



Study of tribotechnical characteristics of composite coatings formed by the method of electrospark alloying

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Abstract

The results of studying the tribotechnical characteristics of composite coatings formed by the electric spark alloying (ESA) method are presented. It has been established that the key factor in controlling the stress-strain state of the “coating-base” system is the optimization of the thickness and continuity of the strengthened layer. Using the finite element method, it was demonstrated that for coatings with a thickness of 100 μm, the minimum stress concentration is achieved when the coating continuity is within 60–80%. Deviations from these values (less than 50% or greater than 80%) lead to an increase in local stresses. Modeling showed that the maximum equivalent stresses are localized at depths up to 30 μm for BK8 coatings and up to 50 μm for KHN25 coatings (with a total layer thickness of 120 μm), which reduces the stress-strain state of the substrate under external loading. Experimental abrasive wear tests in an environment with loosely fixed abrasive particles showed that the minimum weight loss is achieved when the coating continuity is 55–75%, with an optimal value of 70% and a ratio of strengthened to unstrengthened areas of 2:1. Comparative analysis of materials revealed that coatings made of WC-8Co alloy (microhardness 10000 MPa) exhibit 1.8–2 times higher weight wear compared with KHN25 alloy (microhardness 8500 MPa). This is explained by the increased fragility of WC-8Co and the low content of the cobalt matrix, which leads to chipping and groove formation when in contact with abrasive particles up to 250 μm in size. The obtained results make it possible to scientifically justify the selection of ESA modes and electrode material compositions for the restoration of machine parts operating under conditions of intensive abrasive action.

Ключові слова: electric spark alloying, coating, wear resistance, abrasive wear, stress-strain state, tribotechnical characteristics.

Introduction

Ensuring the operational reliability and competitiveness of modern mechanical engineering depends on the development of effective methods for strengthening working surfaces. Since significant material losses are caused by friction and premature wear of tribological units, the search for technologies for forming wear-resistant structures is a priority task [1]. A promising tool for surface modification is the ESA method. It allows not only the creation of layers with high hardness and corrosion resistance but also the effective restoration of worn parts while minimizing thermal loads on the substrate. Due to its low energy consumption and the possibility of local control over the properties of the formed coatings, ESA meets modern environmental and economic requirements. The study of the micromechanical characteristics of such layers opens the way to scientifically grounded control of wear kinetics and improvement of technologies for creating composite protective coatings.

Literature review

A key stage in designing the technological process of electric spark alloying is the scientifically justified selection of electrode materials, since they determine the final functional parameters of the coating. According to



an analysis of scientific studies [2–4], the efficiency of forming composite layers depends on a complex of factors, among which the leading role is played by the physicochemical compatibility of the anode with the substrate surface, the features of reverse mass transfer, and the specifics of structure formation on the working surfaces of electrodes.

Since alloying elements are transferred directly under the action of electrical discharges, the composition of the selected material directly correlates with the wear resistance and anticorrosion characteristics of the strengthened part [5, 6]. Modern criteria for electrode selection require high electrical conductivity to stabilize discharge processes, as well as thermal and mechanical resistance to extreme loads in the processing zone. Particular attention in research is paid to the ability of materials to form stable phases, which is a critical factor for ensuring high adhesion and durability of protective coatings under complex operating conditions [7–9].

The choice of components of composite materials is limited by their compatibility [10]. Solving the problem of regulating the compatibility of components within a single coating makes it possible to fully utilize the tribotechnical properties of composite coatings. When selecting composite coatings, it is necessary to consider the ability of the part material to physically and mechanically interact with the coating material. The coefficients of thermal expansion of the strengthened part material and the coating material should differ minimally to ensure maximum adhesion strength between the coating and the surface of the part.

Under conditions of modern development of materials science, the electric spark alloying method is gaining particular relevance as a highly effective technology for surface modification that opens new opportunities for the functional improvement of parts in leading industries. Modern ESA research is focused on the development of innovative electrode materials, particularly those based on refractory compounds and nanostructured additives [12], which significantly expand the application limits of this method for extreme operating conditions.

