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RESEARCH

Influence of Continuity of Electric Spark Coatings on Wear Resistance of Aluminum Alloy

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A B S T R A C T

The replacement of ferrous metals with lighter non-ferrous ones, in particular with aluminum and its alloys, is of great importance for reducing the specific material consumption of products. Modification of aluminum alloy D16 with combined electro spark coating VK8 + Cu is considered. Based on the method of finite element analysis of the Nastran software complex, an optimal coating continuity was determined at the level of 55 - 65%, which provides efficient workability of the coating via reducing the residual stresses in the base and tangent stresses in the plane of adhesive contact, optimization of the coating continuity, distribution of contact loads, and formation of optimal surface geometry. The results of modeling the stress-strain state of the coating-base at a coating continuity of 60% and a normal load of 600 N indicate a 30 MPa increase in equivalent stresses in a unit element of the coating and a decrease of this parameter by 100 MPa in the base as compared with an unmodified D16 surface, indicating the localization of normal stresses mainly in the combined coating. It was experimentally established that at a combined coating continuity of 60%, reduction of D16 wear by 2 times and decrease in the average power of acoustic emission by 1.33 times are provided, which testifies to the efficient structural adaptability of the coating-base under friction. The mechanisms of increasing the wear resistance of the VK8 + Cu coating according to the rheological-kinetic model, which reflects the correlation between processes of fracture and deformation under friction, are considered. It is determined that the high wear resistance of the combined coating is due to the combination of rheological properties of hard alloy VK8 with a fracture toughness of 13.2 MPa·m$^{1/2}$ and plastic copper material with a fracture toughness of 100 MPa·m$^{1/2}$, which contributes to the efficient relaxation of stresses under friction.

1. INTRODUCTION

The reliability of mechanical systems is laid at the design stage, provided during the manufacture and confirmed during the operation of machines and mechanisms. Improvement of reliability, economy and productivity of mechanical engineering products, reduction of their specific material and energy consumption is achieved, first of all, by the use of materials and advanced reinforcing technologies that allow increasing strength, wear resistance, corrosion resistance, and other physical and mechanical properties of machine elements. The replacement of ferrous metals with lighter non-ferrous ones, in particular with aluminum and its alloys, is of great importance for reducing the specific material consumption of products. According to [1] analyzed that the use of aluminum alloys in industry is increasing thanks to their structural strength, increased plasticity, and optimal cost.

However, the expansion of the scope of practical use of aluminum alloys for the manufacture of body parts and various friction pairs is prevented by the failure to meet the high technological requirements for the performance characteristics because of their insufficient hardness and low wear resistance. In particular, the destruction of surface layers due to fatigue and wear can be caused by cyclic and dynamic loads arising during operation.

The elimination of these shortcomings is associated with improvement of the composition and quality of the surface layers of products by applying advanced methods for modification of surface layers, which provide increase in their wear resistance.

In current machine building, various methods of surface hardening, such as vacuum nitriding, PVD coating, electrospark alloying, chemical-thermal treatment, etc., are widely used to improve the workability and durability of machine parts and their restoration.

According to [2] showed that laser alloying is a promising method which can be used in order to form very thick and hard layers. The results of using the PACVD technology and magnetron sputtering by [3] demonstrate that both a great surface area of actual contact of surfaces hardened with wear-resistant coatings and a low coefficient of friction can be achieved.

At small- and medium-sized plants, where the range of parts is wide and often changed, it is economically reasonable to apply cheap, convenient, and mobile hardening and restoration processes. Such technologies include, in particular, the microplasma spark method, or electrospark alloying. By simplicity and energy saving, it is the most suitable for restoring the size of worn machine parts and strengthening them [4]. Depending on the type of electrode, one can get a high-strength wear-resistant coating or a coating with low coefficient of friction. It was established by [5] that it is especially efficient to use VK8 alloy as a material for electrodes to restore automobile aluminum pistons through increasing the hardness of the workpiece, whereas to reduce the coefficient of friction, a copper electrode was used.

According to [6] showed that it is possible to produce a wear-resistant coating on aluminum alloys, the strength of which is 5-6 times that of hardened steel, via using the electrospark alloying method with electrodes from the Al-Sn alloy. It is shown that it is possible to obtain nanostructured layers with an increased thickness (up to 2 mm), suitable for the repair of worn surfaces of component parts made of aluminum alloys during electrospark alloying of the surface of the aluminum alloy (D1) by the processing electrode of an Al–Sn alloy (20% Sn) with the use of the high current density and two-phase technology for producing a multilayer coating (applying–melting) [7].

