger values were observed on the rear surface of the restored segment's blade. A technological process for restoring the working surfaces of the Duracut Knife Sections of the John Deere 900 combine harvester header using EDS has been developed. The proposed technology allows for the restoration and strengthening of the working surfaces of segments in grain harvesting and forage harvesting combines, as well as mowers. Comparative operational tests on the John Deere 900 combine harvester during wheat harvesting showed that after processing with EDS, the wear resistance of the Duracut Knife Sections increased to 1.43 - 1.65 ha/mm after 90 hectares of use, which is 1.5 - 1.9 times higher than the standard segments restored without hardening. For the EDS-hardened segments, the blade thickness were maintained after the operational tests, indicating the presence of the self-sharpening effect. The resource of the Duracut Knife Sections restored with EDS was 1.7 - 2.4 times higher than that of standard segments restored without hardening.

Key words: wear resistance, friction coefficient, electrodiffusion strengthening, header segment, durability.

Introduction

Segments are mass-produced for equipping new agricultural machinery but are primarily used to replace worn-out parts. The highest failure rate in grain harvesters occurs in the harvesting unit, with approximately one-third of these failures due to the breakdown of cutter bar segments. Operational experience shows that standard segments, both domestic and foreign, have a relatively low service life. This leads to forced downtime of agricultural equipment due to the replacement of worn parts.

During operation, cutter bar segments in grain and forage harvesters, as well as in mower cutting mechanisms, undergo abrasive wear. As the cutting edges dull, agricultural requirements and deadlines are compromised, crop losses increase, and energy consumption rises, ultimately raising production costs and reducing the competitiveness of agricultural enterprises.

Therefore, extending the service life of harvester cutter bar segments is a highly relevant issue. To achieve this, it is necessary to selectively form reinforced layers with different properties on the working surfaces of segments during restoration. Unfortunately, existing strengthening technologies and methods cannot fully provide the desired results. In our view, the most promising approach involves restoration and reinforcement techniques based on electrical treatment.

Literature review

Restoring and strengthening components allow agricultural machinery to regain its operational lifespan and, in some cases, extend it by up to 2.5 times. This is especially crucial when it comes to repairing imported components. To enhance the durability of harvester header components, it is necessary to create coatings with high physical and mechanical properties or apply a reinforced layer to the wearing cutting surfaces [1].

Standard cutting mechanism segments are typically made from tool-grade carbon steels such as U8, U9, and U10. During production, these components undergo hardening to a hardness level of HRC 50–55 through high-frequency induction hardening (HFH) along the cutting edge of the segment [2]. These tool-grade carbon steels exhibit high hardness and reduced brittleness [3]. However, field operation experience with segments made from U8, U9, and U10 steels shows that, despite heat treatment, they lack sufficient wear resistance, wear down quickly to their minimal limit, and have a short service life.

Recently, manufacturers have increasingly used steels such as 65 and 65G for segment production. These segments undergo edge hardening with tempering to the specified hardness [4], penetrating up to 1 mm deep. However, practical field experience indicates that such segments also suffer from poor wear resistance and degrade rapidly. The primary causes of standard segment failure include rapid dulling, which increases the energy consumption of the cutting process and negatively impacts both the cut quality and overall harvesting efficiency.

Methods for increasing the service life of harvester cutting mechanism components by altering material composition or design have well-documented drawbacks [5]. Therefore, preference is given to methods that enhance the durability of components. Existing methods for extending the service life of cutting mechanism components are primarily implemented by increasing the wear resistance of cutting surfaces.

A review of the literature indicates that the dulling of standard segment blades results from rounding, abrasion, deformation, and chipping of the cutting edge. This occurs because standard segment processing leads to either excessively high or insufficient surface hardness [6]. The following technological methods provide high surface hardness: electrolytic hardening, high-speed induction boriding, nitriding, thermodiffusion chromizing, and plasma metallization. However, boriding has disadvantages, such as increased brittleness of borides and high internal stresses in the treated part. Unfortunately, plasma metallization involves complex equipment, the release of harmful compounds, ultraviolet radiation, and high noise levels. Thermodiffusion chromizing significantly affects the thermal state of the part and contributes to air pollution, gas contamination, and workplace dust. Nitriding is associated with high internal stresses, long processing times, and complex equipment. Using welding for cutting elements is impractical because it requires extensive machining to achieve the required segment geometry.

