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THE INFLUENCE OF ELECTROLYTIC PLASMA HARDENING ON THE PERFORMANCE CHARACTERISTICS OF WORKING PARTS OF AGRICULTURAL MACHINERY

Abstract: *In this paper, we investigate the improvement of the operational and mechanical properties of 45 steel used in agricultural machinery by electrolytic plasma quenching (EPH). The experiments were carried out under three treatment modes: 320 V voltage, 50 A current and exposure time of 9 seconds. Microstructure analysis showed the formation of a martensitic layer with a thickness of 500-550 microns, which led to an increase in the microhardness of steel from 200 HV to 683 HV, that is, 3.4 times. The zonal structure*

of the material is revealed: a reinforced (martensitic) layer with a thickness of 500 microns, a thermal impact zone of 200-250 microns and a basic matrix. The results of the study confirmed the high efficiency and reliability of EPC as a method of hardening highly loaded working bodies of agricultural machinery. The introduction of this technology makes it possible to reduce the cost of replacing parts by 30-35%, increase the efficiency of equipment and contribute to the development of domestic agricultural machinery. The use of a 20% sodium carbonate solution, which does not pollute the environment, during the EPH ensured an even distribution of electric current in the cell and contributed to achieving an optimal cooling rate of the sample.
Key words: *electrolytic plasma hardening (EPH), microhardness, wear, steel 45, electrolyte.*

Introduction

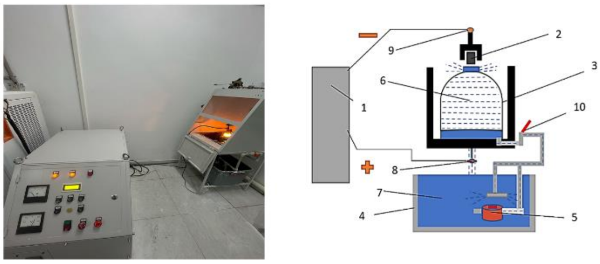
Currently, 85-90% of breakdowns and malfunctions of agricultural machinery are related to the wear of its components. The main factors contributing to wear are the accumulation of dust and dirt, as well as intense loads that cause increased friction, which reduces the efficiency of the equipment [1-3]. Kazakhstan's agriculture is provided with tractors, combine harvesters, and other agricultural machinery, but this is not enough to achieve high efficiency in the industry. According to the Ministry of Agriculture of the Republic of Kazakhstan, the average wear rate of the machine and tractor fleet is about 80%. A significant part of the machinery is older than 15 years: the wear rate of tractors is 79%, combines – 54%, seeders – 86%, harvesters – 63%. This negatively affects the productivity and quality of agricultural work [4-5]. Special attention is required for tillage equipment that operates in difficult conditions. Plows, cultivators, harrows, and other aggregates are subjected to heavy loads due to constant contact with hard soil, stones, and abrasive particles. The high level of their wear leads to a deterioration in the quality of tillage, which negatively affects crop yields and health. Kazakhstan annually sows about 21 million hectares of acreage [6-8]. More than 150 thousand tractors, 88 thousand seeders, and about 40 thousand grain and forage harvesters are involved in field and harvesting operations. With the recommended rate of equipment renewal at the level of 10-12,5%, the actual figure is only 1-3%. This leads to a decrease in production efficiency, deterioration of product quality, and significant losses at all stages of the agricultural cycle [9-11]. The lack of modern machinery and the slow pace of its renewal negatively affect the yield and competitiveness of agricultural products, as well as soil fertility and the overall sustainability of agricultural production.

Various surface treatment technologies are used to create new machinery parts, improve their performance, or restore worn parts. Among them, laser processing, surfacing, and electron beam processing can be distinguished, which are capable of solving these tasks. However, these methods are characterized by high cost, both of the processes themselves and of the materials used. One of the advanced methods of heat treatment of steel related to chemical and thermal technologies is electrolytic plasma hardening (EPH). This process is based on intense heating of the metal surface resulting from the formation of a vapor-gas shell in the electrolyte under the action of electrical discharges. In addition to effective hardening, EPH promotes the activation of diffusion processes such as cementation, nitriding, and nitrocarburizing. As a result, the surface of the steel is saturated with carbon and nitrogen atoms, which significantly improves its mechanical properties, including increased hardness and wear resistance [12-15].

Materials and methods

To establish the optimal regime of electrolyte-plasma hardening (EPH), samples of grade 45 steel measuring 15x15x15 mm were prepared and sanded manually sequentially on sandpaper with a grain size from P100 to P2500, which were subjected to standard heat treatment in certain temperature conditions: quenching at 880-900°C and post-cooling in the electrolyte. Then, electrolytic plasma quenching was additionally applied at a temperature of about 850°C for 9 seconds and cooling in electrolyte at a temperature 25-30°C for 3 seconds. These different heat treatment methods made it possible to compare and evaluate the effect of each of them on the mechanical properties of steel 45 [16-18].

