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PHYSICO-TECHNOLOGICAL ANALYSIS OF ELECTRO-SPARK MACHINING OF RECONDITIONED PARTS MADE OF STRUCTURAL AND TOOL STEELS

The reliability and durability of friction units in modern weapons and military equipment largely depend on the physical and mechanical properties of the materials of the parts and the quality of their surface treatment. One of the promising methods for improving the performance characteristics of weapons and military equipment is electrospark alloying (ESA), which allows the creation of hardened coatings with high wear resistance. The article deals with the physical processes occurring during ESA, particularly electrical erosion, polar material transfer, and structural and phase transformations of the surface layer. It is shown that using electrodes with nanostructured modifiers to form ultra-strong coatings with specified functional characteristics is promising. Further improvement of the design of installations for mechanized coating formation, which ensures process stability and high productivity, is significant. The process modes, electrode parameters, and their influence on the formation of coatings are analyzed. The formation mechanism of surface layers and features of their crystallization are presented. It was found that using ESA promotes the formation of white layers with a fine-grained structure, characterized by high mechanical properties and corrosion resistance. A further analysis of the technological parameters of ESA demonstrated a significant effect of the electrode material on the composition and characteristics of the obtained coatings. The influence of pulse discharge modes on the depth of penetration of alloying elements into the surface layer of the part was determined. It is shown that special attention should be paid to the influence of the gas environment of the interelectrode gap on the kinetics of the material transfer process. In practical terms, the research results demonstrate the effectiveness of using ESA for the restoration and strengthening of parts operating under difficult operating conditions, in particular in the friction units of the vehicle. The authors' experiments have confirmed the possibility of adjusting the microhardness and thickness of coatings by optimizing the processing modes and composition of the electrode material. As a result, it was concluded that electric spark alloying is an effective method of strengthening the surfaces of parts, ensuring their durability and operational reliability, and surpassing traditional technologies in several key parameters.

Key words: *electric spark alloying, structural steels, machine parts, equipment components, wear-resistant coatings, electrical erosion, phase transformations, microhardness, technological parameters.*

Relevance of the work. The reliability and durability of most modern and highly complex weapons and military equipment largely depend on the performance and service life of numerous friction units (tribosystems) and their various systems, mechanisms, individual machines, and assemblies.

In most cases, the failure of parts in mechanisms and machines begins at the surface areas. The surfaces of these parts are susceptible to wear, corrosion, fatigue, and other forms of damage. The reliability of tribosystems is primarily determined by the wear resistance of the moving and mating parts, which is influenced by the physical and mechanical properties of the materials used and the quality of the mating surfaces. The properties of tribosystem materials, like all structural materials, depend on their chemical composition and structure. For friction unit parts, the structure and properties of the surface layers are critical for the reliability and durability of the tribosystem. In today's environment of intensive operation for weapons and military equipment, the performance requirements for these products are becoming increasingly stringent. Enhancing newly manufactured components and worn parts is essential while extending their service life; this is a highly pressing task. One method of improving the performance of individual weapons and military equipment parts is to introduce new low-density materials that satisfy both technological and mechanical requirements.

The study aims to analyze how improving the equipment components for electric spark alloying can increase the durability and wear resistance of restored worn surfaces.

To achieve this goal, it is necessary to solve several problems: to analyze the physical processes of electric spark treatment (EST) and its effect on structural and phase transformations; to analyze the EST modes, alloying electrode materials on the phase composition of coatings; to substantiate the technologies for restoring worn surfaces of parts by electric spark alloying; to determine the effect of electric spark alloying modes on the microhardness and thickness of the formed coatings. Of course, within the framework of a single article, it is possible only partially to disclose individual tasks.

The object of the research is the physical processes of the restoration of parts by electrospark alloying. The subject of the study is the principles and technologies of restoration, as well as the features of obtaining wear-resistant coatings of individual parts by electrospark alloying. The practical significance of the results obtained is to provide the physical and mechanical properties, durability, and wear resistance of the restored worn surfaces of individual elements of the weapons and military equipment.

Analysis of recent research and publications. Article [1] provides an overview of modern thermal spraying technologies used in modern industry to strengthen machine parts. Particular attention is paid to analyzing coatings' microstructure, mechanical characteristics, and adhesive properties. The advantages and disadvantages of various spraying methods, such as cold spraying, plasma spraying, and high-speed oxy-fuel flame (HVOF) spraying, are discussed. The article contains the results of studies of the influence of sputtering parameters on the wear resistance and corrosion resistance of coatings.

