УДК 629.017:629.083 DOI:10.18372/0370-2197.2(111).21316

O. O. MIKOSYANCHIK[1], V. B. SHAMRAI[2], O. P. YASHCHUK[1], O. V. LOPATA[3],
S. R. MNATSAKANOV[1], O.O. HANZIAK[1]
[1]State University «Kyiv Aviation Institute», Kyiv, Ukraine
[2]Secretariat of the Cabinet of Ministers of Ukraine, Kyiv, Ukraine
[3]G. S. Pisarenko Institute for Problems of Strength, Kyiv, Ukraine

IMPROVING THE ABRASION RESISTANCE OF STEELS BY FORMING HETEROGENEOUS ELECTROSPARK COATINGS

The work is dedicated to increasing the operational life of agricultural machinery parts operating under conditions of intensive dynamic and abrasive environmental impact. The aim of the study is to determine the effect of continuity, microstructure, and phase composition of heterogeneous composite electrospark coatings based on tungsten and chromium carbides on their abrasive wear resistance. Surface modification of specimens made of 65G and 40X13 steels was carried out by electrospark alloying on "Elitron-22" micro-welding equipment using a VK8 tungsten-cobalt system electrode and a KHN25 chromium carbide-nickel system powder mixture, respectively. Tribological stability tests were conducted in an environment of loose silicon carbide abrasive particles according to an adapted procedure of the ASTM G65 standard. According to the analysis results, regular changes in the chemical composition of the formed coatings were recorded compared to the initial anode materials. An increased cobalt content of up to 12.6 wt. % was detected in the tungsten carbide-cobalt system, which is due to its preferential melting under the action of pulsed discharges with the formation of a developed surface matrix. For the chromium carbide-nickel system, a decrease in chromium concentration to 55.8 wt. % was determined due to thermal burnout, with relative stability of the nickel binder, which was 26.8 wt. %. The wear kinetics assessment showed that the minimum weight loss of both types of coatings is achieved at their continuity of 55–75%. At the same time, the KHN25 electrospark coating demonstrates 1.8–2.0 times higher wear resistance compared to VK8. The higher abrasive resistance of the KHN25 coating is explained by its fine-grained structure and the presence of a ductile nickel matrix, which provides effective relaxation of local stresses and inhibits brittle chipping of carbide phases during micro-cutting by the abrasive.

Keywords: *electrospark alloying, coatings, wear resistance, abrasive wear, microstructure, continuity, testing.*

Introduction. The complexity of the wear process in agricultural machinery components (AMC) is due to the dynamic nature of the loads on friction surfaces, the heterogeneity of the abrasive environment in terms of particle size distribution and chemical composition, as well as the complex kinematics of contact and particle movement. The failure of tribological interfaces occurs due to micro-cutting under conditions of single or repeated mechanical action by abrasive elements. The differentiated selection of materials and optimization of the design parameters of working parts to increase their service life require a systematic tribological approach. A promising direction for ensuring the service life of components is the selection of hardening technologies for the working parts of agricultural machinery, the justification of rational technological parameters, and the use of wear-resistant materials. When selecting these composite materials (CM), the decisive criterion is achieving an optimal balance between high strength characteristics and a sufficient level of ductility to prevent brittle fracture of the modified surfaces. Heterogeneous wear-resistant composite coatings fully meet this set of physical and mechanical properties. The selection of composite materials capable of ensuring predictable wear resistance of working surfaces under severe abrasive wear conditions is a key area of development in modern surface hardening technologies and surface engineering.

Review of the literature and analysis of unresolved issues. The greatest improvement in the tribological properties of AMC components is achieved by creating protective hardening coatings [1] and forming composite structures with minimal wear [2]. Coatings must meet the following requirements: a coefficient of thermal expansion close to that of the substrate material; no adverse effect on the properties of the components; diffusion inertness with respect to the component material; sufficient adhesion; a set of necessary operational characteristics; and economic feasibility [3, 4].

The wear resistance, corrosion resistance, and other properties of CMs depend on their composition [5, 6]. Iron, nickel, copper, and hardfacing alloys are used as matrix materials for wear-resistant coatings [7]. Self-fluxing alloys based on nickel and iron have found the most widespread application in the formation of wear-resistant composite coatings [8].

Ferroalloys are used as coating materials and as alloying additives to strengthen and restore parts that are subjected to abrasive and corrosion-mechanical wear during operation [9]. The feasibility of using ferroalloys in CM is justified by their low cost, availability, and the ability to improve the operational properties of parts and working components of agricultural machinery. Ferroalloys can be used both in their pure form and as alloying additives. The high performance of ferroalloys is due to the chromium, titanium, boron, manganese, molybdenum, tungsten, and other materials included in their composition [10].

In metal-matrix composites reinforced by dispersion, the fillers consist of dispersed particles of refractory phases-oxides, nitrides, and carbides [11]. When strengthening the working parts of AMCs, it is advisable to use CMs that include wear-resistant fillers, such as chromium carbide and tungsten carbide.