The authors of [4] suggest extending the lifespan of harvester segment blades by electrolytic chrome plating. However, when the coating thickness exceeds 32 μm, excessive cracking occurs, leading to coating delamination. Additionally, the application of electrolytic coatings, including electrolytic chrome plating, is characterized by high labor costs, low environmental friendliness, and relatively low efficiency.

Among the most promising [6] and effective methods for restoring worn surfaces, the following are considered the most justified.

The most promising and effective methods for restoring worn surfaces reasonably include electrocontact techniques. The advantages of electrocontact welding include high hardness and wear resistance of the coating, minimal heating of the part, low machining allowance, no burnout of alloying elements, favorable working conditions, and more. However, after electrocontact welding of a steel strip, it is necessary to perform chemical-thermal or thermomechanical treatment, or surface hardening, to achieve a uniform microstructure in the heat-affected zone.

In the cutting units of harvesting machines, the primary challenge in addressing segment wear and durability lies in ensuring their self-sharpening during plant cutting. This should help maintain the segment's initial optimal profile while significantly reducing the pressure of the cut plant stems on the cutting edge.

In agricultural and engineering sciences, the theoretical models of Goryachkin V.P. and Reznik N.E. have found widespread application in describing the interaction between a blade and the material being cut. Meanwhile, the self-sharpening effect of a reinforced blade is explained by the phenomenological model of Tkachev V.N. [7]. Some authors use original approaches and integrate the aforementioned models.

By controlling the wear rate of different blade surfaces, self-sharpening can be achieved [6]. The blade surfaces must resist wear differently, ensuring equal wear rates for both the more and less loaded areas while maintaining a constant blade profile.

When determining the required parameters of cutting blades in harvesting machinery, it is necessary to consider their operating conditions. The wear pattern of blade segments depends on their interaction with the cut mass and abrasive particles [8]. At high movement speeds of cutting components, intensive wear can occur even in the absence of abrasive particles in organic matter.

Studies on segment wear during operation show that the wear intensity on the rear side is significantly higher than on the front side [9]. As a result, the blade's microgeometry changes, reducing its cutting ability. This necessitates the subsequent restoration of the required working surface parameters of the segments.

The essence of the self-sharpening phenomenon lies in the selective wear of the blade, which preserves its necessary shape and cutting properties.

The authors of [10] have established that to ensure the self-sharpening effect of grain harvester segments, the hardness ratio between the rear and front surfaces of the blade should be within the range of HV2/HV1 = 1.26–1.30.

Based on information about the wear characteristics of the cutting elements under consideration, it can be concluded that increasing their durability through self-sharpening during operation may be achieved by applying hard and wear-resistant coatings of the required thickness to the working surfaces [9].

The longevity of thin-bladed cutting components made of steel that has undergone hardening and tempering is relatively low, reducing the reliability and, consequently, the productivity of agricultural machinery [10].

Chromium plating the segments on the rear side results in less wear compared to chromium plating on the front side [7]. Extending the lifespan of segments is possible by forming coatings on the working surface that provide high hardness without increasing the brittleness of the metal from which the segment is made.

Foreign researchers suggest achieving a self-sharpening effect by strengthening the front and rear surfaces of the blade segments with a laser beam to an approximate depth of 254–1016 μm [8]. The preferred thickness of the hardened layer on the rear and front surfaces of the segment is 508 μm.

Research on the wear resistance of structures with hard inclusions is of great interest, as these inclusions can significantly influence the scratch formation mechanism during friction against a metallic surface [10].

Many researchers assert that the wear resistance of alloys increases with a higher concentration of carbides in the structure and their greater hardness [11]. This viewpoint is difficult to dispute.

