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ANALYSIS OF THE EFFECTS OF ELECTROLYTIC PLASMA HARDENING ON THE MECHANICAL CHARACTERISTICS OF STEEL 45 EMPLOYED IN THE PRODUCTION OF HARROW TEETH

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The paper investigates the impact of electrolytic plasma treatment (EPT) on the wear resistance of harrow teeth fabricated from grade 45 steel. Experimental results demonstrate that EPT leads to a 2–2.5 fold increase in microhardness and a more than three-order-of-magnitude reduction in the wear coefficient. Numerical modeling using COMSOL Multiphysics was employed to assess the behavior of harrow teeth under operational conditions. The model, based on Archard's law, enabled the calculation of contact stresses during the interaction of a harrow tooth with dense soil, as well as the prediction of wear thickness and volume under various load conditions. The computed contact stress values were utilized to estimate wear ($4.58\cdot10^7$ N/m^2 when moving horizontally and $5.31\cdot10^8$ N/m^2 when immersed in soil). The calculations reveal that hardened teeth exhibit significantly lower wear volumes (≈11.7–11.8 mm^3/km), while for the original steel 45 without EPT, this figure is approximately 79 cm^3/km. The study findings confirm that electrolytic plasma hardening effectively reduces harrow tooth wear, extends their service life, and allows service life prediction without full-scale testing. This hardening method holds promise for agricultural machinery, as it enhances the durability of working components and can help lower operating costs.

Keywords: *electrolytic plasma hardening (EPH), microhardness, wear, grade 45 steel, contact pressure, harrow teeth.*

INTRODUCTION

The agricultural sector in Kazakhstan plays a crucial role in ensuring the country's food security. According to 2023 data, agricultural land covers approximately 23.4 million hectares, on which around 18,000 agricultural enterprises operate. The total need for agricultural machinery among these enterprises reaches 230 billion tenge, with the majority of the equipment imported from abroad. The main suppliers of agricultural equipment to Kazakhstan are Russia, Ukraine, and Belarus, while domestic production accounts for only about 10%. In contrast, in countries like the USA and the EU, the cost of agricultural equipment can reach hundreds or even thousands of dollars per hectare. In Kazakhstan, however, such investments are significantly lower, partly due to the high cost of imported equipment. This underscores the importance of developing domestic production of agricultural machinery in the country [1].

In addition to the issue of heavy reliance on imported equipment, the natural and climatic characteristics of Kazakhstan also play a significant role. The country exhibits a diverse range of soil conditions, from arid deserts in the south to black soil steppes in the central and northern regions. The fluctuating temperatures, uneven precipitation, and continental climate contribute to the formation of soils with varying levels of humus and density. Southern regions are dominated by lighter, saline soils, while the northern areas feature loamy and clayey black soils with high natural fertility. However, the increased rigidity and density of virgin or arid lands pose challenges, escalating the strain on agricultural machinery components.

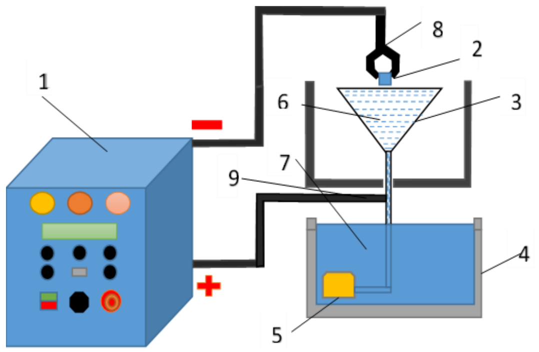
Among the crucial working parts, harrow teeth hold a special position. These components are used after plowing to break up soil clods and level the field surface. They facilitate soil loosening, weed elimination, and moisture retention, ultimately enhancing crop yields. Nonetheless, during operation, the teeth undergo abrasive and corrosive wear due to constant friction against the dense soil and exposure to aggressive environmental factors. The frequent replacement of worn teeth imposes a significant financial burden on agricultural enterprises. Although recycling and restoration of these parts is possible, it often leads to a deterioration in their strength and performance characteristics [2].