According to [8] presents the results of studding surface structure of the AK5M7 aluminum alloy hardened by the Electro Spark Alloying technique with subsequent annealing. Analysis of crystallite size values, microdistortion of phase crystal lattices found on the surface, microhardness, and wear resistance allows concluding that, the degree of defectiveness of the surface structure plays a decisive role in its wear resistance.

The effect of complex treatment consisting of electric spark deposition (ESD) of coatings and ultrasonic impact treatment on the microhardness of Al-6Mg alloy surface layers was studied by [9]. The ESD process with copper, titanium, or tungsten electrodes leads to formation different intermetallic phases in surface layers of 25—50 μm thickness (mostly Al_3Ti, $Al_{12}W$, and Al_2Cu), which affects the relaxation resistance of the alloy in cyclic loads and thermal effects.

Thus, a promising way of increasing the wear resistance of aluminum alloys is their surface hardening. Furthermore, important consideration should be given to the choice of a hardening method, the use of which is conditioned by both economic and technological requirements. At this, preliminary assessment of the efficiency of the selected method should be made with taking into account the processes of structural adaptation of modified surfaces under friction [10,11].

An important step is also choice of methods for analysis of modeling modified surfaces and techniques for control of tribological parameters of friction pair during testing [12]. This paper offers to use the finite element analysis method to select an optimal coating continuity on the modified surface and to analyze acoustic emission (AE), which is an efficient diagnostic method in the current tribo-monitoring. The observed correlations between the AE signal and the friction coefficient should be properly considered according to the different material properties during industrial friction condition monitoring using AE technology [13]. The analysis of the kinetics of friction pairs wear used the main provisions of the rheological-kinetic model of destruction of surface layers. This model takes into account the influence of the rheological characteristics of the material on the qualitative changes in the surface layers during friction. The main indicator for assessing the course of the wear kinetics of friction pairs is fracture toughness, which predicts the intensity of deformation processes in the surface layers during friction.

The purpose of the research was to establish the dependence of the electrospark coatings wear on the density of their formation on the D16 aluminum alloy.

- To achieve this purpose, the following tasks were solved:
- Determination of the optimal density of electrospark coating application by assessing the stress-strain state of the coating - base using the method of finite element analysis of the Nastran software package;
- The identification of changes in the antifriction properties of the contact in conditions of sliding friction;
- Determination of the change in the parameter of the averaged acoustic emission power for the studied friction pairs;
- Establishing the correlation between the kinetics of destruction of the coating - base material and the tribotechnical characteristics of contact.

2. MATERIALS AND METHODS

2.1 Experimental setup for research

Tribological studies of the friction and wear processes of the contact surfaces were carried out on a serial friction machine 2070 SMT-1 for 240 min in the limit oiling mode with an oil consumption of 1.2 l/h (Figure 1).

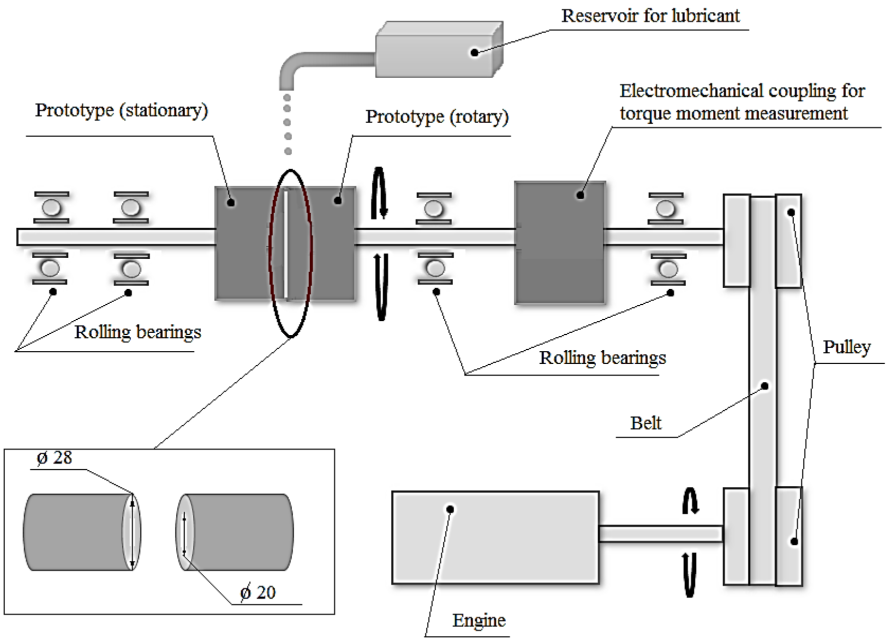


Fig. 1. Kinematic scheme of the friction machine 2070 SMT-1.