Electrolytic plasma hardening of 45 steel samples, as well as their subsequent research, were carried out at the Hardening Technologies and Coatings Engineering Center (Shakarim Semey University, Kazakhstan). A special installation designed for heating local areas of large-sized products was used to carry out EPH. The installation is a complex that includes a power source and an electrolyte cell, which are integrated into a chemical cabinet. A 50 kW power supply provides a constant positive voltage of up to 380 V and a current of up to 150 A, depending on the load [19]. The power supply is controlled using a digital module, which also has an interface for connecting to a personal computer via a COM port, allowing precise control of process parameters.



1 – Power supply; 2 – sample; 3 – cone electrolyzer made of stainless steel; 4 – electrolyte bath; 5 – pump; 6 – electrolyte; 7 – reversible electrolyte; 8 – cathode (-); 9 – anode (+); 10 – flow controller

Figure 1 – Appearance and schematic diagram of the EPH installation

A visual study of sample processing at EPH was carried out using a high-speed EVERCAM 2000-16-C camera manufactured by General Optics LLC, Moscow, Russian Federation. The video was shot at 1000 frames per second. The processing of the received video files was carried out in the SRV_HS program supplied by the camera manufacturer.

A JEOL 6390LV scanning electron microscope was used to study the microstructure of the initial sample at magnifications of 700x.

Scanning electron microscopy (SEM) using a TESCAN VEGA Compact device was used to study the microstructure and phase composition of steel 45 after treatment with the method of electrolyte-plasma hardening (EPH). This microscope provides a detailed analysis of morphological changes in the surface of the material, allowing the identification of characteristic structural elements.

Metallographic microanalysis was performed on the grinds of steel samples, which were pre-polished using a paste based on chromium dioxide, and then etched with a 4% alcohol solution of nitric acid.

The microhardness of the studied samples was determined using the HV-1 DT device at an indenter load of P = 1 N and exposure for 10 seconds, in accordance with the requirements of GOST 9450-76.

The results of the study

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

Table 1 – Parameters of EPH Modes for 45 Steel

Sample	Cone area	Electrolyte content	U, B	t, s	I, A
№ 1	0,05m^2	20% Na_2CO_3+80% H2O	320	9	50

The electrolyte, which is a solution of sodium carbonate in distilled water, circulates in an electrolysis cell with a flow rate of 60 liters/min, provided by an electric pump. During circulation, it washes the anode located inside the cell. Through the upper opening of the cell, the electrolyte returns to the electrolytic bath, while washing the hardened part (cathode) installed at an adjustable distance [20].

When an electric voltage is applied between the anode and the cathode, the electrolyte ions (Na^+ and OH^-) acquire directional movement, which leads to intense heating of the cathode and the near-cathode layer of the electrolyte. As a result of this process, a combined-cycle shell is formed. Ionized electrolyte vapors form an environment in which electrical discharges occur between the electrolyte and the cathode sample, which further increases the sample temperature over time [21-22]. The process of electric discharge formation in EPH is shown in Fig. 2.

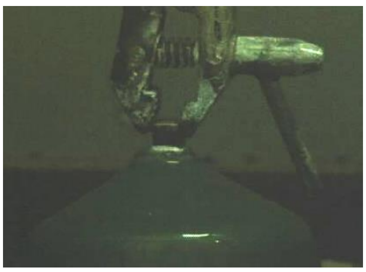


Figure 2 – Formation of a combined-cycle gas shell during EPH

Metallographic analysis using a scanning electron microscope has shown that in the initial state (Figure a, original), the surface of steel 45 has a ferrite-pearlite structure. After the electrolyte-plasma hardening procedure for 9 seconds (Figure b), the formation of a martensitic structural phase in the structure of steel 45 is observed (Fig. 3).

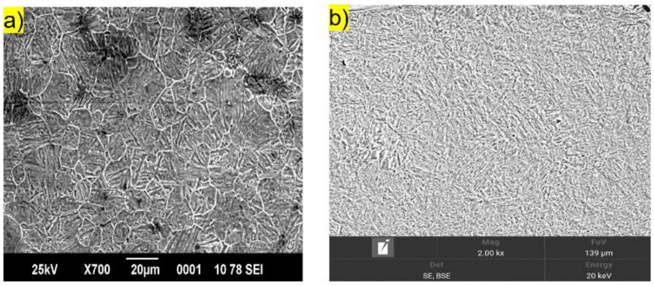


Figure 3 – Microstructure of steel 45, studied using SEM:
a) before hardening (original); b) af

Figure 4 shows an image of a cross-section of sample b, the thickness of the modified layer of which is 500-550 microns.