Numerous surface hardening techniques, including surfacing, metallization, and heat treatment, are being increasingly employed to enhance the wear resistance and extend the service life of harrow components. However, methods such as surfacing and metallization often necessitate relatively expensive equipment and materials. Alternatively, electrolytic plasma hardening, a chemical-thermal treatment approach, is being investigated as a more environmentally friendly and cost-effective solution. This process involves the intensive heating of the steel surface during the formation of a vapor-gas shell in the electrolyte, facilitated by an electric discharge. This allows for localized hardening and, if necessary, diffusion processes, resulting in a significant improvement in the hardness and wear resistance of the material [3–6]. Nevertheless, the optimization of physical parameters and efficiency during local hardening remains a pertinent issue, as it is crucial to fully evaluate the impact of electrolytic plasma hardening on the mechanical properties of harrow teeth and ensure reliable protection against wear in challenging soil conditions. Unfortunately, the relationship between changes in mechanical properties and the physical parameters of the electrolytic-plasma hardening method, including the consideration of efficiency under different conditions, has not been extensively studied.

MATERIALS AND METHODS.

To determine the optimal parameters for electrolytic-plasma hardening, 200×16×16 mm samples of grade 45 steel were prepared and manually ground using sandpaper with a grain size range of P100 to P2500. These samples underwent standard heat treatment, including hardening at 880–900 °C and tempering at 600–650 °C. Additionally, electrolytic-plasma hardening was applied at temperatures of approximately 850 °C for 8 seconds and 1200 °C for 9 seconds. MEGEON26003 K-type thermocouple, connected to a MAX6675 digital module, was used to monitor the sample temperature during processing. The thermocouple was inserted 2 mm from the surface to transmit data digitally to a microcontroller for initial processing. For the MEGEON26003 thermocouple, the measurement error is no more than 5%. This comparative analysis of the various heat treatment methods enabled the evaluation of their impact on the mechanical properties of the grade 45 steel.

The electrolytic-plasma hardening of grade 45 steel samples and the subsequent investigation were conducted at the Engineering Center for "Strengthening Technologies and Coatings" in Semey, Kazakhstan. The researchers utilized a specialized apparatus designed for heating localized areas of large-scale products to perform the EPH process. This apparatus is a complex system comprising a power source and an electrolytic cell, integrated into a chemical cabinet. The power source, rated at 50 kW, provides a constant positive voltage of up to 380 V and a current of up to 150 A, depending on the load. Furthermore, the power source is regulated by a digital module, which also features an interface for connecting to a personal computer via a COM port, enabling precise control over the process parameters.



1 – power source; 2 – blank (sample); 3 – conical stainless steel electrolyzer; 4 – sump; 5 – pump; 6 – electrolyte; 7 – electrolyte bath; 8 – cathode (−); 9 – anode (+)

Figure 1. Physical configuration and basic diagram of the EPH installation

To investigate the microstructure and phase composition of grade 45 steel after processing by the electrolytic-plasma hardening method, scanning electron microscopy was conducted using a TESCAN VEGA Compact device. This instrument enables detailed examination of the material's surface morphology and identification of characteristic structural features. For the metallographic analysis, the steel samples were polished using chromium dioxide paste and then etched with a 4% alcohol solution of nitric acid.

Furthermore, the microhardness of the steel samples was measured using an HV-1 DT device, applying an indenter load of 1 N and a holding time of 10 seconds.

Tribological evaluations were conducted using an Anton Paar TRB3 tribometer, employing a ball-on-disk testing scheme under the following parameters: wear radius of 3 mm, friction path of 100 m, sample rotation speed of 2 cm/s, and an applied load of 10 N. A 100Cr6 ball with a diameter of 6 mm served as the counter-body material. Furthermore, a precision roughness tester HY2300 was utilized to quantify the wear volume.