Table 1. chemical composition of the material of the friction pairs (% by weight).

D16 (GOST 4784-97),foreign analogues of the material D16: USA - 2024, AA2024, AA2124; Germany - 3.1355, $AlCuMg_2$; European Union- ENAW-2024, ENAW-$AlCu_4Mg_1$							
Al	**Mg**	**Fe**	**Si**	**Mn**	**Cu**	**Ti**	**Zn**
90.9- 94.7	1.2- 1.8	0.5	0.5	0.3- 0.9	3.8- 4.9	0.15	0.25
30HGSA (GOST 4543 - 71),), foreign analogues of the material 30HGSA: Czech Republic – 14331; Poland - 30HGSA; Bulgaria - 30ChGSA							
C	**Si**	**Mn**	**Ni**	**S**	**P**	**Cr**	**Cu**
0.28- 0.34	0.9- 1.2	0.8- 1.1	0.3	0.025	0.025	0.8- 1.1	0.3

One of the samples rotated at a frequency of 400 min^{-1}, while the other (stationary) was fixed coaxially. Their end surfaces were pressed to each other with an axial load of 600 N (Figure 1). The contact surfaces were examined according to the following scheme: in the friction pair D16 + coating / 30HGSA, the moving element was a model sample of duralumin D16 + coating (Table 1). Engine oil $M10G_2K$ (GOST-8581-78) was used as a lubricant medium. The volumetric temperature of oil was 20 ^{0}C.

In the course of the experiment, simultaneous registration of friction moment, average informational characteristic of AE, the average power of the AE signal ($W_{yc} \cdot 10^{-5}$, V^2), which is proportional to the wear rate (average value was 20 ms), was chosen to study the dynamics of formation and destruction of secondary structures [14]. Processing of AE signals under friction and wear and measuring the wear rate were performed with the use of the AE method described in [15]. This technique allows one to estimate the wear rate of contact surfaces.

A block diagram of registration and processing of AE signals consists of the basic elements that ensure the registration and processing of AE signals from the friction contact (Figure 2).

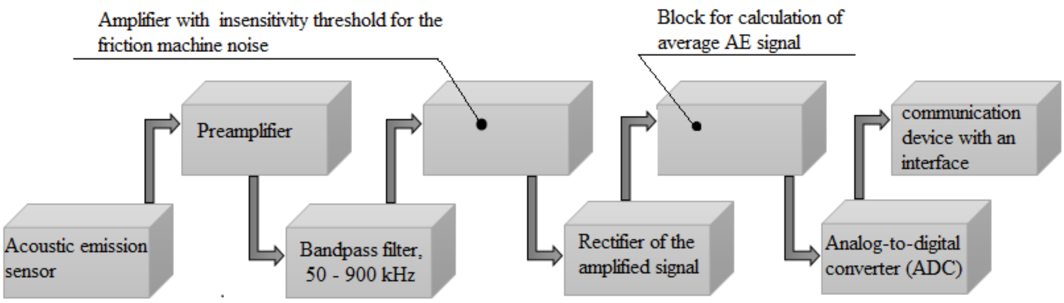


Fig. 2. Block diagram of registration and processing of AE signals.

Each of the presented basic elements can be considered as an independent module that performs certain functions.

The route of amplification of AE signals works according to the unchanged algorithm, and the whole process of measuring and processing information is provided by the joint work of a specialized module of analog and pre-digital processing AP08 and a personal computer (PC). Communication of AP08 and PC is ensured with a separate serial interface BX 485 and software.

This approach allows distribution of functions among the devices of the channel for registration and processing of AE signals according to their designation and execution of required operations, such as measurement and data transmission, storage, and processing as well as generation of the results, analysis and display of information, and control of all processes.

The operation principle of the channel for AE signal recording and processing is discussed as follows: when registering the kinetics of tribosystem processes under friction, the elastic shifts that occur in the material are converted by the AE sensor made of PTS-19 TsTS-19 piezoceramics into a weak electrical signal (1 - 10 mV). Analysis of the AE signal spectrum using an oscilloscope showed that the most energy of the AE radiation is concentrated in the range of 50 - 900 kHz. Further, the weak signal of the Sensor is amplified by the broadband preamplifier 2.