In [12], it is noted that to replace tungsten-cobalt hard alloys used in the manufacture of wear-resistant parts and cutting elements for plows, cultivators, plowshares, and other agricultural machinery, hard alloys based on titanium carbide, doped with vanadium carbide and tungsten nanocaride with a nickel-chromium matrix, have been developed. These alloys have higher hardness and wear resistance and ensure reliable and long-lasting performance under operating conditions.

Choosing the right method for applying wear-resistant coatings is a key factor in extending the service life of agricultural machinery components that operate under conditions of intense abrasive wear and significant mechanical stress. Optimizing the application technology makes it possible to significantly improve the physical and mechanical properties of the surface layer of components, minimize maintenance costs, and increase the overall operational efficiency of the machinery. The choice of method for forming composite coatings is determined by the following main factors: operating conditions of the agricultural machinery; part design; type of part material and composition of the composite coating; and economic feasibility [13]. Currently, the electric spark alloying (ESA) method is used to modify the physical-mechanical, tribological, and operational properties of part working surfaces in a specified direction. The main feature of the ESA method is the discrete nature of the process [14]. Thus, a single electrical discharge ensures the stability of the physical and mechanical properties of a specific section of the coating. The magnitude of the working current allows for the adjustment of the coating's penetration depth into the surface being hardened, as well as the height and length of the individual section.

The electric spark alloying process offers the following advantages [15]: it increases the wear resistance of friction surfaces by structurally and energetically adapting the materials during friction and creating an optimal surface microgeometry; it eliminates stress concentrations caused by contact loads and interrupts the crack initiation process; enables the minimization of the stress-strain state of the surface by altering the continuity and dimensions of discrete regions on the surface of the workpiece being hardened; allows for achieving high adhesive strength between the coating and the substrate, as well as high cohesive strength of the coating.

Despite existing research, the issue of optimizing the compositions and technological parameters for applying heterogeneous coatings remains insufficiently studied; therefore, the justification of the formation modes for such wear-resistant structures is of particular relevance for improving the reliability of working parts of internal combustion engines under conditions of intense abrasive wear.

The aim of this study is to investigate the effect of the compactness and phase composition of tungsten and chromium carbide-based composite electric spark coatings (ESC) on their resistance to abrasive wear, in order to establish optimal hardening parameters for gas turbine engine components.

Materials and methods. Wear-resistant coatings were formed using the electric spark alloying method with the "Elitron-22" micro-welding equipment (Table 1).

Table 1

Main modes of EIP formation for surface strengthening

Basic characteristics and modes	Values	
Coating material	VK8	KHN25
Material of the surface to be hardened	65G	Steel 40X13
Working current, *A*	1.5	
Electrode oscillation amplitude, *mm*	0.2 – 0.5	

The materials selected for applying composite coatings are the WC-Co hard alloy grade VK8 and the KHN25 (Cr-Ni-C) alloy, in which chromium carbide is used as the hard refractory phase (Table 2).

Table 2

Composition of KNH 25 alloy (% wt.)

Alloy grade	Chromium carbide	Nickel
KHN25	73 … 75	22 …25

The application of a coating with variable continuity is carried out by changing the electrode displacement speed. During electrospark deposition (ESD), the movement of the electrode makes it possible to form a different coating topography on the hardened surface of the part. By changing the current and voltage, it is possible to ensure the ratio of coating continuity to its thickness.

When forming composite coatings, specific areas of the substrate, located in a certain manner on the surface to be hardened, were hardened with a defined coverage (ψ):

$$\psi = S / S_O, \qquad (1)$$

where S is the area corresponding to the formed coating sections, and S_O is the total area of the surface to be hardened.

Composite coatings of variable continuity were formed in the form of micro zones (up to 1.0 mm) with a continuity of ψ = (20...90) %; the accuracy of determining the coating continuity was ±5%.

For testing the abrasion resistance of coatings, a bench test rig was used in an environment containing loosely suspended abrasive particles (Fig. 1). Roller 1 is driven by electric motor 2 via gearbox 3. Gearbox 3 is connected to the electric motor via a belt drive 4. Holder 5 with the specimen 6 is mounted on lever 7 and pressed against roller 1 by a force generated by load 8. Abrasive from hopper 9 flows through chute 10 into the friction zone. The angle of inclination of the chute guide 10 is (45°±2). The roller diameter is 45–50 mm, and the roller width is 20 ± 0.1 mm.