After tribological tests were carried out on an Anton Paar TRB3 tribometer in the ball-on-disk mode, the obtained wear volume values for each sample of grade 45 steel were used to calculate the wear coefficient using the simplified Archard formula [7]. Since we already know the normal pressing force of the ball, the friction path, and the material hardness has been experimentally determined, this allowed us to derive the wear coefficient k using the following formula.

$$k = \frac{\Delta V - H}{F \cdot s}, \tag{1}$$

where ΔV is the wear volume (mm^3 or m^3) obtained on the tribometer; H is the hardness of the sample material, given in Pa or MPa, F is the load on the ball (N), s is the total friction path (m).

This coefficient reflects the relative intensity of material loss during dry friction and subsequently serves as an input value in the calculation models of wear.

The wear model was then developed in COMSOL Multiphysics 6.2. This approach allows us to study the force interaction between harrow teeth and soil and to estimate potential wear in conditions as close to real ones as possible, but without conducting expensive and lengthy field experiments.

As part of the modeling in COMSOL, a two-dimensional formulation was chosen, in which a conditional plane section of the "harrow tooth-soil" system was considered (Figure 2).

The Solid Mechanics module was used as the main physical interface, where the Elasto-Plastic Soil Material block with the Modified Cam-Clay model was used to describe the soil properties. This type of model takes into account such soil parameters as Young's modulus, Poisson's ratio, angle of internal friction and adhesion, and also makes it possible to adequately describe the elastic-plastic behavior of typical loamy or steppe black soils. To simulate the harrow tooth material, the American steel grade AISI1045 was used, which is an analogue of the domestic steel 45. Its properties included basic characteristics (Young's modulus, Poisson's ratio, yield strength), sufficient for the correct calculation of the stress-strain state of the metal element.

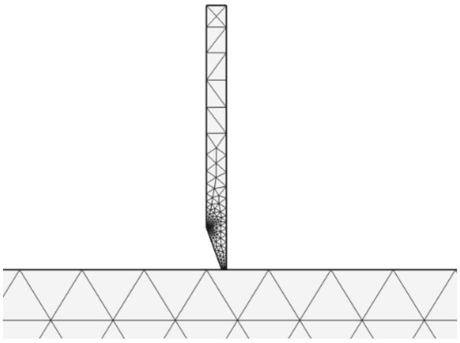


Figure 2. Two-dimensional computational model in COMSOL program

The calculation was carried out in a quasi-stationary mode, divided into two main stages. First, the model determined the load on the tooth during vertical immersion in the soil: a given part of the tooth boundary moved downwards with a small step, and the soil provided resistance described by the Modified Cam-Clay model [8]. This made it possible to obtain the distribution of normal and tangential stresses, as well as the corresponding plastic deformations of the soil near the working element. In the second stage, the tooth was fixed vertically, but “dragged” in the horizontal direction, which reflects the process of real field cultivation. The contact pressure and friction arising from the tooth displacement were determined from the solution of the elastic-plastic problem for soil and elastic for steel. Subsequently, the calculated stress and contact pressure fields were used together with the wear coefficient (obtained from tribotests) to estimate the potential loss of tooth material in accordance with the Archard formula. This integrated approach provides a link between experimental wear data and numerical modeling, allowing us to predict the service life of hardened harrow teeth under various soil conditions.

Results and discussion

For a more detailed analysis of electrolytic-plasma hardening, the same electrolyte compositions and different processing modes presented in Table 1 were used, which made it possible to evaluate the influence of these parameters on the properties of steel grade 45.

Table 1. Parameters of EPH modes for steel 45

Sample	Area of a cone anode	Electrolyte composition	U, V	t, s	I, A
No. 1	0,05 m^2	20% Na_2CO_3+80% water	250	8	50
No. 2	0,05 m^2	20% Na_2CO_3+80% water	260	9	50

The electrolyte (a solution of sodium carbonate in distilled water) circulates in the electrolyte cell using an electric motor at a flow rate of 60 l/min and washes the anode located inside the cell. Through the upper opening of the cell, the electrolyte flows back into the sump, washing the hardened part (cathode) installed at an adjustable distance. When an electric voltage is applied between the anode and cathode, the electrolyte ions: Na+ and OH− are set to an ordered motion, as a result of which the cathode and the near-cathode layer of the electrolyte quickly heat up, thereby forming a vapor-gas shell. The vapors of the ionized electrolyte create an environment where an electric discharge jumps between the electrolyte and the sample-cathode and the temperature of the sample increases with the passage of time (Figure 3) [9–10].