Study [2] is devoted to characterizing coatings obtained by cold spraying. The authors consider the peculiarities of coating microstructure formation, their hardness, adhesion to the base material, and the effect of sputtering modes on mechanical properties. They analyze the applications of cold spraying, including the aviation, automotive, and energy industries. A comparative analysis of the efficiency of cold spraying compared to traditional coating methods is presented.

Paper [3] presents an overview of the mechanical properties of coatings obtained by high-speed oxy-fuel flame (HVOF) spraying. The influence of process parameters on coatings' hardness, shear strength, and wear resistance is discussed. Experimental data on structural changes in coatings depending on the composition of powder materials and application temperature are presented. Particular attention is paid to analyzing the use of HVOF coatings to strengthen parts operating under intense friction and high temperatures.

Paper [4] investigates the mechanical characteristics of thermal barrier coatings based on zirconium dioxide stabilized with yttrium oxide obtained by plasma spraying. It analyzes the coatings' microstructure, strength, hardness, and adhesive properties to the substrate. Particular attention is paid to the effect of porosity on heat resistance and resistance to thermal stress, which makes these coatings promising for the aviation and energy industries. Article [5] studies the relationship between the microstructure and mechanical properties of coatings applied by thermal spraying. The paper discusses the peculiarities of coating formation using various methods, including HVOF and plasma sputtering. The authors investigate the effect of powder particle size, sputtering temperature, and other process parameters on the formation of microcracks, adhesion, and the hardness of the resulting coatings.

Study [6] focuses on the wear and corrosion resistance of tungsten carbide (WC) coatings obtained by HVOF sputtering. Experimental results demonstrating the improvement of the mechanical characteristics of parts using such coatings are presented. Particular emphasis is placed on the influence of coating thickness and sputtering process parameters on performance properties and on their application in aggressive environments, particularly in the oil and gas industry. Article [7] investigates the mechanical and tribological properties of coatings produced by plasma sputtering. Particular attention is paid to the coatings' wear resistance and friction coefficient during operation under high loads. The influence of the coatings' structure on their wear resistance and durability is analyzed, which makes them promising for use in the mechanical engineering and aviation industries.

The review article [8] analyzes modern thermal spraying methods, including cold, plasma, and HVOF spraying. The authors consider the main features of each technique, their application in industry, and the advantages and disadvantages of improving the mechanical characteristics of parts. They also discuss prospects for developing spraying technologies, including their combination with other surface treatment methods. Article [9] analyzes the current state of cold gas-dynamic spraying technology. It considers the main technical and economic advantages of this method, such as the absence of thermal changes in the substrate material and the possibility of coating temperature-sensitive materials. The author discusses the possibilities of using cold spraying in the aerospace, automotive, and medical fields. Article [10] discusses innovative functional coatings obtained by thermal spraying. Special attention is paid to "smart" coatings that change their properties depending on operating conditions. The author analyzes current trends in developing coatings with high wear, oxidation, and corrosion resistance and their potential application in aviation and biomedical engineering.

Study [11] evaluates the properties of coatings obtained by thermal spraying, which resist high-temperature oxidation and corrosion. It considers the influence of coating composition and sputtering parameters on their performance. The results of tests of coatings in aggressive environments are presented, confirming their effectiveness for use in the energy and chemical industries.

Article [12] studies detonation-sprayed coatings based on titanium and chromium borides alloyed with nickel-aluminum-chromium alloy. It analyzes the microstructure, hardness, and wear resistance of such coatings, as well as their resistance to thermal stress. The work demonstrates the advantages of detonation spraying in creating high-strength and corrosion-resistant coatings for use in the aviation and defense industries.

The generalization of works [13–16] shows that using electrodes with nanostructured modifiers to form ultra-strong coatings with specified functional characteristics is extremely promising. Further improvement of the designs of installations for mechanized coating formation, which ensure process stability and high productivity, is significant and in demand.

Material and research results. Steel properties can be changed by changing its chemical composition or structure under the influence of external energy impact by various methods (mechanical, thermal, energy, or their combinations), including electric spark treatment (EST).