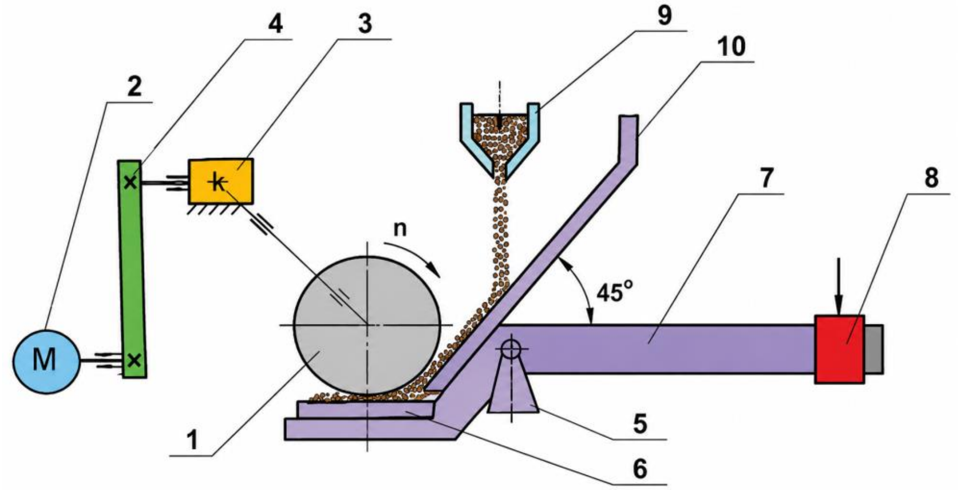

Fig. 1. Schematic diagram of a test rig for bench testing of reinforced specimens for abrasive wear with loosely bound abrasive particles.

The testing methodology was based on the principles of ASTM G65 [16], adapted for the study of thin electrospark coatings ESCs (equivalent to Procedure C). To preserve the integrity of the coating and prevent deformation of the substrate during testing, the parameters were modified: a reduced load of 47 N and a linear velocity of 0.158 m/s were applied.

The samples were fabricated as plates 30 mm wide, 30-50 mm long, and 2-3 mm thick. Silicon carbide with a grain size of up to 250 μm was used as the abrasive material.

Structural analysis of the ESCs was performed using optical microscopy on an IE200M digital inverted microscope. The elemental composition and microstructural features were investigated using energy-dispersive X-ray spectroscopy (EDS/EDX) with an electron microscope-based microanalysis system.

Research results and their analysis. To select the optimal parameters for ESCs with a discontinuous structure, experiments were conducted to determine the dependence of the abrasion resistance of EIP-reinforced steels on the continuity of the coating. Figure 2 shows the dependence of the weight loss of the coating on its continuity during friction in an abrasive environment.

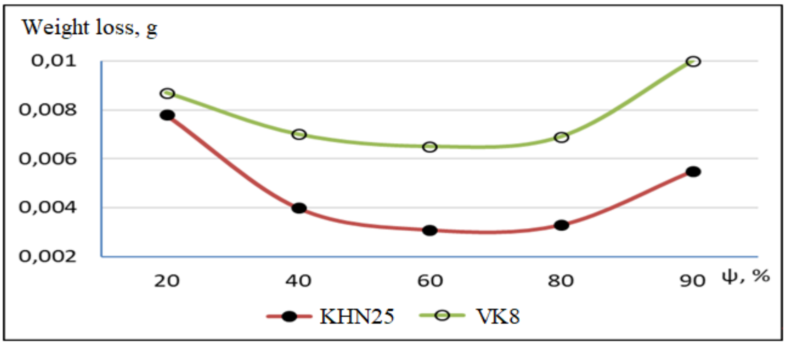

Fig. 2. Relationship between the weight loss of experimental samples with ESCs and the coating density (ψ).

At a solidity of ψ = 55-75%, the minimum abrasive wear of the ESCs was observed, regardless of the type of coating under study. It was determined that the best quality indicators for the hardened surfaces were obtained at a solidity of ψ = 70% and a ratio of hardened to unhardened coating areas of 2:1. The obtained research results are similar to those in [17].

For ESC VK8, weight loss under the action of unbound abrasive particles is 1.8–2.0 times higher than that of ESC KHN25. This is due to the fact that the microhardness of the VK8 ESC is 1.3 times higher than that of KHN25 coatings, which causes the brittleness of this coating. Additionally, the high microhardness of the VK8 coating leads to a reduction in resistance to abrasive wear due to a decrease in tangential shear resistance when a hard abrasive particle is embedded, which is caused by the low proportion of the matrix component (cobalt) in the structure of the VK8 hard alloy. Under the action of loose abrasive, the following failure mechanisms predominate for the VK8 coating: micro-cutting of the surface by abrasive grains; formation of deep friction grooves; brittle spalling of hard carbide phases; detachment of individual microvolumes of the coating; development of microcracks in the surface layer (Fig. 3a).