To improve the tribotechnical properties of parts, it is advisable to use metal-matrix composite materials with ceramic fillers [11]. The choice of metal-matrix composites is justified by high values of strength characteristics, elastic modulus, and their stability up to the melting temperatures of the base metal. The main function of ceramic fillers is to strengthen the metal matrix of composite materials and the composite coating as a whole.

The study of tribotechnical properties of composite coatings makes it possible to scientifically control wear processes and improve technologies for creating protective coatings.

Purpose

To evaluate the tribotechnical properties of composite electric spark coatings (ESC), taking into account the physicochemical interaction between the material of the material and the coating.

Objects of research and experimental conditions

The electric spark alloying process was carried out using an “Elitron-22” installation at a discharge energy of 0.5 J, operating current $I = 0.5 \dots 1.5$ A, voltage $U = 25 \dots 55$ V and electrode cross-section of 4–16 mm². During coating formation, the electrode was moved relative to the tool surface at a speed of 1...5 m/s.

During electric spark alloying of steels, electrodes made of tungsten carbide hard alloy WC-8Co and composite powder material KHN-25 were used (Table 1).

Table 1

Composition of composite powder KHN-25 (wt.%)

Alloy grade	Chromium carbide (%)	Nickel (%)
KHN-25 (Cr-Ni-C)	73..75	22...25

By varying the voltage and current during electric spark alloying, it is possible to control the ratio between coating continuity and thickness. This ratio determines the operational reliability of strengthened surfaces and improves the tribotechnical properties of the strengthened surface layer. The choice of EAS modes, electrode material, and material of the part to be strengthened is presented in Table 2.

Table 2

Selection of base material, electrode material, and ESA regimes

No.	Base material	Electrode material	Current (A)
1	40Cr13	KHN25	2.5
2	65G	WC-8Co	3.7

Experimental evaluation of coating wear resistance was performed on a specialized test stand according to GOST 23.208-79, which correlates with the international standard ASTM G65. The experiment simulated surface destruction under the action of loosely fixed abrasive particles with grain size up to 250 μm.

Analysis of the main results

As a result of modeling the stress - strain state of the electric-spark coating–substrate system using the finite element method in the licensed software package MSC Visual Nastran for Windows, it was established that for electric-spark coatings with a discontinuous structure, a reduction of shear loading in the substrate material can be achieved by increasing the continuity of the coating. An increase in coating continuity ensures the localization of shear stress within local regions of the coating. A reduction in the shear component of the load and an optimal distribution of the specific normal load over the contact zone can be achieved by decreasing the size of the coating contact areas with the part surface and by applying the coating with a continuity of 60...80%. In this case, the value of the specific normal distributed load increases less than the shear load decreases.

When the coating continuity increases to >80% (i.e., the distance between coating parts decreases) or decreases to <50%, stress concentration increases. For coatings of different thicknesses, the maximum reduction in stresses is observed at a coating continuity of 60...80% (Figure 1, 2).