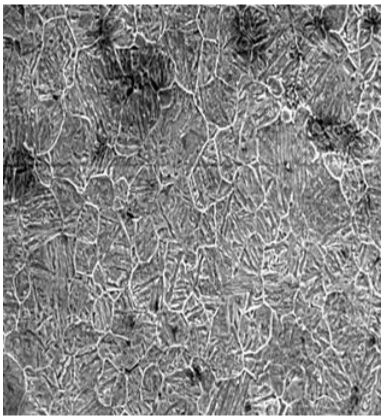
a)

b)

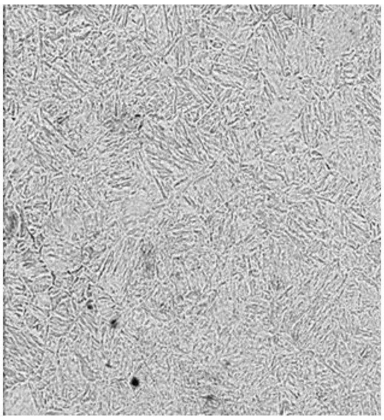
c)

Figure 3. Processing of harrow teeth during EPH

Metallographic analysis and scanning electron microscopy studies show that in the initial state the surface of steel 45 has a ferrite-pearlite structure. After the electrolytic-plasma hardening procedure for 5 seconds, samples No. 1, 2, the formation of a martensite phase component in the structure of steel 45 is observed (Figure 4). With an increase in the current supply time to 8 seconds in total (sample No. 1), strengthening of martensite grains is observed.



a)



b)

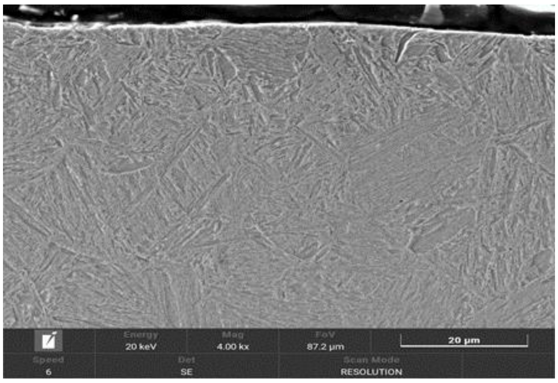
c)

Figure 4. Microstructure of grade 45 steel, studied using scanning electron microscopy (SEM): a) before; b, c) after EPH

Figure 5 shows the microstructure of the cross-section of steel 45 after EPH (sample No. 2). The thickness of the modified layer is approximately 500–550 µm.

The visual appearance of grade 45 steel harrow teeth is illustrated in Figure 6. The leftmost image depicts the original sample, while the center and rightmost images correspond to samples 1 and 2, respectively.

The investigation demonstrated substantial modifications to the microstructural characteristics of grade 45 steel following the application of electrolytic plasma hardening. Analysis revealed that the steel surface became enriched with refined martensite, which enhanced the material's wear resistance. These structural alterations were primarily confined to the surface layers, while preserving the flexibility of the underlying bulk volume.



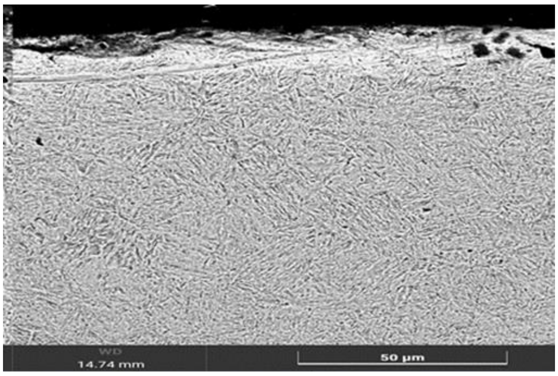


Figure 5. Microstructure of the cross-section of steel 45 after EPZ treatment, obtained using a scanning electron microscope (SEM)