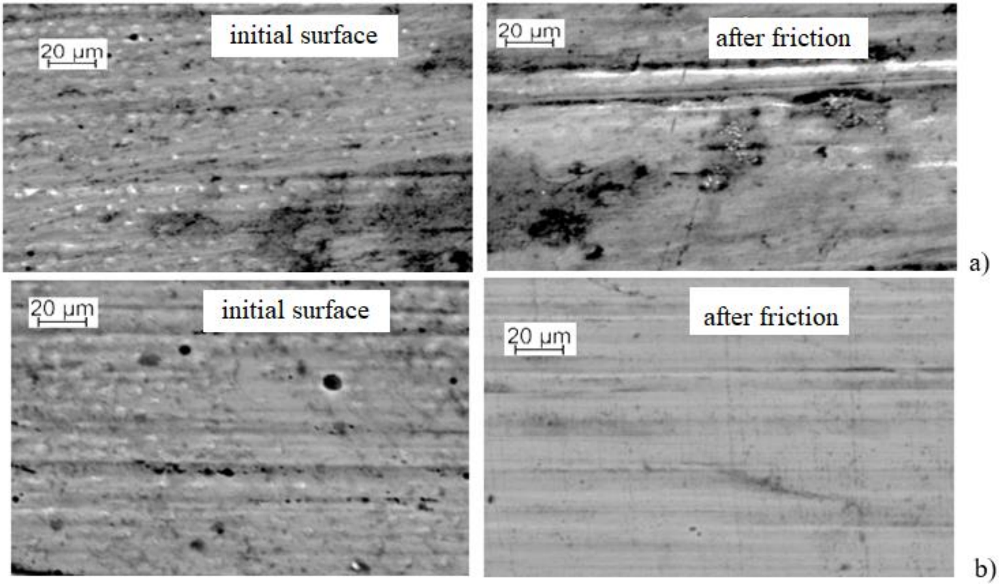

Fig. 3. Appearance of the initial surface and the surface after friction under the influence of loose abrasive: a – VK8, b – KHN25.

For the KHN25 ESC, the wear tracks are characterized by a homogeneous structure, indicating a high degree of resistance of the ESC to the embedding of abrasive particles. The presence of a plastic nickel phase ensures the coating's ability to undergo local plastic deformation without intense brittle fracture. The nickel matrix facilitates the redistribution of contact stresses and reduces the concentration of local destructive loads. As a result, the surface retains a more uniform structure even after prolonged exposure to abrasives. The KHN25 coating exhibits the following characteristics during friction: moderate micro-cutting; plastic deformation of the surface layer; partial smoothing of friction grooves; inhibition of microcrack propagation; and increased resistance to spalling (Fig. 3b).

From a materials science perspective, the tribological properties of electric-spark coatings are determined by their phase composition, microstructure, the ratio of hard to ductile components, and the nature of interphase interactions among the coating components.

Fig. 4 presents a comparative analysis of the phase composition and microstructure of the VK8 (WC–Co) and KHN25 (Cr_3C_2–Ni) electric spark coatings, obtained using electron microscopy and energy-dispersive X-ray spectroscopy (EDS).

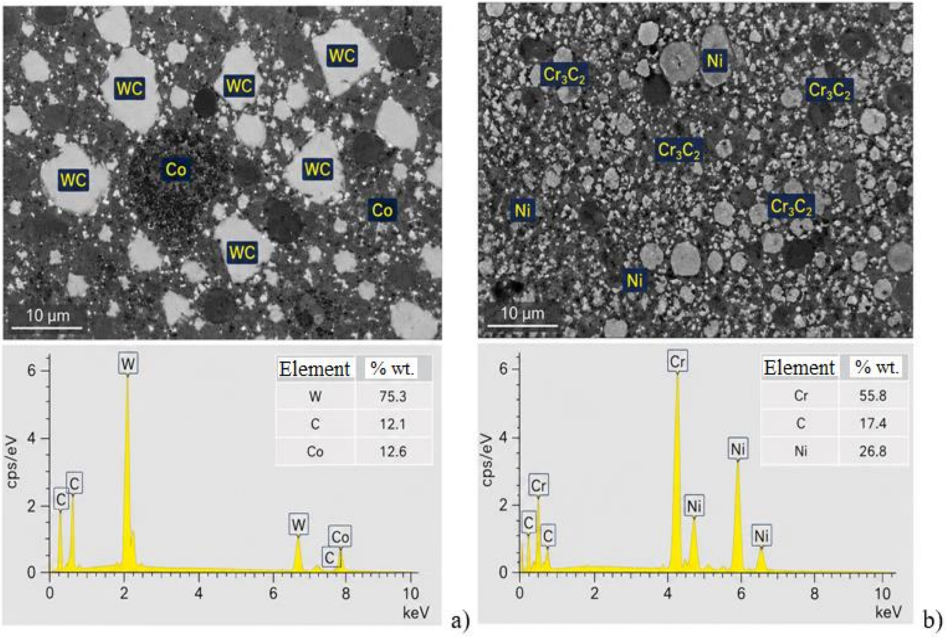

Fig. 4. Comparative analysis of the phase composition and microstructure of the VK8 (a) and KHN25 (b) electrospark coatings.

The microstructure of the VK8 ES coating shows the presence of light-colored, large inclusions of hard tungsten carbide (WC) grains in a cobalt binder matrix (darker areas) (Fig. 4a). The EDS spectrum confirms the presence of the main elements—W, C, Co.

In the VK8 coating (WC–Co system) on a 65G steel substrate, the following elemental distribution (mass %) was recorded: tungsten (W) – 75.3; carbon (C) – 12.1; cobalt (Co) – 12.6. The increased cobalt content relative to the nominal anode composition (8 wt.%) is due to its intense melting under the action of pulsed discharges, the formation of a developed metallic matrix, and the localized scanning of the interface zone. ESC VK8 is characterized by a high concentration of hard carbide phases. Hard carbide grains effectively resist abrasive penetration; however, they fracture brittle when critical stresses are exceeded. As a result, large grooves and areas of localized damage form on the surface. In addition, the high hardness of VK8 is accompanied by a decrease in shear tangential resistance when interacting with abrasive grains. This facilitates the micro-cutting process and accelerates material loss.