Thus, to reduce wear on cutting components of agricultural machinery, it is necessary to develop strengthening methods that not only enhance the wear resistance of steel but also provide a self-sharpening effect for the blades [6].

In recent years, significant attention has been given to utilizing the self-sharpening effect in cutting mechanisms. One of the promising methods for improving the wear resistance of blade tools in this direction is gas-flame spraying [7]. This treatment results in a hardened layer thickness of up to 1000 μm, with the restored surface achieving a hardness of HRC65.

Another promising method for increasing wear resistance is the application of hardening coatings to the surfaces of cutting unit segments in grain harvesters. One such method is electro-spark treatment (EST), which can be applied both during manufacturing and repair processes [8]. As a result of low-voltage EST, a layer with a modified microstructure and a thickness of 10–30 μm forms on the surface of the part [9]. The application of electro-spark coatings to the cutting surface of the harvester finger increases its wear resistance by 1.7 to 2.2 times compared to standard versions and extends its service life by up to 2 times [10].

The advantages of electro-spark deposition (ESD) include the simplicity of technological operations, low energy consumption, and minimal heating of parts, even those with complex geometries. However, increasing the thickness of electro-spark coatings with high contact density remains a challenge [11].

A unique method that combines mechanical and thermal effects on a restored part is electromechanical processing (EMP) [12]. Among EMP techniques aimed at improving wear resistance [13], electromechanical restoration has been tested as a method for enhancing part dimensions while improving their physical and mechanical properties. The hardened layer depth after electromechanical surface hardening can reach up to 2 mm, with surface hardness ranging from 42 to 68 HRC. However, the maximum hardness is observed at a depth of 0.10 to 0.15 mm from the treated surface. Therefore, EMP requires an additional allowance for final surface finishing.

Overall, most existing hardening methods are unsuitable for the cutting segment components of harvesting machinery [12]. The current situation in the agricultural sector necessitates comprehensive scientific research.

Purpose

The purpose of the research is to increase the service life of the segments of grain harvester combines by developing a restoration technology with strengthening through electrodiffusion strengthening (EDS).

Research methodology

The research program included the following objectives: to conduct theoretical and experimental studies on the EDS segments of grain harvesting combine headers, to study the patterns of hardened layer formation on the working surfaces of EDS segments, to carry out comparative operational tests of the hardened combine segments, and to develop a technology for restoring segments using electrode diffusion hardening.

The theoretical research was based on the laws of upward diffusion in steels. Standard methods were used for the experimental research, including: experimental design planning, microhardness measurement, metallographic analysis, scanning electron microscopy, X-ray fluorescence analysis, energy-dispersive spectroscopy, X-ray diffraction phase analysis, and wear resistance testing. The results of the studies were processed using standard methods of mathematical statistics.

In accordance with the set goals and objectives of the dissertation, a selection of agricultural machinery components was made. For the research, worn-out serial segments Duracut Knife Sections (Canada) with a large upper notch were chosen. These segments are installed on grain harvesters for various crops.

The choice of electrolyte for the EDS process was based on its performance at processing temperatures of 800–850 °C, weakly oxidative properties, availability, environmental cleanliness, safety for humans, and low cost.

To evaluate the microstructure of the segments, a metallographic method according to ISO 643:2019 was used. Some of the segments strengthened by EDS were cut. Subsequently, microsections were made from the obtained fragments for research [13].

The microhardness of the segments was determined using the Vickers restored indentation method (6361-4:2014) on a PMT-3M microhardness tester (3-3.1377) with a load on the diamond tip of 1.962 N.

To determine the chemical composition of the segment material, the X-ray fluorescence method was used. Primary X-rays irradiate the analyzed alloy and cause secondary X-ray radiation. The resulting spectrum depends on the elemental composition of the material. The element was determined based on the dependence of the radiation intensity on its mass fraction in the alloy.