Figure 6. Visual appearance of harrow teeth: initial (far left) and after EPH (sample 1 and 2)

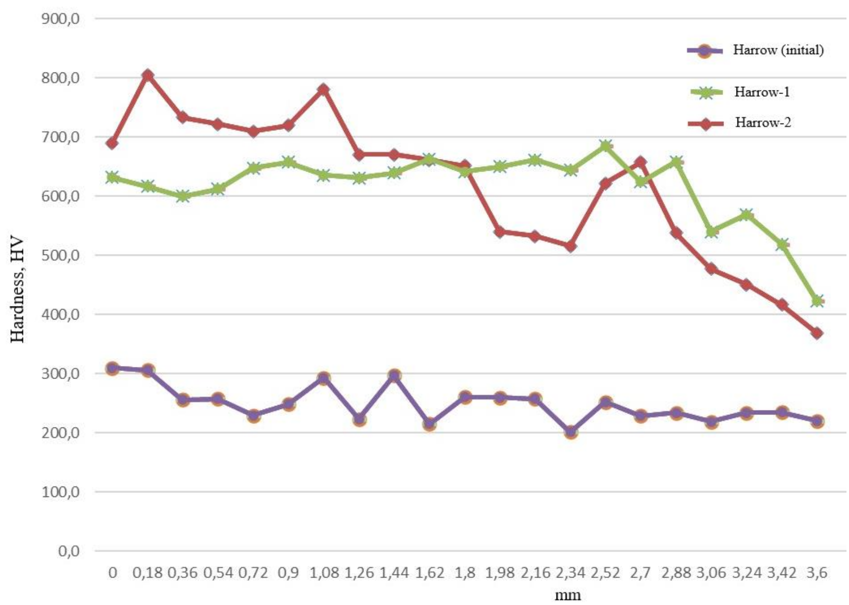


Figure 7. Sample hardness distribution by depth (measurement error ±10 HV)

To determine the effect of structural surface transformations after EPH on the mechanical properties of grade 45 steel, the microhardness and wear resistance of the samples were determined. Figure 7 shows the distribution of microhardness values depending on the duration of exposure to EPH [11–12]. The microhardness of grade 45 steel in the initial state is 250–300 HV±10 HV. It was found that after EPZ, the microhardness of steel 45 increases by 2–2.5 times depending on the initial state.

The microhardness of the sample after EPH increases, however, some difference in the change in hardness of samples treated with different heating times is observed. A significant increase in the microhardness of the sample after EPH for 5–7 s may be associated with the refinement of blocks inside the austenite grain [13–14].

Figure 8 shows the results of tribological tests of the surface of grade 45 steel samples using the ball-on-disk scheme, which contains the results of measuring the wear volume. The study of the wear resistance of steel 45 samples before and after EPH showed that the treated samples demonstrate a smaller wear volume compared to the original.

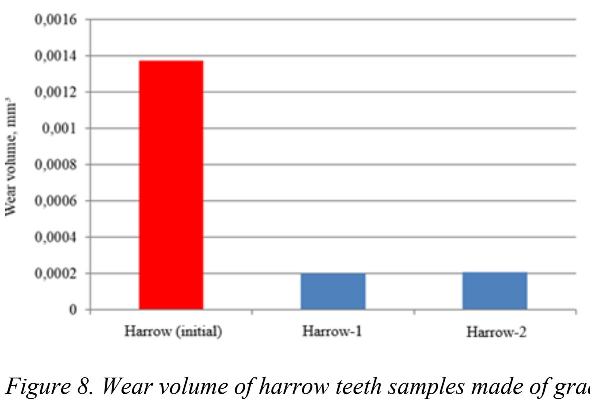


Figure 8. Wear volume of harrow teeth samples made of grade 45 steel before and after EPH (±10% measurement uncertainty)

It can be seen that the treated samples demonstrate a noticeable reduction in the amount of wear compared to the original (not subjected to EPH) sample. The significant reduction in material loss is explained by the increased hardness and formation of a more wear-resistant steel structure after local high-temperature exposure.