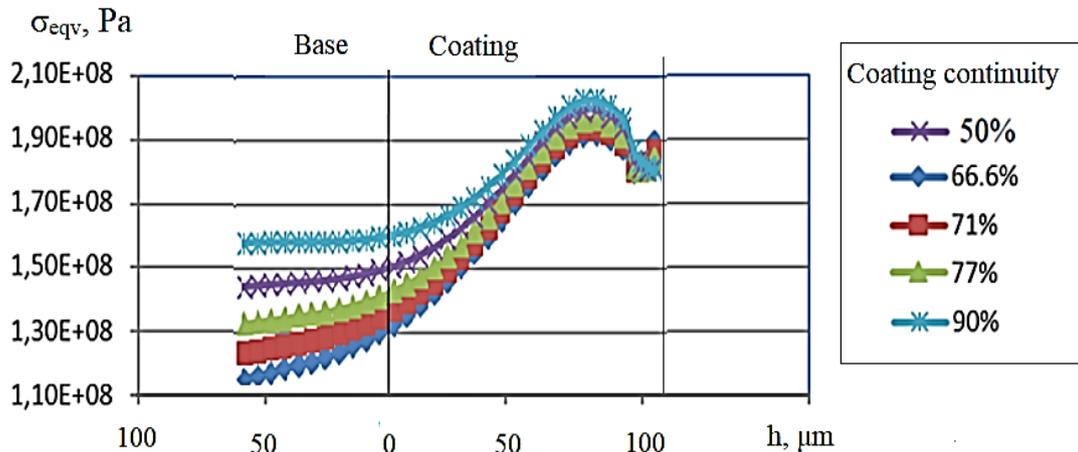


Fig. 1. Equivalent stresses along the depth from the coating surface into the substrate (65G steel) as a function of the continuity of the WC-8Co coating (coating thickness (h) 120 μm).

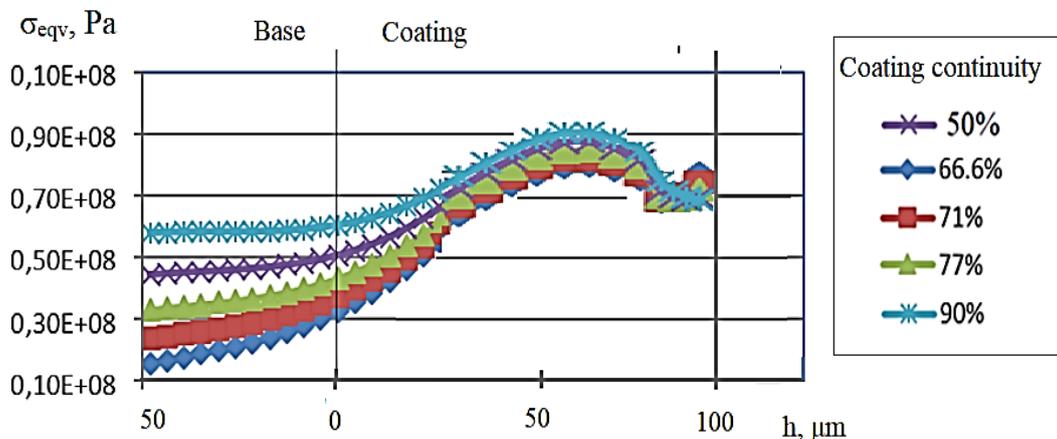


Fig. 2. Equivalent stresses along the depth from the coating surface into the substrate as a function of the continuity of the KHN25 coating (coating thickness (h) 120 μm).

It was established that the harder WC-8Co material forms a coating that ensures localization of the maximum equivalent stresses along the depth up to 30 μm, while a coating of lower hardness, KHN25, ensures localization of the maximum equivalent stresses at a depth of up to 50 μm for a coating thickness of 100...300 μm. Regardless of the coating type, the maximum equivalent stresses develop within the coating itself, which reduces the stress–strain state of the substrate.

The use of electric-spark composite coatings with an optimal combination of thickness and continuity makes it possible to improve the tribological performance of strengthened and restored components.

Applying a coating with variable continuity is achieved by changing the electrode movement speed. During ESA, moving the electrode allows the formation of different topographies of the coating on the strengthened surface of the part. By adjusting the current and voltage, it is possible to control the ratio of coating continuity to its thickness.

Composite coatings with variable continuity were formed in the form of microzones (up to 1.0 mm) by changing the electrode movement speed, allowing control of the coating continuity within the range of 20...90%.

To select the optimal continuity of the coatings, which would provide high abrasive resistance, experiments were conducted in an abrasive environment under sliding conditions. Figure 3 shows the dependence of the weight wear of the coating on its continuity (ψ).