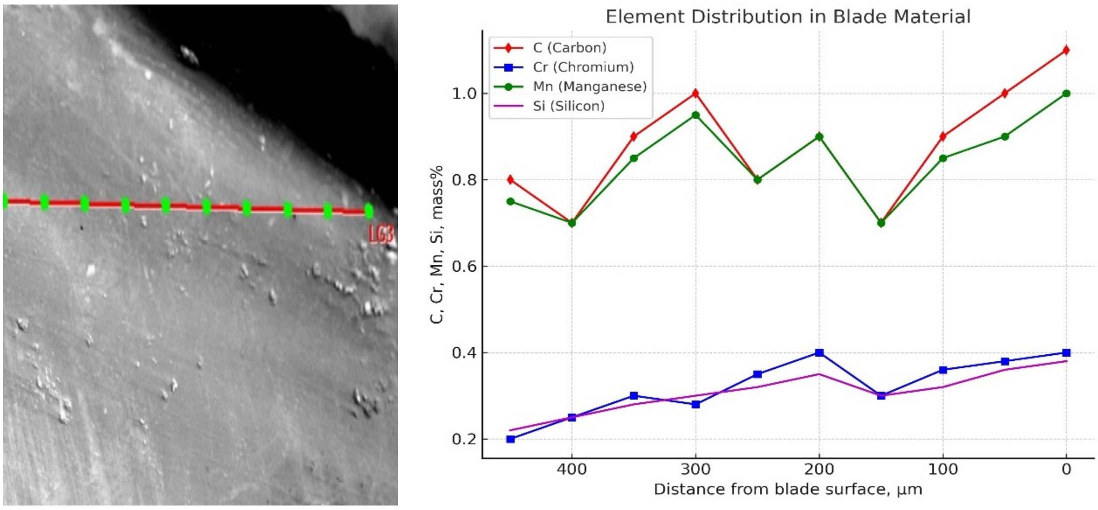
Operating experience shows that during operation, the segments of grain harvester headers are subject to abrasive wear, with their back side wearing out more. In this regard, a method for testing segments for wear resistance during friction against loosely fixed abrasive particles according to (23.208-79) was chosen for laboratory studies. The tests were carried out on a friction machine SMC-2 using the "roller – plate" scheme.

Research results

In EDS with a current density of 0.120 A/cm², the microhardness of the blade's front surface increases significantly, leading to a reduction in the analyzed ratio. In contrast, at a current density of 0.011 A/cm², surface hardening is minimal, resulting in a negligible difference between the microhardness of the blade's front and rear surfaces. Consequently, the ratio between these values approaches unity.

According to the research plan and methodology, wear resistance tests of restored and new segments were conducted using the SMTs-2 friction testing machine, with friction against loosely fixed abrasive particles [14].

For some segments after EDS, a quantitative microanalysis of element concentrations across the cross-section was performed using energy-dispersive spectroscopy. Fig. 1, a shows the spectral analysis areas with marked points on the image obtained from a scanning electron microscope (SEM). Fig. 1, b presents the corresponding distribution of alloying element concentrations by depth on the hardened front surface of the segment blade after EDS at a current density of 0.070 A/cm².



a b

Fig. 1. Distribution of alloying elements by depth on the reinforced front surface of the segment blade after EDS: a - spectral analysis areas (SEM ×250); b - element concentration

In segments subjected to EDS, an increased concentration of carbon and alloying elements was detected in the hardened layer to a depth of up to 400 µm. Due to diffusion segregation during EDS, the concentration of carbon in the working surfaces of the segments increased by 1.6-1.8 times, chromium by 2.2-2.4 times, silicon by 1.7-2.1 times, and manganese by 1.1-1.3 times [15]. Notably, after electro-diffusion hardening, the concentration of alloying components on the rear surface of the segment blade was higher than on the front surface, specifically: carbon by 0.07 wt.%, chromium by 0.12 wt.%, silicon, and manganese by 0.02 wt.%. The microstructure of the Duracut Knife Sections segment after EDS at a current density of 0.095 A/cm² consists of medium- and coarse-needle martensite [16]. On the front and rear surfaces of the segment blade after EDS, the precipitation of strengthening phases is observed, appearing as small, irregularly shaped light inclusions (Fig. 2). The strengthening phases are locally concentrated on the working surfaces of the segment as separate inclusions. The average size of the inclusions is 1.9 µm. Pearlite is present in the form of isolated small-area regions.