Electrospark alloying of metal surfaces is a phenomenon of electrical erosion and polar transfer of anode material to the cathode during pulsed discharges in a gas environment. The EIL process begins when the anode approaches the cathode and, at a distance between them equal to the breakdown value, the development of a spark discharge begins, which in many cases continues and ends after the electrodes come into contact [4–7]. After the breakdown of the interelectrode gap, localized foci of melting and evaporation develop on the surface of the electrodes, which cause electrical erosion of the electrodes. The eroded anode material is mainly transferred to the cathode. This ensures the formation of a surface layer on the cathode with the specified performance characteristics and physical and chemical properties. Since the anode material transfer process takes place in a gas environment, chemical compounds may be formed. As a result, the particles separated from the anode may not look like the anode material (Fig. 1).

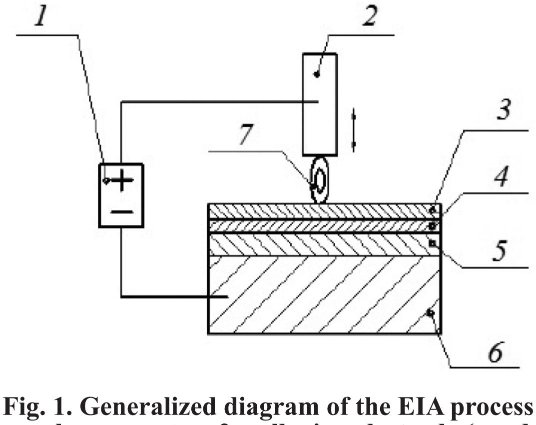

Fig. 1. Generalized diagram of the EIA process:
1 – pulse generator; 2 – alloying electrode (anode);
3 – coating layer; 4 – modified (hardened) layer;
5 – thermal impact zone; 6 – part (cathode); 7 – spark

Then, the anode (electrode) moves away from the cathode, and a layer of anode material remains on the latter's surface, which is firmly connected to the cathode [5].

In turn, the value of the changed characteristics is determined by the technological parameters of electrospark alloying (ESA), and specific physical and chemical properties will depend on the composition and properties of the electrode materials. Similarly, papers [5–7, 12, 13] consider the interaction of the anode with the cathode in contact under vibration. In compact materials used as the anode, the most common processing option is switching the anode with the cathode by vibration. In this case, the ESA process also begins with the anode approaching the cathode and the breakdown of the interelectrode gap. According to Townsend's theory of interelectrode gap breakdown, the minimum breakdown voltage in air at normal atmospheric pressure, depending on the electrode material, is 250–300 V [13].

Whereas when working with compact materials, the process under vibration conditions usually occurs at voltages U_p = 15...200 V, which are below the minimum of the Paschen curve and at distances equal to 0.01...10 μm, and the anode vibration frequency is usually in the range of 50...300 Hz. Based on these data, by the Paschen curve, the breakdown of the interelectrode gap at ESA can occur only when the electrodes are in contact. However, the studies obtained by [2, 5, 13, 14–16] and other scientists indicate that breakdown at such voltages occurs before physical contact of the electrodes.

At the onset of breakdown, an electric explosion of the contact bridge is reproduced at the initial stage, which provides preliminary surface cleaning and further formation of the interelectrode space for developing a plasma discharge. After the breakdown and the beginning of the spark discharge formation in $10^{-7}...10^{-8}$ s, the gas-discharge plasma of the channel, interacting with local areas of the anode and cathode, causes their electrical erosion. As a result, the electrode material is ejected into the interelectrode gap in the form of vapor and liquid droplet phases, and vapor evaporation and liquid phase ejection begin. At the moment of brittle fracture of the electrode material, a solid phase can enter the gap with steam and liquid during electrical erosion.

Electrical erosion, which occurs in gases and liquids due to the interaction of the spark discharge plasma with the electrode surface, is a complex process. Intense chemical interactions of materials, adhesion, and transfer of the anode material to the cathode also accompany mechanical contacts between the anode and cathode. A certain amount of energy, which in turn is carried by steam and liquid flows, depends on the thermophysical properties of the electrode material and the discharge parameters. Since these phenomena occur in a relatively small interelectrode gap, which gradually decreases, favorable conditions are created for the transfer of energy from the flows to the opposite electrodes. At the electrodes, in places of energy release under the influence of the electron-ion component of the gas-discharge plasma and flows of vapors and liquids, characteristic areas in the form of craters and molten erosion products are formed on the cathode surface in the form of a hole (a trace on the treated surface obtained as a result of the impact of electric discharges) and around it [11–17]. Therefore, during ESA, the surface of the workpiece (cathode) has the form of faces and depressions, the geometric dimensions and frequency of which determine the roughness and continuity of the treated surface. The emission of vapors and liquid droplets from the melt surface can occur as the pulse discharge develops. The emission of vapors and liquids and the reduction of the gap gradually lead to a significant increase in pressure in the electrode gap.