For the KHN25 coating (a chromium carbide Cr_3C_2 and nickel matrix Ni system) applied to 40X13 high-chromium steel, the elemental composition is (wt. %): chromium (Cr) – 55.8; carbon (C) – 17.4; nickel (Ni) – 26.8 (Fig. 4b). The decrease in chromium concentration compared to the initial mixture composition (75 wt.% Cr_3C_2) is due to its partial oxidation and burnout during micro-welding. At the same time, the detected nickel content (26.8 wt.%) is close to the initial value (25 wt.%), indicating high stability of the liquid-phase transfer of the bond.

The abnormally high carbon values in both spectra (12.1% and 17.4%, respectively, for ESC VK8 and KHN25) are a result of adsorption contamination of the polished surface by hydrocarbons in the electron microscope chamber, which is accounted for by the automatic intensity normalization algorithm and slightly underestimates the final fractions of metallic components.

The microstructure of the KHN25 ESC is finer-grained and more homogeneous compared to VK8 (Fig. 4). The light particles correspond to chromium carbides, while the darker matrix corresponds to the plastic nickel matrix.

The presence of a ductile nickel matrix ensures a more uniform load distribution and relaxation of contact stresses; inhibits the development of microcracks; increases crack resistance when abrasive particles are embedded during friction; and increases the energy required for fracture. When an abrasive particle is embedded, part of the energy is expended not on fracture but on the plastic deformation of the nickel matrix. This reduces the intensity of spalling of the carbide component of the ESC and increases the stability of the surface layer.

Thus, the higher wear resistance of the KHN25 ESC is explained by the optimal combination of hard carbide phases and a ductile nickel matrix, which ensures effective relaxation of contact stresses and inhibits the development of destructive processes in the surface layers of the coating under conditions of friction in an abrasive environment.

Conclusions

1. It has been established that the kinetics of abrasive wear of heterogeneous electric spark coatings depend significantly on their topography on the surface being hardened. The minimum weight loss of the VK8 and KHN25 ESCs is achieved when their discrete continuity is within the range of 55–75%. At the same time, the best indicators of quality and durability of working surfaces were recorded at 70% continuity and a rational ratio of hardened to unhardened areas of 2:1.

2. The composite ESC KHN25 of the chromium-nickel carbide system exhibits significantly higher abrasion resistance compared to the VK8 alloy of the tungsten-cobalt system: under conditions of intense action by unbound silicon carbide abrasive particles, the weight loss of the VK8 coating is 1.8–2.0 times greater than that of the KHN25 coating.

3. It has been proven that the difference in wear resistance of the coatings in an abrasive environment is due to their structural and mechanical properties and the nature of their interaction with the abrasive. The VK8 coating has higher microhardness (1.3 times), which leads to brittleness and intense micro-cutting, the formation of deep grooves, and spalling of the carbide phases. ESC KHN25 has a finely dispersed,

homogeneous structure and is characterized by a combined wear mechanism, where local plastic deformation predominates without intense brittle fracture.

References

1. Zakharov A. V. Prediction of wear resistance of working bodies of tillage equipment during their restoration by electroslag surfacin. *Visnyk of Kherson National Technical University: Engineering sciences*. 2024. № 4. C.24-32. https://doi.org/10.35546/kntu2078-4481.2024.4.3

2. Shamrai V., Mikosianchyk O., Lopata L. et al. Composite materials for wear-resistant coatings of agricultural machinery parts. *Problems of Friction and Wear*. 2023. 1(98). C. 4-13. https://doi.org/10.18372/0370-2197.1(98).17356

3. Denysenko M. I., Rublov V. I. Tekhnolohichni metody zabezpechennia dovhovichnosti robochykh orhaniv i nadiinosti silskohospodarskykh mashyn. *Konstruiuvannia, vyrobnytstvo ta ekspluatatsiia silskohospodarskykh mashyn*. 2013. Vyp. 43(2). C. 7-17.

4. Rogovskii I. L., Borak K. V., Maksimovich E. Yu. et al. Wear resistance of blade and disc working bodies of tillage tilling machines hardened by electrodes T-series. *Journal of Physics: Conference Series*. 2020. Vol. 1679. 042084. DOI:10.1088/1742-6596/1679/4/042084

5. Wang Y., Li D., Nie C. et al. Research Progress on the Wear Resistance of Key Components in Agricultural Machinery. *Materials*. 2023. *16*(24). 7646. https://doi.org/10.3390/ma16247646

6. Stavinskiy A., Vakhonina L., Martynenko V. et al. The use of surface strengthening to increase the wear resistance of working bodies of agricultural machines. *Ukrainian Black Sea Region Agrarian Science*. 2024. 28(2). P.21-32. DOI:10.56407/bs.agrarian/2.2024.21