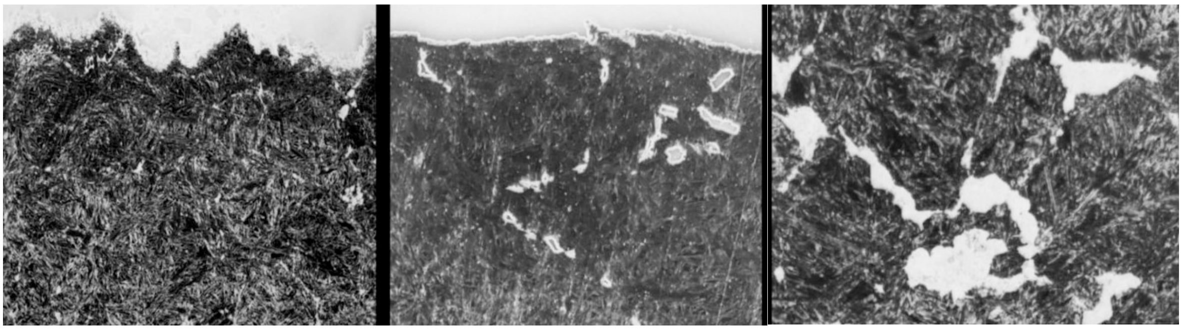


Fig. 2. Microstructure of the Duracut Knife Sections segment after EDM with a current density of 0.095 A/cm²: a - surface layer; b - surface layer with highlighted strengthening phases; c - core (×500)

Fig. 3 shows the comparison graphs of experimental and theoretical microhardness values of the working surface of the segment as a function of current density and voltage during EDM

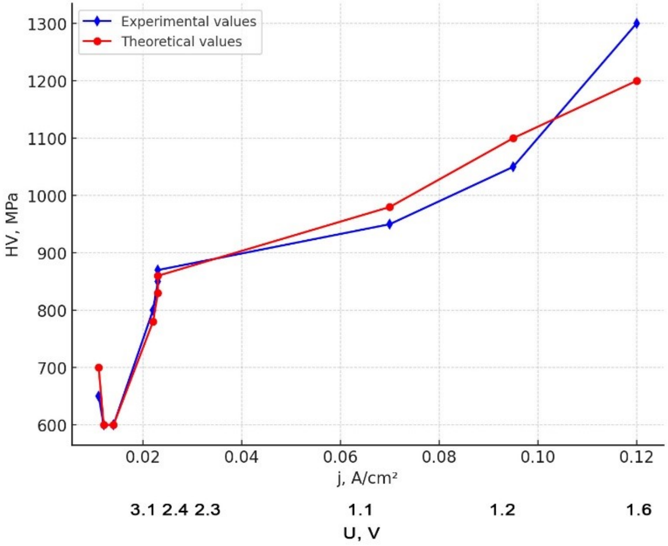


Fig. 3. Comparison of experimental and theoretical values of microhardness of the working surface of the segment as a function of EDS modes

The difference between the theoretical and experimental values of microhardness for the working surface of the segment, depending on the EDS modes, ranges from 0.5% to 9.8%, with an average difference of 5.5% [17]. Overall, comparative operational tests showed that after the combine harvester had processed 90 hectares, the wear resistance of the segments Duracut Knife Sections, restored with strengthening through electrode diffusion treatment, was 1.43-1.65 hectares/mm, which is 1.5-1.9 times higher than that of the standard segments (0.85-0.93 hectares/mm), restored without strengthening (Fig. 4). During the tests, no failures or downtime due to the loss of operational condition of the tested parts were observed [18].