A continuous mode of recording information about the kinetics of wear processes using AE signal processing during tribosystem wear is provided with consistent recording and saving of each measurement result in the PC hard disk. The information is recorded through the operating device.

To determine the wear of friction pairs, the method of artificial bases (indentation) was used on a multifunctional device "PMT - 3" intended to study the surface layers wear of materials by assessing the diameter of the hole on the initial surface and after the experiment.

2.2 Materials

Model annular samples of friction pair were made of steel 30HGSA and duralumin D16, on the surface of which test alloys were deposited by the electrospark method. Electrospark deposition was performed on a standard industrial installation "Elitron 22A" [16] in air at a specific duration of surface treatment 1 min/cm^2. The electric pulse duration was 200 µs. The combined VK8 + Cu coating was applied in two stages: first the hard alloy VK8 (W – 91,7%; Co – 7,4-8%; O – 0,4%; C – 0,6-0,66%; Fe – 0,3% (GOST-3882-74)) was applied, and then the copper coating was applied under similar electrospark modes.

As a coating material, hard alloy VK8 and copper were used whose physicomechanical properties are listed in Table 2.

Table 2. Physicomechanical properties of duralumin D16, alloy VK8, and Cu.

Properties	D16	VK8	Cu
Density, kg/m^3	2800	14600	8940
Linear expansion coefficient, 10^{-6}, K^{-1}	23	45	16.7
Coefficient of thermal conductivity, t/(m·K)	170	54	401
Specific heat, J/(kg·K)	1000	150	385
Young's Module,·10^{11} Pa	0.71	6.0	1.15
Shear Module, 10^{11}Pa	0.27	2.5	4.24
Poisson's ratio	0.3	0.196	0.33

To obtain evenly hardened layers of the required roughness and continuity, a further surface treatment with surface plastic deformation was performed, followed by finishing. At surface plastic deformation the method of static stamping was used, the maximum effort was 190 MPa. The obtained roughness was in the range of Ra = 0.7 - 0.5 µm. Thus less cycle time.

2.3 Deposition modelling of coatings with different continuity by the ESD method

The finite element analysis, implemented in the current Nastran software complex, was used to simulate the continuity of electrospark coating and estimate its stress-strain state (SSS). Such a calculation requires geometric parameters of the coating and the base, their physical properties, the value and direction of the load, as well as the scheme of fixing the base.

Simulation began with construction of primitives in the form of curves and volumetric figures. Having constructed a solid state model in space, we divided it into finite elements that could be with intermediate nodes for more accurate calculation or without them.

The program used allows one to quickly change various geometrical parameters and load values for the base-coating complex (Figure 3). As known, the basic characteristics of an electrospark coating is its continuity S on the base (the ratio of the work area of a part to the area of the electrospark coating) and thickness h. Different densities and thicknesses of the coating were simulated using the calculations.

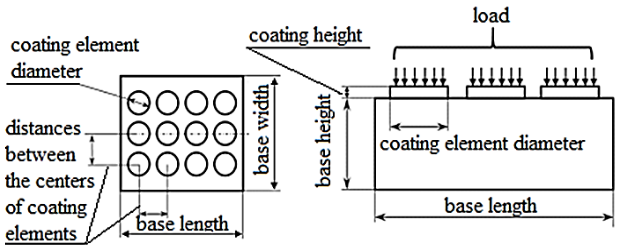
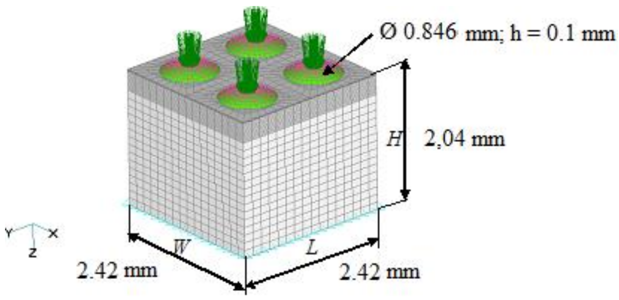


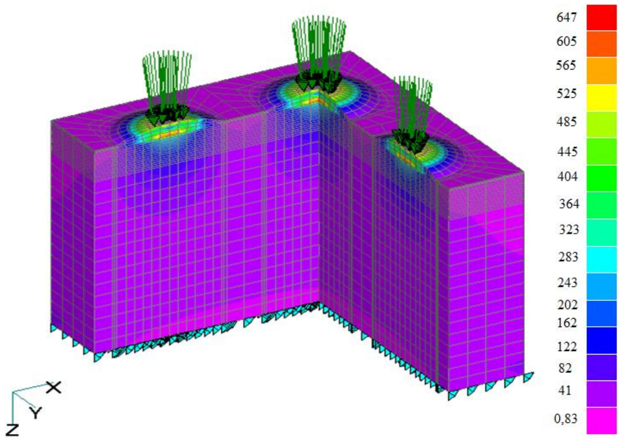
Fig. 3. Schematic of the model of electrospark coating with applied distributed load.