7. Mikosianchyk O., Shamrai V. Increasing the performance properties of agricultural equipment parts with composite coatings. *Problems of Friction and Wear*. 2022. 4 (97). C. 44-49. https://doi.org/10.18372/0370-2197.4(97).16958

8. Lopata L., Kachynska I., Solovykh A., Katerinich S. Creation of wear-resistant composites coated on the basis of powder-based self-flowing alloys by electro-contact sintering. *Problems of Friction and Wear*. 2024. 3(104). C. 15-22. https://doi.org/10.18372/0370-2197.3(104).18974

9. Teker T, Karataş S, Yilmaz S O. Microstructure and wear properties of FeCrC, FeW and feti modified Iron based alloy coating deposited by PTA process on AISI 430 steel. *Archives of Metallurgy and Materials*. 2014. 59(3). P. 925–933. DOI:10.2478/amm-2014-0156

10. Ulas M., Altay O., Gurgenc T., Özel C. A new approach for prediction of the wear loss of PTA surface coatings using artificial neural network and basic, kernel-based, and weighted extreme learning machine. *Friction*. 2020. 8(6). P. 1102–1116 https://doi.org/10.1007/s40544-017-0340-0

11. Hlushkova D.B., Volchuk V.M. Fractal study of the effect of ion plasma coatings on wear resistance. *Functional Materials*. 2023. 30 (3). P. 453-457. https://doi.org/10.15407/fm30.03.453

12. Koval I., Bodrova L., Kramar H. et al. Wear resistant hard alloys for agricultural machines elements. *Visnyk TNTU* (*Tern*.). 2020. № 2 (98). P. 33-39. https://doi.org/10.33108/visnyk_tntu2020.0

13. Yushchenko K.A., Borysov Yu.S., Kuznietsov V.D., Korzh V.M. Inzheneriia poverkhni: pidruchnyk. Kyiv: Naukova dumka, 2007. 559 c.

14. Tarelnyk V. B., Gaponova O. P., Kirik G. V. et al. Cementation of Steel Details by Electrospark Alloying, *Metallofiz. Noveishie Tekhnol*. 2020. 42, No. 5. P. 655–667 (in Ukrainian). https://doi.org/10.15407/mfint.42.05.0655

15. Wang J., Zhang M., Dai S., Zhu L. Research Progress in Electrospark Deposition Coatings on Titanium Alloy Surfaces: A Short Review. *Coatings*. 2023. 13. 1473. https://doi.org/10.3390/coatings13081473

16. Doering A., Danks D., Mahmoud S., Scott J. Evaluation of ASTM G65 abrasive – Spanning 13 years of sand. *Wear*. 2011. Vol. 271, Is. 9–10. P. 1252-1257. https://doi.org/10.1016/j.wear.2011.01.051

17. Storozhenko M., Umanskyi O., Tarelnyk V. et al Structure and wear resistance of FeNiCrBSiC–MeB$_2$ Electrospark Coatings. *Powder Metall Met Ceram*. 2020. 59. P. 330–341. https://doi.org/10.1007/s11106-020-00166-1

Received: May 19, 2026
Accepted: May 25, 2026
Published: May 31, 2026

Oksana Mikosianchyk – Doctor of Technical Sciences, Professor, Head of the Department of Applied Mechanics and Materials Engineering, State University "Kyiv Aviation Institute", 1 Lubomyra Huzar Ave., Kyiv, Ukraine, 03058, E-mail: oksana.mikos@ukr.net, https://orcid.org/0000-0002-2438-1333

Vitaliy Shamrai – Doctor of Philosophy in Applied Mechanics (PhD), Secretariat of the Cabinet of Ministers of Ukraine, 12/2 Hrushevskoho St, Kyiv, Ukraine, 01008, E-mail: vitalii.shamrai76@gmail.com https://orcid.org/0000-0002-1746-5213

Olesia Yashchuk – Senior Lecturer at the Department of Professional Foreign Languages, State University "Kyiv Aviation Institute", 1 Lubomyra Huzar Ave., Kyiv, Ukraine, 03058, E-mail: olesia.yashchuk@npp.kai.edu.ua , https://orcid.org/0009-0000-6712-3804

Oleksandr Lopata - Doctor of Philosophy in Applied Mechanics (PhD), senior researcher of the department of strength of materials and structural elements in thermoforce fields and gas flows, G. S. Pisarenko Institute for Problems of Strength of National Academy of Sciences of Ukraine, 2, Salovo-botanical Street, Kyiv, Ukraine, 01014, E-mail: lopata-sasha@ukr.net, https://orcid.org/0000-0001-5266-6486

Stepan Mnatsakanov – Bachelor's degree candidate in Higher Education, specializing in 134 «Aviation and rocket-space engineering», educational and professional program «Aircraft Eguipment», State University "Kyiv Aviation Institute", 1 Lubomyra Huzar Ave., Kyiv, Ukraine, 03058, E-mail:8388503@stud.nau.edu.ua, https://orcid.org/0009-0008-5416-2714