Several forces act on the converging liquid volumes of the cathode and anode: hydrodynamic pressure from the flares, gas kinetic pressure from the channel, electric field force, electrodynamic force, and reactive pressure.

As a result, the volume of liquid metal ejected from the hole is deformed under the influence of the resultant of these forces. Because this occurs practically in contact, the possibility of merging the liquid phases of the electrode materials and their intense hydrodynamic mixing is not excluded [8, 11].

Due to the polar effect of erosion and some of the previously mentioned factors, the transfer of eroded anode material to the cathode in the process of electrospark alloying forms surface layers on the cathode, which is the result of the interaction of electrode materials and the environment of the interelectrode gap. During polar transfer, the amount of liquid phase on the anode exceeds the cathode erosion, and subsequently, the surface layer formed on the cathode should mainly consist of anode material. However, hydrodynamic mixing can contribute to the fact that in this layer, it is possible to obtain a coating over the entire volume up to the surface not only of the anode material but, in some cases, also of cathode materials.

The crystallization and interaction of the liquid phases of the electrode material during electrospark alloying occur mainly on the surface of the cathode.

According to the authors of [7–11, 13], the melts of the electrode (anode) material, interacting with the environment and the cathode material, remain on its surface. As a result, the physical and chemical properties of the anode and cathode surfaces change.

The presence of the cathode material in the anode surface layer occurs both due to the flow of the vapor-droplet mixture and the mixing of the liquid phases, as well as because the electrode materials are prone to setting. The authors' experiments confirm that the properties of the surface layer change significantly during ESA. The surface layer is formed by the molten metal that remains on the hole's surface, and the adjacent metal layer is subjected to structural changes due to the rapid heating and cooling of the metal. However, the properties of this layer are not fully defined. Therefore, it is divided into zones to study the layer's properties, as shown in Fig. 2.

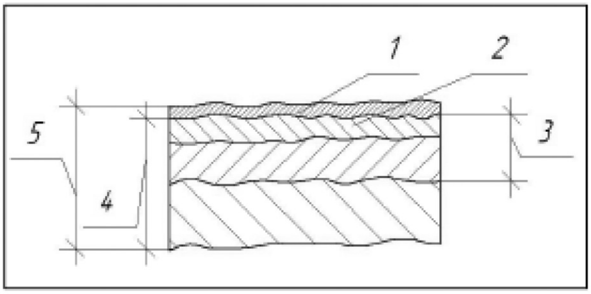

Fig. 2. Surface layer obtained after ESA: 1 – zone of deposition of the electrode (anode) material; 2 – "white" layer formed from the molten material of the workpiece; 3 – zone of thermal influence; 4 – zone of plastic deformation; 5 – changed surface layer

These zones have no clear distinction and overlap. Nevertheless, all central parts of the zones have characteristics that affect the properties of the entire surface and determine the possibility of further exploitation. Reputable researchers, particularly specialists from the Institute of General Energy of the National Academy of Sciences of Ukraine (Academician V. P. Babak and his scientific school), divide it into a white layer, a transition layer, and unchanged workpiece material (Fig. 3).

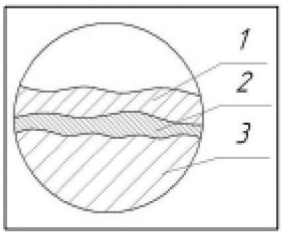

Fig. 3. Altered cathode surface layer obtained after ESA. 1 – "white" layer; 2 – transition layer; 3 – unchanged workpiece material

It is now believed that chemical and thermal transformations are observed in the «white» layer, a transition layer that includes a thermal impact zone and a diffusion zone under which there is an unchanged product material (cathode). The authors of [7–10, 12–14] believe that the distribution of zones depends on the base material and modes of electric spark alloying. The "white" layer has a fine-grained structure with high chemical resistance, making it difficult to detect by etching.