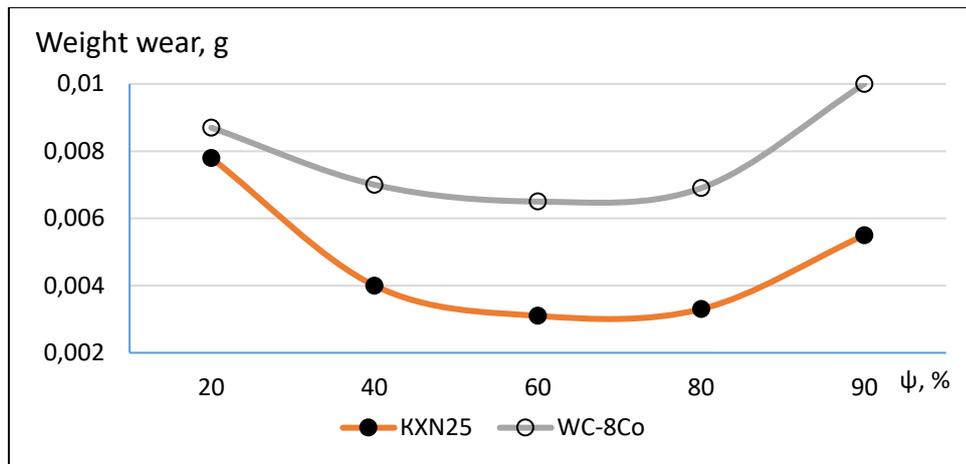


Fig. 3. Dependence of the weight wear of experimental samples with ESA coatings on the coating continuity.

At a continuity of $\psi = 55...75\%$, minimal abrasive wear of the electrical discharge coatings is observed, regardless of the type of coating studied. It has been determined that the best quality indicators of the reinforced surfaces are obtained at a continuity of $\psi = 70\%$ and with a ratio of reinforced to non-reinforced areas of the coating of 2:1.

For ESC WC-8Co, the mass loss under the action of loose abrasive particles is 1.8–2 times higher than the mass loss of ESC KHN25. This is related to the fact that the microhardness of ESC WC-8Co is 1.3 times higher than that of the KHN25 coating (microhardness of WC-8Co – 10000 MPa, KHN25 – 8500 MPa), which causes brittleness of this coating. Additionally, the high microhardness of the BK8 coating leads to a decrease in resistance to abrasive wear due to a reduction in tangential shear resistance when a hard abrasive particle penetrates, which is explained by the low fraction of the matrix component (cobalt) in the structure of the BK8 hard alloy. The friction tracks of ESC WC-8Co are characterized by the presence of large grooves and signs of chipping (Fig. 4). For ESC KHN25, the friction tracks are characterized by a uniform structure, indicating a high degree of resistance of ESC to the penetration of abrasive particles.