Olena Hanziak – Higher education applicant for a Bachelor's degree in specialty G9 «Applied Mechanics», educational and professional program «Applied Mechanics of Composite Structures and Technical Systems», State University "Kyiv Aviation Institute", 1 Lubomyra Huzar Ave., Kyiv, Ukraine, 03058, E-mail: 9149231@stud.kai.edu.ua, https://orcid.org/0009-0005-3357-8532

О. МІКОСЯНЧИК, В. ШАМРАЙ, О. ЯЩУК, О. ЛОПАТА, С. МНАЦАКАНОВ, О. ГАНЗЯК

ПІДВИЩЕННЯ ОПОРУ АБРАЗИВНОМУ ЗНОШУВАННЮ СТАЛЕЙ ФОРМУВАННЯМ ГЕТЕРОГЕННИХ ЕЛЕКТРОІСКРОВИХ ПОКРИТТІВ

Робота присвячена підвищенню експлуатаційного ресурсу деталей сільськогосподарських машин, що працюють в умовах інтенсивного динамічного та абразивного впливу середовища. Метою дослідження є встановлення впливу суцільності, мікроструктури та фазового складу гетерогенних композиційних електроіскрових покриттів на основі карбідів вольфраму й хрому на їхній опір абразивному зношуванню. Модифікування поверхонь зразків зі сталей 65Г та 40Х13 здійснювали методом електроіскрового легування на мікрозварювальному обладнанні «Елітрон-22» з використанням електрода ВК8 системи вольфрам-кобальт та порошкової суміші КХН25 системи карбід хрому-нікель відповідно. Випробування на триботехнічну стійкість проводили в середовищі незакріплених абразивних частинок карбіду кремнію за адаптованою методикою стандарту ASTM G65. За результатами аналізу зафіксовано закономірні зміни хімічного складу сформованих покриттів порівняно з вихідними матеріалами анодів. У системі карбід вольфраму-кобальт виявлено підвищений вміст кобальту до 12,6 мас. %, що зумовлено його переважним плавленням під дією імпульсних розрядів із формуванням розвиненої поверхневої матриці. Для системи карбід хрому-нікель визначено зниження концентрації хрому до 55,8 мас. % внаслідок термічного вигорання за відносної стабільності нікелевої зв'язки, яка становила 26,8 мас. %. Оцінка кінетики зношування показала, що мінімальний ваговий знос обох типів покриттів досягається за їхньої суцільності 55–75%. При цьому електроіскрове покриття КХН25 демонструє у 1,8–2,0 рази вищий опір зношуванню порівняно з ВК8. Вища абразивна стійкість покриття КХН25 пояснюється його дрібнодисперсною структурою та наявністю пластичної нікелевої матриці, яка забезпечує ефективну релаксацію локальних напружень і гальмує крихке викришування карбідних фаз при мікрорізанні абразивом.

Ключові слова: електроіскрове легування, покриття, зносостійкість, абразивне зношування, мікроструктура, суцільність, випробування.

Список літератури

1. Захаров А. В. Прогнозування зносостійкості робочих органів ґрунтообробної техніки під час їх відновлення методом електрошлакового наплавлення. *Вісник ХНТУ: Інженерні науки.* 2024. № 4. С.24-32. https://doi.org/10.35546/kntu2078-4481.2024.4.3

2. Шамрай В.Б., Мікосянчик О.О., Лопата Л.А. та ін. Композиційні матеріали для зносостійких покриттів деталей сільськогосподарських машин. *Проблеми тертя та зношування*. 2023. 1(98). С. 4-13. https://doi.org/10.18372/0370-2197.1(98).17356

3. Денисенко М. І., Рубльов В. І. Технологічні методи забезпечення довговічності робочих органів і надійності сільськогосподарських машин. *Конструювання, виробництво та експлуатація сільськогосподарських машин*. 2013. Вип. 43(2). С. 7-17.

4. Rogovskii I. L., Borak K. V., Maksimovich E. Yu. et al. Wear resistance of blade and disc working bodies of tillage tilling machines hardened by electrodes T-series. *Journal of Physics: Conference Series*. 2020. Vol. 1679. 042084. DOI:10.1088/1742-6596/1679/4/042084

5. Wang Y., Li D., Nie C. et al. Research Progress on the Wear Resistance of Key Components in Agricultural Machinery. *Materials*. 2023. *16*(24). 7646. https://doi.org/10.3390/ma16247646

6. Stavinskiy A., Vakhonina L., Martynenko V. et al. The use of surface strengthening to increase the wear resistance of working bodies of agricultural machines. *Ukrainian Black Sea Region Agrarian Science*. 2024. 28(2). P.21-32. DOI:10.56407/bs.agrarian/2.2024.21

7. Мікосянчик О.О., Шамрай В.Б. Підвищення експлуатаційних властивостей деталей сільськогосподарської техніки композиційними покриттями. *Проблеми тертя та зношування*. 2022. 4 (97). С. 44-49. https://doi.org/10.18372/0370-2197.4(97).16958