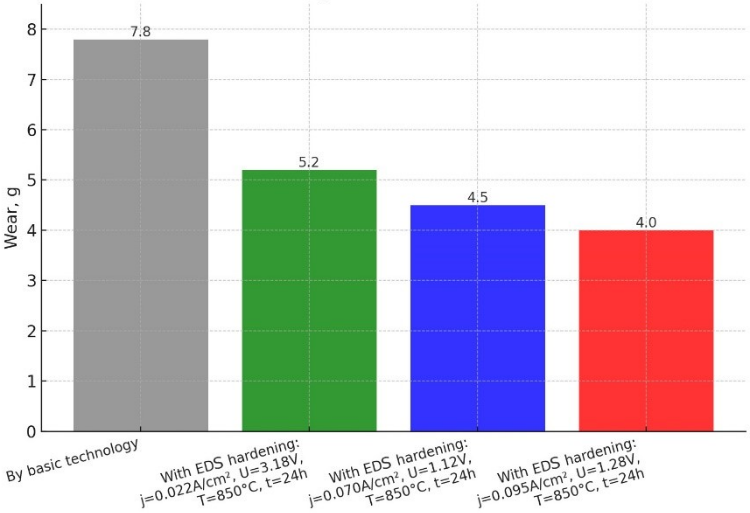


Fig. 4. Wear diagram of the refurbished segments Duracut Knife Sections after testing with 90 hectares of use

Based on the test results, the lifespan of the Duracut Knife Sections segments restored with EDS hardening [19] ranged from 3.0 to 4.4 ha per unit, which is 1.7 to 2.4 times higher than that of standard segments (1.8 ha per unit) restored without hardening (Fig. 5).

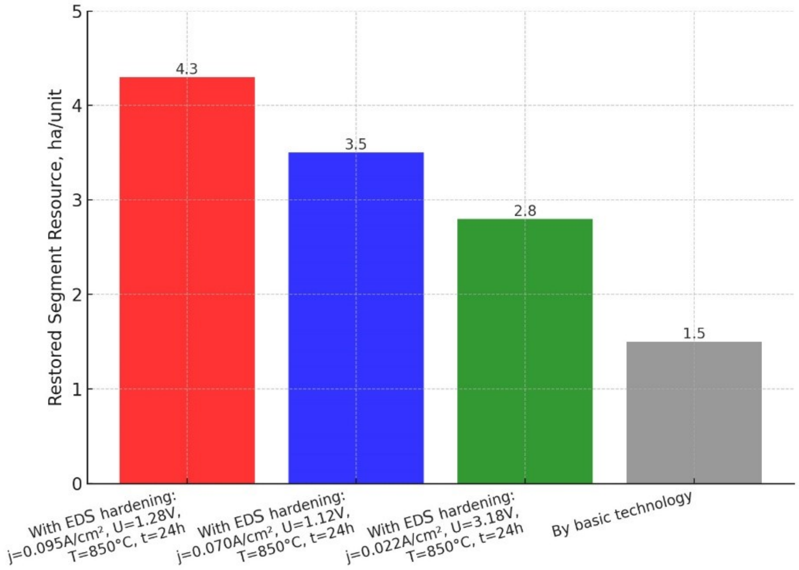


Fig. 5. The resource of restored segments Duracut Knife Sections

Thus, the use of electro-diffusion hardening increases the wear resistance and service life of the restored segments Duracut Knife Sections of the cutting unit of the John Deere 900 grain harvester.

Conclusions

1. Increasing the service life of grain harvester header segments during restoration is ensured by electrodiffusion treatment with selective formation of hardened layers with different characteristics.

2. A mathematical model of EDS of segments has been developed that describes the upward diffusion of carbon from the core to the front and back surfaces of the segment blade and allows determining its concentration in the hardened layer. Experimental studies have established that after EDS the microhardness of the working surfaces of Duracut Knife Sections segments increases by 1.03-2.09 times to a depth of 200-500 µm. As a result of diffusion segregation during EDS, the concentration of carbon in the working surfaces of the segments increased by 1.6-1.8 times, chromium by 2.2-2.4 times, silicon by 1.7-2.1 times, and manganese by 1.1-1.3 times. The formation of hardening phases in the working surfaces of the restored segments after EDS has been established. The segments restored with EDS hardening have a relative wear resistance 1.3 times greater than that of new segments. 3. A method for electrodiffusion hardening of the working surfaces of segment knives and an installation for its implementation have been developed, allowing for a selective increase in the microhardness and wear resistance of restored parts. An installation has been assembled that provides for the simultaneous hardening of 64 segments in a crucible with an internal diameter of 120 mm, a height of 230 mm and an electrolyte volume of 1.8 dm^3.