When dividing the model into finite elements, it is necessary to increase the continuity of the grid in the areas where a large voltage gradient is possible. It is also necessary to take into account the number of model elements, since the time of calculations increases by the parabolic law with increasing the number of finite elements.

According to the model, the geometric dimensions of the coating elements change, where as the base area remains unchanged. (Figure 4) presents a model with a coating continuity of 38.4%. The model includes 38,114 nodes and 38,016 elements.



(a)



(b)

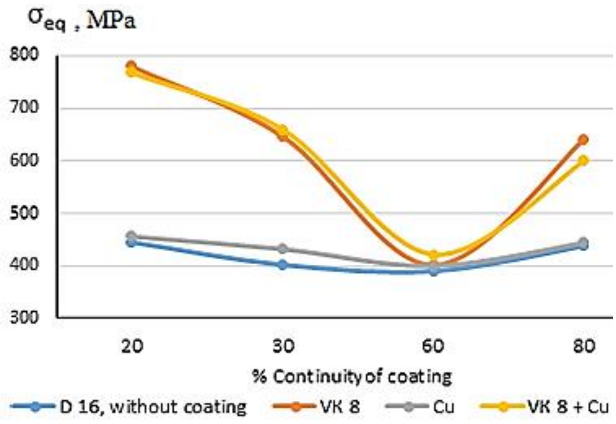
Fig. 4. Finite element model (a) and stress-strain state of coating-base (b) with an ESD coating continuity of 38.4%.

In the present modeling and studies, the coating continuity was analyzed within 20 - 80%.

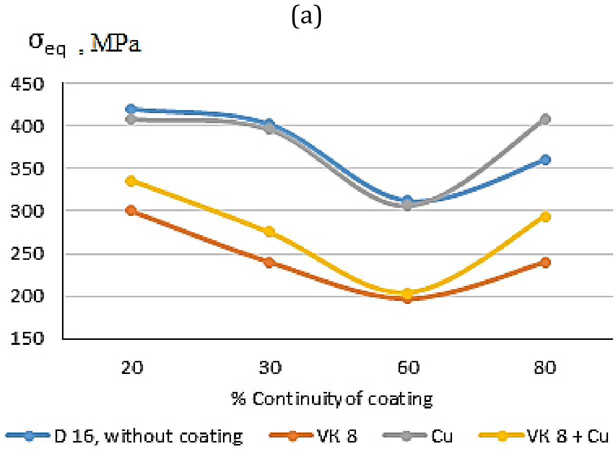
3. RESULTS AND DISCUSSION

3.1 Stress-strain state of discrete ESD coatings

The simulation of the distribution of equivalent stresses (σ_{eq}) on a unit element of the coating under a load of 600 N on the selected surface area showed the dependence of σ_{eq} on the continuity of the base coverage. An important step in the modeling procedure is to estimate the distribution of σ_{eq} both in the coating and in the base under the coating area (Figures 5 and 6).



(a)



(b)

Fig. 5. Dependence of the distribution of equivalent stresses on coating continuity: (a) in the element of EIL coating; (b) in the base under the coating element.

The analysis of the presented results regarding the distribution of σ_{eq} in both the coating element and the base showed the presence of a minimum extreme of σ_{eq} in the interval corresponding to the coating continuity within 55-65%.

As the coating continuity increases from 20 to 60% for materials VK8, Cu, VK8 + Cu, the maximum values of σ_{eq} reduce in the coating by 1.95, 1.14, and 1.81 times and in the base by 1.52, 1.33, and 1.65 times, respectively. Further increase in the deposition continuity of the investigated coatings leads to the growth of σ_{eq} in both the coating element and the base. First of all, this is related to the increase in the maximum stresses due to the increase in the residual stresses in the coating and tangential stresses in the plane of adhesion contact. The advantages of discrete coatings consist in the improved structural and energetic adaptability under friction thanks to the optimal geometry, decrease in stress concentration, and reduction of cracks formation, as established in [17].