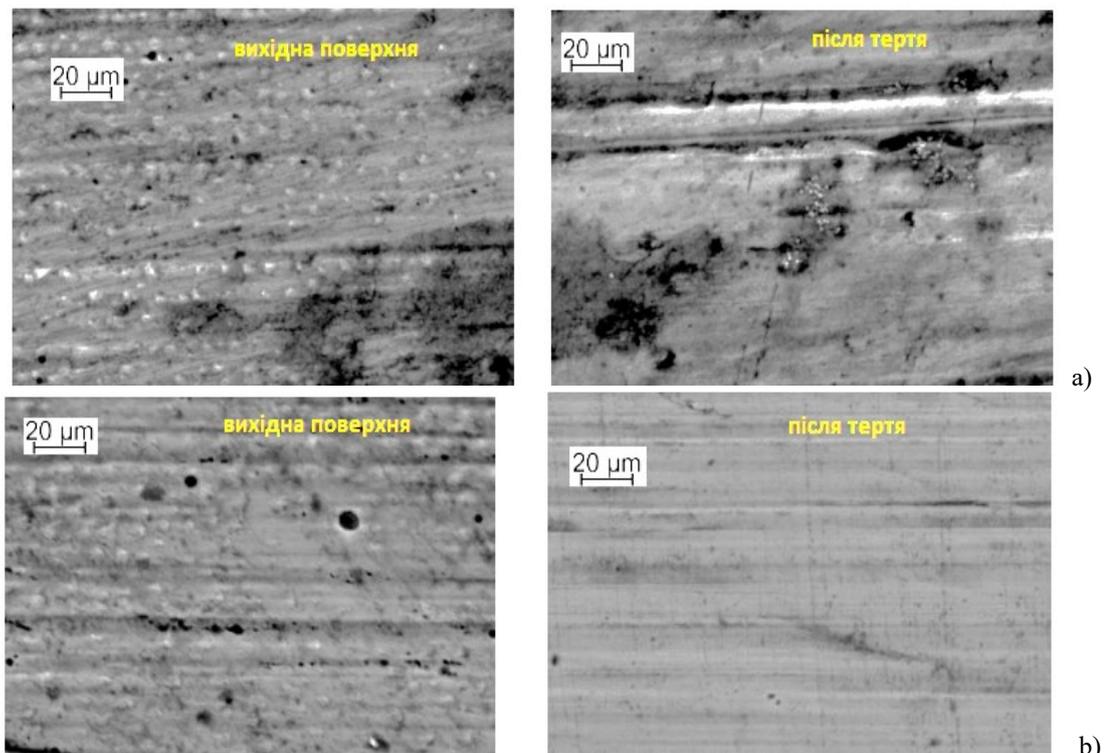


Fig. 4. Appearance of the initial surface and the surface after friction under the influence of loose abrasive particles: a) – WC-8Co, b) – KHN25.

Thus, the established dependencies allow scientifically justified control of wear kinetics by varying alloying regimes to achieve an optimal balance between continuity, thickness, and toughness of composite coatings.

Conclusions

1. Finite element modeling showed that the minimum stress–strain state of electric spark coatings can be achieved by selecting optimal values of coating thickness and continuity. When continuity exceeds 80% or drops below 50%, stress concentration increases. Maximum stress reduction occurs at 60..80% continuity.

2. It was determined that the minimum abrasive wear of discrete electric spark coatings occurs at a continuity of 55..75%. KHN25 coatings demonstrated the highest resistance to abrasive particle penetration.

3. For ESC (electric spark coating) WC-8Co coatings, weight wear under loose abrasive particles is 1.8-2 times higher than for KHN25 coatings, due to the higher microhardness (1.3 times greater), increased brittleness, reduced tangential shear resistance during abrasive penetration, and the low cobalt matrix content in the WC-8Co alloy.

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Мікосянчик О. О., Шамрай В.Б., Лопата Л.А., Мнацаканов Р.Г., Носко П.Л., Семак І.В.
Дослідження триботехнічних характеристик композиційних покриттів, сформованих методом електроіскрового легування

Представлено результати дослідження триботехнічних характеристик композиційних покриттів, сформованих методом електроіскрового легування. Встановлено, що ключовим фактором керування напружено-деформованим станом системи «покриття — основа» є оптимізація товщини та суцільності зміцненого шару. За допомогою методу скінченних елементів доведено, що для покриттів товщиною 100 мкм мінімальна концентрація напружень досягається при суцільності в межах 60–80%. Відхилення від цих значень (менше 50% або більше 80%) призводить до зростання локальних напружень. Моделювання показало, що максимальні еквівалентні напруження локалізуються на глибині до **30 мкм** для ВК8 та до **50 мкм** для КХН25 (при загальній товщині шару 120 мкм), що знижує напружено-деформований стан основи в умовах дії зовнішнього навантаження. Експериментальні випробування на абразивне зношування в середовищі нежорстко закріпленим абразивом показали, що мінімальний ваговий знос забезпечується при суцільності покриття 55–75%, з оптимальним показником 70% та співвідношенням зміцненої і незміцненої ділянок 2:1. Порівняльний аналіз матеріалів виявив, що покриття зі сплаву ВК8 (мікротвердість 10000 МПа) має у 1,8–2 рази вищий ваговий знос порівняно зі сплавом КХН25 (мікротвердість 8500 МПа). Це пояснюється підвищеною крихкістю ВК8 та низьким вмістом кобальтової матриці, що призводить до викришування та утворення борозен при контакті з абразивними частками розміром до 250 мкм. Отримані дані дозволяють науково обґрунтовано підбирати режими ЕІЛ та склад електродних матеріалів для відновлення деталей машин, що працюють в умовах інтенсивного абразивного впливу.

Ключові слова: електроіскрове легування, покриття, зносостійкість, абразивне зношування, напружено-деформований стан, триботехнічні характеристики.