The formation of a «white» layer during electric spark alloying is associated with the effect of the transfer of electrode (anode) material to the cathode. The increased heat removal rate causes the temperature within the small layer to drop to the melting point and the corresponding phase transformations. Therefore, the crystallization and phase transformations accompanying the ESA process subsequently form nonequilibrium fine-grained structures. This layer looks like white stripes on a microscope, so it got its name. The «white» layer is poorly etched because it is in contact with the high-speed, high-temperature tempering zone, which has a more positive electrochemical potential. To eliminate the influence of this zone, the "white layer" is treated with reagents. Upon completion of the spark discharge and crystallization of the materials, the electrospark alloying phase begins on the anode and cathode surfaces – a dense physical contact occurs.

The last phase of the ESA process begins with reducing mechanical pressure between the electrodes, which is associated with removing the alloying electrode from the cathode (workpiece). It ends with the breakdown of the electrical circuit with the removal of the anode from the workpiece to a distance significantly exceeding the breakdown distance. In cases where specialized pulse generators (RC type) are used, a short arc may appear in the last phase of the process, which is a break in the contact system. Studies show that in ESA modes, the arc is absent when the Up voltage is in the range of 15–50 V. This is because during the contact break, due to transients, the voltage across the capacitor connected in parallel with the spark gap does not reach the maximum value of the short arc ignition potential. Higher voltage values do not significantly change the process of short arc formation since electrode erosion, in this case, can be neglected.

Compact electrodes represent the dynamics of the electro-spark alloying process and can have several options related to the characteristics of the electrode material, pulse parameters, kinematics of electrode movement, etc.

The process of electrospark alloying with compact electrodes includes the following cycles: formation of electrical contact between the anode (electrode) and the cathode (part), after the electrodes approach and breakdown between the electrode gap; electrical erosion of the electrodes; polar transfer and formation of a surface layer on the surface of the cathode (part or tool); breakdown of electrical contact between the anode and the cathode, at the moment of electrode divergence.

In addition, the processes at the anode and cathode are considered elementary, caused by the flow of a single discharge (erosion, interaction of material transfer), and accumulative, which are associated with the repeated action of pulsed discharges (creation of residual stresses, phases). Electrical erosion of electrodes is the destruction of the electrode surface, which is accompanied by metal removal at the moment of passing electric discharges between the electrodes. Electrical erosion of electrodes is a process that occurs at the interface between the discharge channel, on the one hand, and the cathode or anode, on the other. In general, electrical erosion is a physical phenomenon consisting of the directed ejection of electrode material under the influence of an independent electric discharge. In the case of electrodes surrounded by a gas environment, the described phenomenon is accompanied by the deposition of the ejected material on the opposite electrode, which, in turn, changes the discharge conditions. Erosion of the electrode alloying and transfer of the anode material to the cathode surface (part) occurs due to the asymmetry of heat in the “hot spot” of the communication bridges formed when the electrodes are closed. Thermophysical and thermoelectric effects mainly determine the contact-bridge transfer of matter. In this case, the energy that passes through the current bridges is used to melt the materials, and as the electrodes continue to pass between them, a molten bridge appears. The bridge breaks off at the alloying electrode’s base because the molten metal’s cooling rate on the surface is much higher. Thus, material transfer is directed towards the electrode, which is further away from the most heated point, often the cathode (part). Lesser erosion of the anode (electrode) compared to the cathode (part) erosion is due to the intense impact of the cooling media used (compressed air). The following phenomena accompany ESA:

– during the electrical erosion of the anode and cathode, the polarity effect is observed, namely, the erosion of one electrode increases over the other;

– electrical erosion of metals depends on the chemical composition of the materials of the electrodes, the part, the environment, etc;

– The amount of material ejected from the anode during the spark mode of a short circuit is no more than 10 %, but when the required modes are provided, it is about 100 % of the total charge of the capacitors.

The impact of an electric spark on the anode consists of melting and evaporation of metal, and on the cathode – as a microexplosion, accompanied by mechanical damage in the form of a hole with edges raised above the surface. The model of transferring material from the anode to the cathode will differ for each metal. When materials with low erosion resistance (tin, zinc) are applied to aluminum, the amount of metal ejected by a single pulse from the anode is significant. From the cathode, it is so negligible that it is neglected. Suppose the electro-erosion resistance of the cathode material is higher than that of the anode material. In that case, a coating is formed on the surface; if it is lower, holes are formed on the cathode surface. No coating is formed since the amount of material deposited on the cathode is less than the material ejected from the cathode surface.