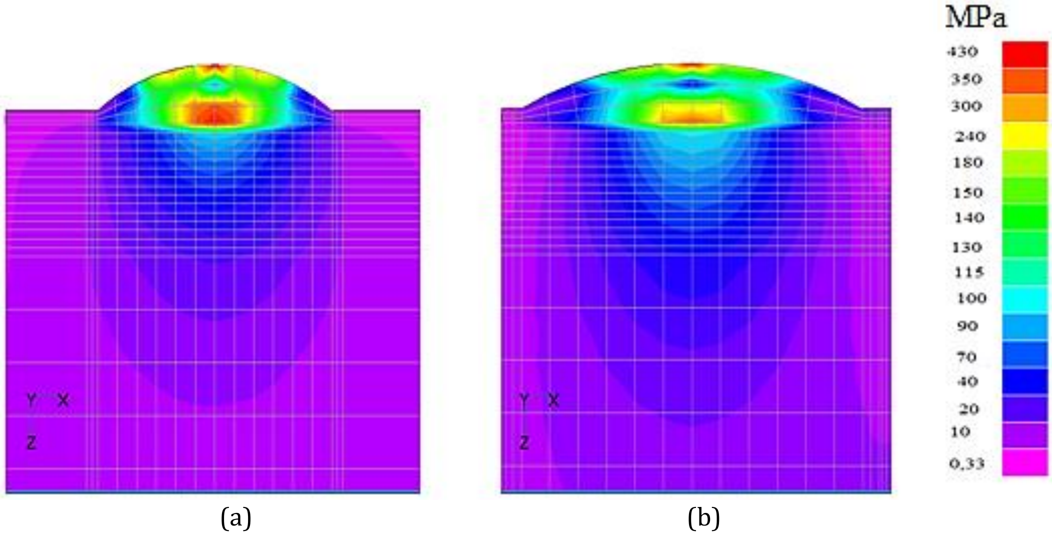


Fig. 6. Distribution of equivalent stresses in unit element for copper coating with a continuity of (a) 20% and (b) 60%.

3.2 Evaluation of the wear resistance of discrete ESD coatings

Let us analyze the wear characteristics of the studied coatings and the average AE power against the coating continuity.

Regardless of the coating material, a general feature of change in its wear was established to be the presence of minimum extreme in the wear-continuity dependence, which corresponds to the continuity 55-65% (Figure 7).

With an increase in coating continuity from 20 to 60%, wear for D16 + VK8, D16 + Cu, and D16 + VK8 + Cu decreases by 15, 125, and 80 times, respectively. If we compare the obtained wear data for ESD coatings with an unmodified D16, for which wear was established at the level of 0.01 µm, then deposition of VK8 on the duralumin leads to increase in the contact surface wear by 4.6 times. Modification of the base with Cu coating or combined VK8 + Cu coating reduces wear by 5 and 2 times, respectively. These wear data correspond to the coating continuity 60%.