8. Лопата Л.А., Качинская І.Р., Солових А.Є., Катеринич С.Є. Створення зносостійких композиційних покриттів на основі порошків самофлюсуючих сплавів електроконтактним припіканням *Проблеми тертя на зношування*. 2024. 3(104). С. 15-22. https://doi.org/10.18372/0370-2197.3(104).18974

9. Teker T, Karataş S, Yilmaz S O. Microstructure and wear properties of FeCrC, FeW and feti modified Iron based alloy coating deposited by PTA process on AISI 430 steel. *Archives of Metallurgy and Materials*. 2014. 59(3). P. 925–933. DOI:10.2478/amm-2014-0156

10. Ulas M., Altay O., Gurgenc T., Özel C. A new approach for prediction of the wear loss of PTA surface coatings using artificial neural network and basic, kernel-based, and weighted extreme learning machine. *Friction*. 2020. 8(6). P. 1102–1116 https://doi.org/10.1007/s40544-017-0340-0

11. Hlushkova D.B., Volchuk V.M. Fractal study of the effect of ion plasma coatings on wear resistance. *Functional Materials*. 2023. 30 (3). P. 453-457. https://doi.org/10.15407/fm30.03.453

12. Koval I., Bodrova L., Kramar H. et al. Wear resistant hard alloys for agricultural machines elements. *Visnyk TNTU* (*Tern*.). 2020. № 2 (98). P. 33-39. https://doi.org/10.33108/visnyk_tntu2020.0

13. Ющенко К.А., Борисов Ю.С., Кузнецов В.Д., Корж В.М. Інженерія поверхні: підручник. Київ: Наукова думка, 2007. 559 с.

14. Tarelnyk V. B., Gaponova O. P., Kirik G. V. et al. Cementation of Steel Details by Electrospark Alloying, *Metallofiz. Noveishie Tekhnol*. 2020. 42, No. 5. P. 655–667 (in Ukrainian). https://doi.org/10.15407/mfint.42.05.0655

15. Wang J., Zhang M., Dai S., Zhu L. Research Progress in Electrospark Deposition Coatings on Titanium Alloy Surfaces: A Short Review. *Coatings*. 2023. 13. 1473. https://doi.org/10.3390/coatings13081473

16. Doering A., Danks D., Mahmoud S., Scott J. Evaluation of ASTM G65 abrasive – Spanning 13 years of sand. *Wear*. 2011. Vol. 271, Is. 9–10. P. 1252-1257. https://doi.org/10.1016/j.wear.2011.01.051

17. Storozhenko M., Umanskyi O., Tarelnyk V. et al Structure and wear resistance of FeNiCrBSiC–MeB$_2$ Electrospark Coatings. *Powder Metall Met Ceram*. 2020. 59. P. 330–341. https://doi.org/10.1007/s11106-020-00166-1

Мікосянчик Оксана Олександрівна – докт. техн. наук, професор, завідувач кафедри прикладної механіки та інженерії матеріалів, Державний університет «Київський авіаційний інститут», пр. Любомира Гузара, 1, м. Київ, Україна, 03058, тел.: +38 044 406 77 70, E-mail: oksana.mikos@ukr.net, https://orcid.org/0000-0002-2438-1333

Шамрай Віталій Борисович – доктор філософії з прикладної механіки, Секретаріат Кабінету Міністрів України, вул. Грушевського, 12/2, м. Київ, Україна, 01008, E-mail: vitalii.shamrai76@gmail.com https://orcid.org/0000-0002-1746-5213

Ящук Олеся Петрівна - старший викладач кафедри іноземних мов професійного спрямування, Державний університет «Київський авіаційний інститут», пр. Любомира Гузара, 1, м. Київ, Україна, 03058, Email: olesia.yashchuk@npp.kai.edu.ua. https://orcid.org/0009-0000-6712-3804

Лопата Олександр Віталійович – доктор філософії з прикладної механіки, старший науковий співробітник відділу міцності матеріалів і елементів конструкцій в термосилових полях і газових потоках Інституту проблем міцності імені Г.С. Писаренко НАН України, вул. Садово-ботанічна, 2, м. Київ, Україна, 01014, тел.: +380632217604. E-mail: lopata-sasha@ukr.net ; https://orcid.org/0000-0001-5266-6486

Мнацаканов Степан Рудольфович – здобувач вищої освіти освітнього ступеня бакалавр за спеціальністю G12 «Авіаційна та ракетно-космічна техніка», освітньо-професійна програма «Обладнання повітряних суден», Державний університет «Київський авіаційний інститут», пр. Любомира Гузара, 1, м. Київ, Україна, 03058, E-mail: 8388503@stud.nau.edu.ua, https://orcid.org/0009-0008-5416-2714.

Ганзяк Олена Олегівна - здобувач вищої освіти освітнього ступеня бакалавр за спеціальністю G9 «Прикладна механіка», освітньо-професійна програма «Прикладна механіка композиційних конструкцій та технічних систем», Державний університет «Київський авіаційний інститут», пр. Любомира Гузара, 1, м. Київ, Україна, 03058, E-mail: 9149231@stud.kai.edu.ua, https://orcid.org/0009-0005-3357-8532.