For quantitative assessment of the strengthening efficiency, along with the wear volume, the dimensionless wear coefficient k was calculated using formula (1) based on Archard's law. Using the data on the wear volume of the samples, the following values of the coefficient k were obtained: $k_1 = 4 \cdot 10^{-3}$ for the initial sample, $k_2 = 1.18 \cdot 10^{-6}$ for the first sample after EPH, $k_3 = 1.37 \cdot 10^{-6}$ for the second sample after EPH.

Below, Figure 9 shows the stress distribution during soil cultivation in COMSOL Multiphysics.

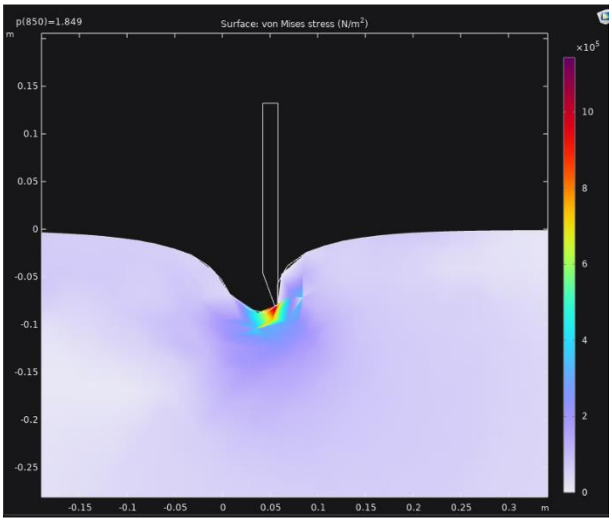


Figure 9. Stress field arising in the soil

Next, the program calculated the maximum contact pressure occurring in the harrow tooth contact zone. The harrow tooth immersion depth was 8 cm. Figure 10 and Figure 11 show graphs of the change in maximum contact stress over time.

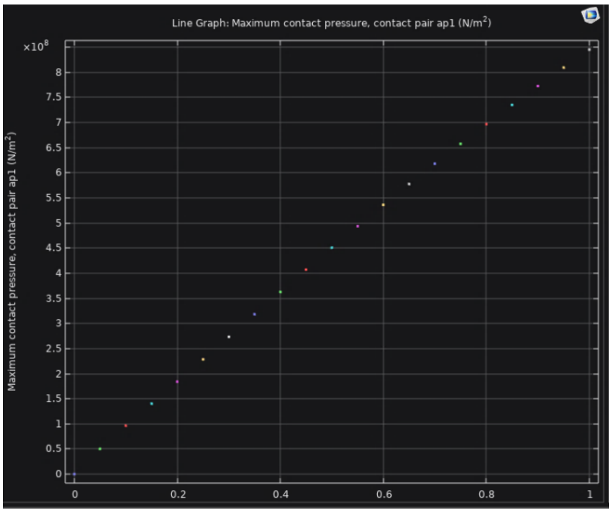


Figure 10. Maximum contact pressure exerted during tooth penetration into the soil

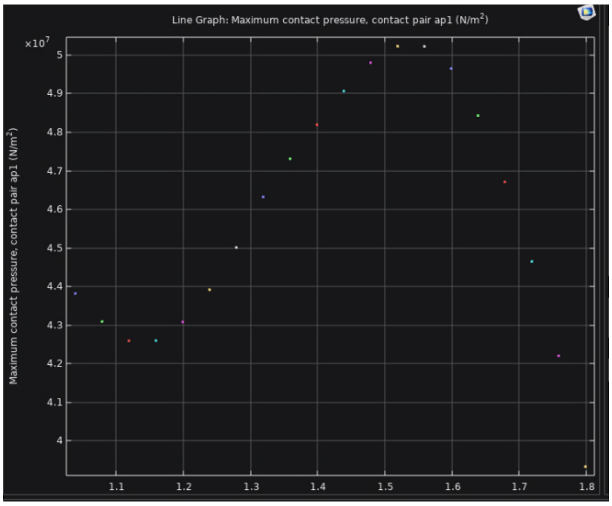


Figure 11. Maximum contact pressure when teeth move in the horizontal direction

Based on the obtained results, the average value of contact stress was determined: $4.58 \cdot 10^7$ N/m^2 when moving horizontally and $5.31 \cdot 10^8$ N/m^2 when immersed in the soil. Now, using these average values, as well as the obtained wear coefficients k, estimates of the wear thickness were obtained using the following formula (simplified Archard formula) [15]:

$$\Delta h = k \frac{p \cdot s}{H}, \qquad (2)$$

where Δh is the wear thickness, k is the wear coefficient, p is the contact stress, s is the distance traveled, H is the material hardness. The hardness values in the calculations were taken based on the results of the experiment after EPO. For simplicity, the value on the surface of the samples was taken. Then, when moving horizontally for 1 km of the section, it was found that the wear volume for the original sample without hardening was about 79 cm^3, for the first sample, a value of 11.8 mm^3 was obtained, for the second sample, the wear volume per 1 km was 11.7 mm^3. The wear thickness was multiplied by the contact area, which was calculated as the product of the immersion depth (8 cm) and the tooth thickness (16 mm). The necessary soil parameters (heavy loam) for modeling in the COMSOL program were taken from the literature [16]. As can be seen from the results, hardening during EPH significantly increases the wear resistance of the harrow teeth, reducing the wear volume by an order of magnitude. It is also worth noting that in reality the teeth may contact unevenly in depth, and there may also be more favorable factors, such as high moisture content in the soil, loosening. Of course, during the modeling, strict conditions were taken, the behavior of the soil in reality may be different. But as a first approximation, the results obtained after assessing the contact stresses made it possible to estimate the wear volumes in the field, without resorting to real tests. Even after analyzing formula (1), it can be noted that the higher the hardness of the sample, the lower the wear volume, which is confirmed by experiments. Such samples in real conditions can withstand significant loads under soil cultivation, which increases their resource, and, therefore, saves money.

CONCLUSION

Analyzing the results of experimental studies on the modification of surface layers of grade 45 steel using electrolytic plasma hardening (EPH), a number of important conclusions can be made:

Electrolytic plasma treatment of grade 45 steel leads to a significant increase in its microhardness (by 3–3.5 times) due to the formation of refined martensite and small blocks inside the grain, which increases resistance to abrasive wear. The tribological tests conducted confirm an effective reduction in the wear volume of samples after EPT compared to the initial state of steel 45. The wear coefficient k as a result of local high-temperature hardening decreases by several orders of magnitude (from $4 \cdot 10^{-3}$ to 10^{-6}).

Modeling in the COMSOL Multiphysics environment taking into account the obtained wear factors and soil parameters (heavy loam) made it possible to estimate the contact stresses in the interaction zone of the harrow tooth and the soil, as well as to predict the thickness and volume of wear under various conditions (vertical indentation and horizontal movement). The calculation results show that hardening of steel 45 by the EPH method significantly (by an order of magnitude or more) reduces the predicted wear of the harrow working parts: the volume of lost material decreases from tens of cm^3 to units of mm^3 per kilometer of travel. This indicates the potential for significant resource savings in the operation of agricultural machinery. Despite the fact that in real field conditions, the actual contact pressure and soil moisture can lead to even more favorable results (or, conversely, to differences in individual situations), the presented approach provides a representative assessment of wear without conducting lengthy and expensive full-scale experiments.

Thus, electrolytic plasma hardening is a promising method for increasing the service life and reliability of harrow teeth, providing an optimal combination of increased hardness of the surface layer and preservation of the strength properties of the base material.