The microstructure can be conditionally divided into 3 zones (1 – a zone of intense structural transformations, a hardened layer; 2 – a zone of thermal influence; 3 – a zone having the structure of the initial matrix. The transition zone has a finer-grained structure, characteristic of the zone of thermal influence, compared with the coarse-grained structure of the matrix.

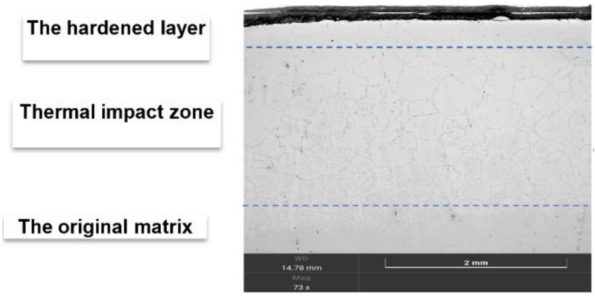


Figure 4 – Formed zones of microstructure after EPH on a cross-section of sample No. 1 made of 45 steel

The study revealed significant changes in the microstructure of steel 45 after electrolytic-plasma hardening (EPH). It was found that in the initial state (original), the surface layer of steel 45 has a ferrite-pearlite structure, while after hardening, it transforms into a fine-grained martensitic structural phase, which contributes to increased wear resistance. These changes mainly affect the surface layers, while maintaining the plasticity of the bulk of the material, which consists of ductile structural elements.

To assess the degree of influence of structural transformations of the surface on the mechanical properties of steel 45 after EPH, the microhardness of the samples was determined. Figure 5 shows the dependence of microhardness values on the duration of exposure to EPH [23]. The microhardness of steel 45 in its initial state is 190-210 HV. Tests have shown that after EPH, the microhardness of steel 45 increases by 3.4 times, depending on the initial state.

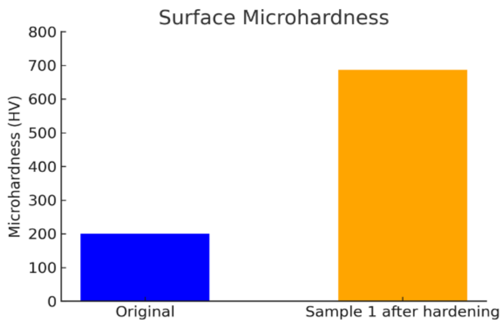


Figure 5 –Graph of hardness after EPH

Conclusion

Analyzing the results of experimental studies on the modification of surface layers of 45 steel using EPH, a number of important conclusions can be drawn. The optimal parameters for hardening the surface of steel 45 in an electrolyte plasma have been determined, which make it possible to create a modified layer with a thickness of 500-550 micrometers with improved performance characteristics. It was found that the morphological structure of steel 45 after EPH is characterized by martensitic grains. It was revealed that the cross-sectional structure of the treated steel 45, depending on the structural composition, is divided into zones: a surface layer with a martensitic structure, below is a zone of thermal action, followed by the main initial metal matrix. It was determined that the microhardness of steel 45 after EPH increases by 3.4 times, depending on the composition of the electrolyte and the duration of heating. Thus, the performed study confirms the effectiveness and practical value of the EPH for improving the working properties of parts of tillage machines used in agricultural machinery, especially in conditions of intense friction and wear.

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ЭЛЕКТРОЛИТТІК-ПЛАЗМАЛЫҚ БЕРІКТЕНДІРУДІҢ АУЫЛ ШАРУАШЫЛЫҒЫ ТЕХНИКАСЫНЫҢ ПАЙДАЛАНУ СИПАТТАМАЛАРЫНА ӘСЕРІ

Осы жұмыста ауыл шаруашылығы техникасында қолданылатын 45 атты болатының пайдалануына және механикалық қасиеттерін арттыру мақсатында қолданылатын электролиттік-плазмалық беріктендіру (ЭПБ) әдісі зерттелді. Эксперименттік зерттеулер нәтежиесінде келесіі өңдеу режимі жүргізілді: кернеу 320 В, ток күші 50 А және әсер ету уақыты 9 секунд. Микроқұрылымдық талдау нәтижесінде қалыңдығы 500-550 мкм мартенситтік қабаттың қалыптасқаны анықталды, бұл болаттың микрокаттылығын 200 HV-ден 685 HV-ге дейін, яғни 3,4 есеге арттырды. Құрылымдық зоналық бөліну айқындалды және қалыңдығы 500 мкм шынықтырылған қабат, 200-250 мкм термиялық әсер ету аймағы және негізгі матрицасы көрсетілген. Зерттеу нәтижелері бойынша ЭПБ әдісінің ауыл шаруашылығы техникасының жұмысшы элементтерін беріктендіруде жоғары тиімділігі мен сенімділігін көрсетті. Бұл технологияны енгізу қосалқы бөлшектерді ауыстыру шығындарын 30–35%-ға төмендетуге, жабдықтарды пайдалану тиімділігін арттыруға және отандық ауыл шаруашылығы машина жасау саласының дамуына ықпал етуге мүмкіндік береді. Электролиттік-плазмалық беріктендіру (ЭПБ) кезінде улы емес 20%-тік натрий карбонат ерітіндісін қолдану арқылы электр тоғының ұяшықта біркелкі таралуын қамтамасыз етіп қана қоймай, үлгінің оңтайлы салқындату жылдамдығына қол жеткізуге көмегін тигізді.