Electric spark alloying changes the dimensions, relief (roughness), and physical, chemical, and mechanical properties of the workpiece’s surface layer, producing working surfaces with the required performance characteristics. To strengthen and increase the wear resistance of the parts’ surface, obtaining them with a minimum roughness ($Ra \approx 10$ μm) and sufficient thickness ($t \sim 0.5$ mm) is desirable.

Conclusions. The analysis of literature sources on surface hardening of parts to improve the mechanical and tribotechnical properties of these parts shows the continuous development of methods. At the same time, the existing surface hardening methods do not fully meet the current requirements for the efficiency of the processes of restoration of weapons and military equipment, for the simplicity of operation, and for the versatility and efficiency of technological restoration processes. Increasing requirements for surface strength and wear resistance of parts of friction units of complex mechanisms and machines of weapons and military equipment leads to the need to improve the known and develop new highly efficient technological methods of surface hardening of structural materials. Methods of surface modification of parts of mechanisms and machines (especially parts of tribosystems) with highly concentrated energy flows have great potential. One of the most promising is the method of electrospark treatment, in which streams of high-energy-density particles are formed and used under pulsed impact on the workpiece, which allows creating surface structures with increased mechanical and tribotechnical properties with considerable simplicity of technological equipment and process efficiency.

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ФІЗИКО-ТЕХНОЛОГІЧНИЙ АНАЛІЗ ЕЛЕКТРОІСКРОВОЇ ОБРОБКИ ВІДНОВЛЮВАНИХ ДЕТАЛЕЙ ІЗ КОНСТРУКЦІЙНИХ І ІНСТРУМЕНТАЛЬНИХ СТАЛЕЙ

Надійність і довговічність вузлів тертя в сучасному озброєнні та військовій техніці (ОВТ) значною мірою залежать від фізико-механічних властивостей матеріалів деталей та якості їхньої поверхневої обробки. Одним із перспективних методів підвищення експлуатаційних характеристик ОВТ є електроіскрове легування (ЕІЛ), що дозволяє створювати зміцнені покриття з високою зносостійкістю. У статті розглянуто фізичні процеси, що відбуваються під час ЕІЛ, зокрема *електричну ерозію, полярний перенос матеріалу та структурно-фазові перетворення поверхневого шару. Показано, що перспективним є використання електродів із наноструктурними модифікаторами для формування надміцних покриттів із заданими функціональними характеристиками, що подальше удосконалення конструкцій установок для механізованого формування покриттів, що забезпечують стабільність процесу та високу продуктивність є вкрай актуальним. Проведено аналіз режимів процесу, параметрів електродів та їхнього впливу на формування покриттів. Наведено механізм утворення поверхневих шарів та особливості їхньої кристалізації. Встановлено, що застосування ЕІЛ сприяє утворенню білих шарів із дрібнозернистою структурою, які характеризуються високими механічними властивостями та корозійною стійкістю. Подальший аналіз технологічних параметрів ЕІЛ продемонстрував значний вплив матеріалу електрода на склад і характеристики отриманих покриттів. Визначено вплив режимів імпульсного розряду на глибину проникнення легуючих елементів у поверхневий шар деталі. Показано, що необхідно особливу увагу приділяти впливу газового середовища міжелектродного проміжку на кінетику процесу перенесення матеріалу. У практичному аспекті результати досліджень демонструють ефективність застосування ЕІЛ для відновлення та зміцнення деталей, що працюють у складних умовах експлуатації, зокрема у вузлах тертя ОВТ. Проведені експерименти авторів підтвердили можливість регулювання мікротвердості та товщини покриттів шляхом оптимізації режимів обробки та складу електродного матеріалу. У підсумку зроблено висновок про те, що електроіскрове легування є ефективним методом зміцнення поверхонь деталей, що забезпечує їхню довговічність і експлуатаційну надійність, перевершуючи традиційні технології за рядом ключових параметрів.*

Ключові слова: *електроіскрове легування, конструкційні сталі, деталі машин, компоненти обладнання, зносостійкі покриття, електрична ерозія, фазові перетворення, мікротвердість, технологічні параметри.*