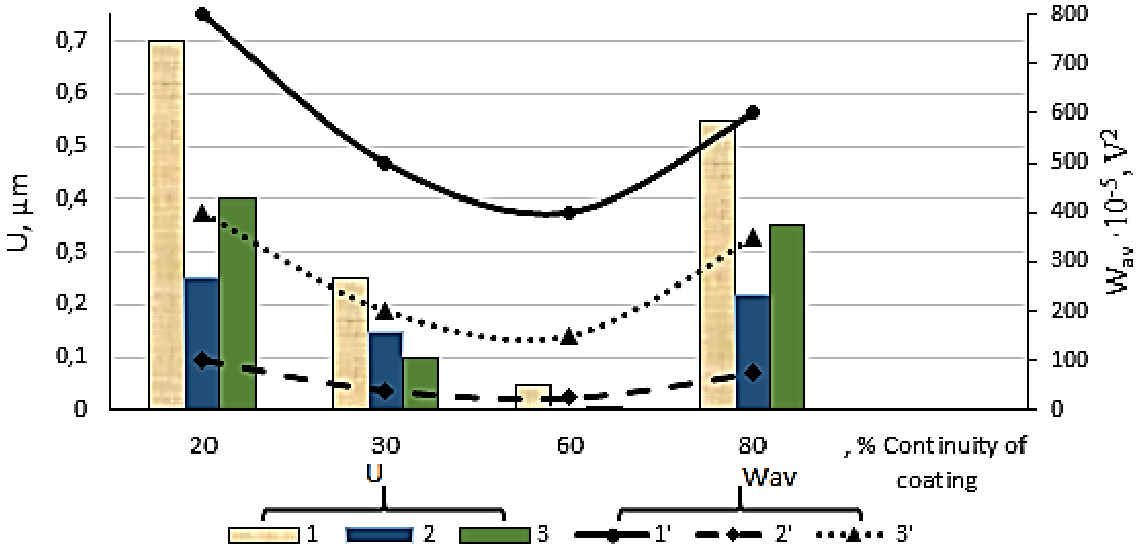


Fig. 7. Dependence of wear (U) and average power of acoustic emission (Wav) of modified D16 on the continuity of ESD coatings: 1, 1', VK8; 2, 2', Cu; 3, 3', VK8 + Cu.

Also, in the conducted experimental studies, correlation between such parameters as wear and average AE power was established (Figure 7). Firstly, the dependence of the Wav change on the coating continuity is characterized by a similar minimum extremum in the coating continuity range 55 - 65%, regardless of coating type. Secondly, increasing the coating continuity from 20 to 60% causes decreasing the parameter Wav of VK8, Cu, and VK8 + Cu coatings by 2, 4, and 2.6 times, respectively. Thirdly, in comparison with the initial D16 material, coatings with a continuity of 60% demonstrate an increase in the parameter Wav by 2 times for the VK8 coating and a decrease in the Wav by 8 and 1.33 times for coatings from Cu and VK8 + Cu, respectively. Thus, the optimal working condition of the studied ESD coatings, indicated by the minimum coating-base wear rate and the average AE power, is a characteristic feature for discrete coatings within the continuity range 55 - 65%. The justification of this range can be made by generalizing the manifestation of the following states (Figure 8):

- (I) increased SSS of the coating elements owing to increasing the contact load due to the decrease in the actual contact area, which causes increased wear of the coating and intensification of AE;
- (II) the mode of efficient workability of a coating, which is provided by reduction of maximum stresses at the expense of optimization of coating continuity, distribution of contact loads, and formation of optimum surface geometry;
- (III) increase in the coating-base SSS due to reducing the distance between individual coating elements and overlapping the residual macro-stress areas between adjacent elements, which, together with the contact and tangential stresses under friction, leads to the creation of local stress concentrators, decrease in relaxation processes, and increase in the intensity of wear and acoustic emission (AE).

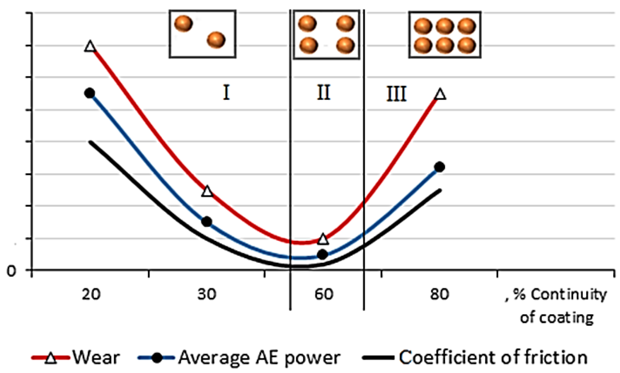


Fig. 8. Generalized scheme of changing tribological parameters of discrete ESD coatings.

3.3 Rheological-kinetic mechanism of ESD coating wears

Wear mechanisms of the investigated coatings were analyzed to establish the optimal continuity for their application. In the friction pair 30HGSA - D16 + coating, the highest wear of the contact surface was characteristic for the D16 + VK8 contact surface (Figure 9).

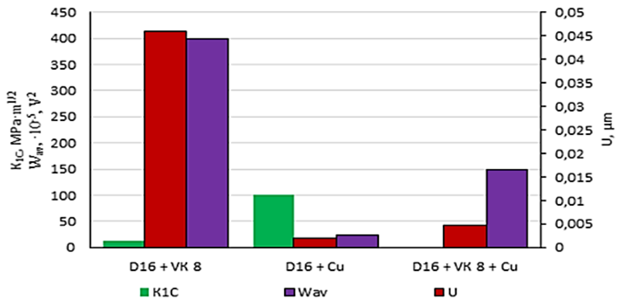


Fig. 9. Wear (U), average AE power (W_{av}), fracture toughness (K_{1C}) for D16 with discrete electrospark coatings with a continuity of 60%.