Түйін сөздер: *электролиттік-плазмалық қатайту (ЭПҚ), микроқаттылық, мартенсит, болат 45, электролит.*

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ВЛИЯНИЕ ЭЛЕКТРОЛИТНО-ПЛАЗМЕННОГО УПРОЧНЕНИЯ НА ЭКСПЛУАТАЦИОННЫЕ ХАРАКТЕРИСТИКИ РАБОЧИХ ОРГАНОВ СЕЛЬСКОХОЗЯЙСТВЕННОЙ ТЕХНИКИ

В данной работе исследуется повышение эксплуатационных и механических свойств стали 45, применяемой в сельскохозяйственной технике, методом электролитно-плазменного упрочнения (ЭПУ). Эксперименты проведены при следующем режиме: напряжение 320 В, сила тока 50 А и время воздействия 9 секунд. Анализ микроструктуры показал формирование мартенситного слоя толщиной 500-550 мкм, что привело к увеличению микротвёрдости стали с 200 HV до 685 HV, то есть в 3,4 раза. Выявлено зональное строение структуры: закалённый (мартенситный) слой толщиной 500 мкм, зона термического воздействия 200-250 мкм и основная матрица. Результаты исследования подтвердили высокую эффективность и надёжность ЭПУ как метода упрочнения высоконагруженных рабочих элементов сельскохозяйственной техники. Внедрение данной технологии позволяет снизить затраты на замену деталей на 30–35 %, повысить эффективность эксплуатации оборудования и способствовать развитию отечественного сельскохозяйственного машиностроения. Применение 20%-ного раствора карбоната натрия, не загрязняющего окружающую среду, при ЭПУ обеспечило равномерное распределение электрического тока в ячейке и способствовало достижению оптимальной скорости охлаждения образца.
Ключевые слова: *электролитно-плазменное упрочнение (ЭПК), микротвердость, мартенсит, сталь 45, электролит.*

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THEORETICAL STUDIES OF THERMAL PROCESSES IN ELECTROLYTIC-PLASMA HARDENING

Abstract: *This article examines the theoretical aspects of thermal processes occurring during electrolytic-plasma hardening (EPH), including the analysis of temperature fields and heating rates. The finite difference method was used for numerical modeling, allowing for a more precise determination of the temperature distribution in the treated material. The heat transfer problem in a flat plate with a thickness of 15 mm was considered, where the boundary conditions were as follows: on one boundary, heating was carried out by a surface thermal flux from the electrolyte plasma, while on the opposite side, heat was dissipated through convection in an air medium. The calculations revealed non-uniform temperature distribution over time and depth, confirming the formation of three distinct structural zones: the hardened zone, the heat-affected zone, and the base matrix. The temperature of the samples during the experiment was measured using a thermocouple positioned 2 mm from the heated surface. Experimental data obtained from the treatment of 45 steel samples confirmed the accuracy of the numerical modeling. The research results demonstrate the effectiveness of numerical modeling, including the finite difference method, in optimizing EPH parameters, thereby reducing the volume of experimental work and lowering technology development costs. The obtained data can be used to improve surface hardening technologies for structural steel components used in agricultural machinery, mechanical engineering, and other industries. The study confirms the potential of EPH for enhancing the operational characteristics of steel products.*
Key words: *Electrolytic-plasma hardening, 45 steel, heat conduction equation, numerical modeling, thermal processes.*

Introduction

Modern material processing technologies are aimed at improving their operational properties, such as hardness, wear resistance, corrosion resistance, and high-temperature stability. One of the promising heat treatment methods that allow achieving these goals is electrolytic-plasma hardening (EPH). This method combines the effects of plasma discharge and electrolysis, enabling not only structural modifications of the material's surface layer but also diffusion saturation with various elements such as carbon, nitrogen, and boron.

EPH is widely applied in mechanical engineering, aviation, and the automotive industry, where increased strength and durability of components operating under high mechanical and thermal loads are required. However, the effectiveness of this method largely depends on the correct selection of