3. The optimal parameters for hardening the segments with a self-sharpening effect are achieved by using sodium tetraborate as the electrolyte and the following EDS modes: voltage 1.12-3.18V, current density 0.022-0.095 A/cm^2, electrolyte temperature 850°C, and processing duration of 2 hours. The greatest influence on the surface hardening and microhardness of the working surfaces of the segment is exerted by the current density during EDS.

4. Comparative operational tests have shown an increase in the lifespan of segments restored with EDS hardening by 1.7-2.4 times compared to the standard segments restored without hardening.

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Марченко Д.Д., Матвєєва К.С. Дослідження технологічного процесу відновлення із електродифузійним зміцненням робочих поверхонь сегментів жаток зернозбиральних комбайнів

У роботі наведено дослідження технологічного процесу відновлення із електродифузійним зміцненням (ЕДЗ) робочих поверхонь сегментів жаток зернозбиральних комбайнів. Досліджено експериментально ЕДЗ відновлених сегментів Duracut Knife Sections. Встановлено, що після ЕДЗ спостерігається підвищення мікротвердості робочих поверхонь сегментів Duracut Knife Sections у 1,03 - 2,09 рази на глибину 200 - 500 мкм. При ЕДЗ з щільністю струму від 0,022 до 0,095 А/см^2 спостерігається співвідношення між твердостю задньої та передньої поверхонь леза від 1,26 до 1,30 разів, що забезпечує ефект самозаточування. Відносна зносостійкість відновлених сегментів зі зміцненням ЕДЗ в середньому в 1,3 рази більша, ніж у нових сегментів. Кількісний мікроаналіз хімічного складу по поперечному перерізу відновлених сегментів, підданих ЕДЗ, виявив підвищення в зміценійй поверхні концентрації сплавоутворювальних компонентів у 1,1 - 2,4 рази порівняно з осердям. Внаслідок дифузійної сегрегації концентрація елементів підвищилась у таких діапазонах: вуглецю в 1,6 - 1,8 рази, хрому в 2,2 - 2,4 рази, кремнію в 1,7 - 2,1 рази, марганцю в 1,1 - 1,3 рази. При цьому більші величини спостерігаються на задній поверхні леза відновленого сегмента. Розроблений технологічний процес відновлення з ЕДЗ робочих поверхонь сегмента Duracut Knife Sections жниварки зернозбирального комбайна John Deere 900. Запропонована технологія дозволяє відновлювати та зміцнювати робочі поверхні сегментів жаток зернозбиральних і кормозбиральних комбайнів, а також косилок. Порівняльні експлуатаційні випробування на зернозбиральному комбайні John Deere 900 під час збирання пшениці показали, що при напрацюванні 90 га зносостійкість сегментів Duracut Knife Sections відновлених з ЕДЗ обробкою становила 1,43 - 1,65 га/мм, що в 1,5 - 1,9 рази вище, ніж у серійних сегментів 0,85 - 0,93 га/мм, відновлених без зміцнення. Протягом випробувань відмов та простоїв через втрату працездатного стану випробуваних деталей не спостерігалося. У сегментів, зміцнених ЕДЗ, після експлуатаційних випробувань зберігалася товщина лез і кут заточування 22 ... 23°, що свідчить про наявність ефекту самозаточування. Ресурс сегментів Duracut Knife Sections, відновлених зі ЕДЗ, вище в 1,7 - 2,4 рази, ніж у серійних сегментів, відновлених без зміцнення.

Ключові слова: зносостійкість, коефіцієнт тертя, електродифузійне зміцнення, сегмент жаток, довговічність.