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СОҚА ТІСТЕРІН ӨНДІРУ ҮШІН ҚОЛДАНЫЛАТЫН 45 МАРКАЛЫ БОЛАТТЫҢ ЭЛЕКТРОЛИТТІК-ПЛАЗМАЛЫҚ ҚАТАЙТУДАН КЕЙІНГІ МЕХАНИКАЛЫҚ ҚАСИЕТТЕРІН ЗЕРТТЕУ

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Бұл жұмыста электролиттік-плазмалық қатайтудан (ЕПҚ) кейінгі 45 болаттан жасалған тырма тістерінің тозуға төзімділігінің әсері зерттеледі. ЭПҚ-дан кейінгі үлгілердің микроқаттылығы 2–2,5 есе артады, ал тозу коэффициенті үш есе азаяды. Пайдалану жағдайында тырма тістерінің мінез-құлқын бағалау үшін COMSOL Multiphysics ортасында сандық модельдеу жүргізілді. Арчард заңына сәйкес қолданылған модель тырма тісінің ауыр саздақпен әрекеттескен кездегі байланыс кернеулерін есептеуге, сондай-ақ әртүрлі жүктеме режимдеріндегі тозудың қалыңдығы мен көлемін болжауға мүмкіндік берді. Тозуды есептеу үшін байланыс кернеуінің есептелген мәндері (көлденеңінен қозғалғанда $4{,}58 \cdot 10^7$ Н/м^2 және топыраққа батырылған кезде $5{,}31 \cdot 10^8$ Н/м^2) пайдаланылды. Есептеу нәтежиелері көрсеткендей, қатайтылған соқа тістері тозудың едәуір аз мөлшерін көрсетеді (≈11,7–11,8 мм^3/км), ал ЕПҚ жоқ бастапқы 45 маркалы болат үшін бұл көрсеткіш ≈79 см^3/км құрайды. Зерттеу нәтижелері бойынша электролиттік-плазмалық қатайтудан кейінгі тырма тістерінің тозуы төмендегенін, олардың пайдалану ресурстарын арттыратынын және табиғи сынақтарсыз қызмет ету мерзімін болжауға мүмкіндік беретінін растайды. Ұсынылған қатайту әдісі ауылшаруашылық техникасында қолдану үшін перспективті болып табылады, өйткені соқалардың беріктігін арттырып қана қоймай, сонымен қатар пайдалану шығындарының төмендеуіне ықпал етуі мүмкін.

Түйін сөздер: *электролиттік-плазмалық қатайту (ЭПҚ), микроқаттылық, тозуға төзімділік, болат 45, контактные напряжения, зубья борон.*

ИЗУЧЕНИЕ ВОЗДЕЙСТВИЯ ЭЛЕКТРОЛИТНО-ПЛАЗМЕННОГО УПРОЧНЕНИЯ НА МЕХАНИЧЕСКИЕ СВОЙСТВА СТАЛИ 45, ИСПОЛЬЗУЕМОЙ ДЛЯ ПРОИЗВОДСТВА ЗУБЬЕВ БОРОН

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В работе исследуется влияние электролитно-плазменной обработки (ЭПО) на износостойкость зубьев борон из стали 45. Экспериментально установлено, что после ЭПО микротвёрдость увеличивается в 2–2,5 раза, а коэффициент износа уменьшается более чем на три порядка. Для оценки поведения зубьев борон в условиях эксплуатации выполнено численное моделирование в среде COMSOL Multiphysics. Применённая модель, основанная на законе Арчарда, позволила рассчитать контактные напряжения при взаимодействии зуба бороны с тяжёлым суглинком, а также спрогнозировать толщину и объём износа при различных режимах нагрузки. Вычисленные значения контактного напряжения ($4{,}58 \cdot 10^7$ Н/м^2 при движении по горизонтали и $5{,}31 \cdot 10^8$ Н/м^2 при погружении в почву) использовались для расчётов износа. Расчёты показали, что упрочнённые зубья демонстрируют значительно меньший объём износа (≈11,7–11,8 мм^3/км), тогда как для исходной стали 45 без ЭПУ этот показатель составляет ≈79 см^3/км. Результаты исследования подтверждают, что электролитно-плазменное упрочнение эффективно снижает износ зубьев борон, увеличивает их эксплуатационный ресурс и позволяет прогнозировать срок службы без проведения натурных испытаний. Представленный метод упрочнения является перспективным для применения в сельскохозяйственной технике, так как он не только повышает долговечность рабочих органов, но и может способствовать снижению эксплуатационных затрат.

Ключевые слова: *электролитно-плазменная закалка (ЭПЗ), микротвердость, износ, сталь 45, контактные напряжения, зубья борон.*