First of all, the reason for the increased wear modified by VK8 surface is related to mechanical and physicochemical properties of this coating. As known, hard VK8 alloy has a low cobalt content, which causes its low plasticity. This, in turn, is the main reason for reducing the ability to relax the stresses under friction. According to the rheological-kinetic concept [18], there is a connection between the processes of fracture and deformation under friction. For the VK8 alloy, the fracture toughness (Figure 9), which characterizes the material ability to resist crack formation, is very low, 13.2 MPa·m$^{1/2}$ [19]. This indicates that in the case of a coating from hard alloy VK8, the dominate process under friction is brittle fracture, conditioned by plastic deformation and generating hard wear-caused particles, mainly of tungsten carbide. High values of average AE power indicate that structural adaptation processes are low. This is also confirmed by the maximum wear of the D16 + VK8 contact surface, compared to the other types of coatings tested. Similar results have been obtained in [20], where it is stated that the high-strength and high-wear-resistant alloy VK8 does not provide the required resource of hardened machine parts because of its low plasticity.

Coverage of D16 with an ESD copper coating does not meet the requirements for the coating strength. Despite the low level of wear and high fracture toughness (100 MPa·m$^{1/2}$ [21]), obtained in modeling the value of σ_{eq} during coating indicates that SSS of coating and base is the same. The rheological-kinetic model of D16 + Cu destruction can be represented as follows: with the same SSS, the base fracture toughness is three times lower than that of Cu [22]. Under friction, under the action of normal and tangential stresses, more intense structural and rheological changes occur in the base under the coating. Thus, against the low average AE power and minimal wear of the plastic coating, the underlying processes of mechanical and deformation changes in the base dominate, whose manifestation requires a longer time than used in this study.

The advantages of modifying D16 with a combined ESD coating VK8 + Cu include the following: firstly, according to the results of modeling SSS, σ_{eq} in the unit element of coating increases by 30 MPa, whereas in the base, under the coating, it decreases by 100 MPa, as compared to the unmodified D16 surface, which indicates the localization of normal stresses predominantly in the combined coating. Secondly, the deposition of a plastic copper material on the hard VK8 alloy provides an efficient combination of rheological parameters of these materials, which contributes to the efficient relaxation of stresses under friction. These processes provide high wear resistance of the combined coatings.

Thus, when choosing a wear-resistant ESD, it is essential to determine an optimum coating continuity, to analyze the SSS of coating-base and to establish possible rheological-kinetic relationship of fracture and deformation processes under friction. Taking these aspects into account will improve the reliability of hardened parts during operation.

Deformation-strength characteristics of metal surface layers play a leading role in providing wear resistance of the contact surfaces, since acceleration/deceleration of the dislocation structure formation during friction depends on the activation of friction pairs. Let us consider the change in microhardness of the surface and near-surface layers of the studied surfaces with a coating continuity of 55 - 65% after 240 min running in a sliding mode (Table 3, Figure 10).

Table 3. Microhardness and linear wear of surfaces studied.

Type of coating	Microhardness of the initial surface, H_{20}, MPa	Microhardness of the surface after friction, H_{20}, MPa	Wear, µm
D16	850	390 (softening)	0.01
D16+Cu	700	755 (hardening)	0.002
D16+VK8	17000	18920 (hardening)	0.046
D16+VK8+Cu	6000	4730 (softening)	0.0048

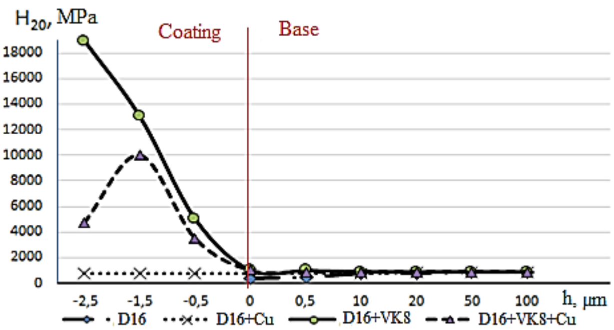


Fig. 10. Microhardness of near-surface layers of metal in depth (negative values correspond to the coating, positive ones – to the base).

Only for the unmodified surface D16, the 2.18 times reduction in microhardness of surface layers under friction was established. Softening was revealed not only in the surface layers of the metal, but also in depth to 30 µm, which is the main prerequisite for reducing wear resistance. The mechanism of this process consists in reducing the resistance to local plastic deformation in the frictional contact, intensification of energetic triboprocesses, and the formation of a loose surface layer of metal with the appearance of submicroscopic defects.

The formation of an electrospark coating from copper provides the realization of a positive gradient of mechanical properties of the metal in depth. Deformation processes are localized predominantly in the coating, but the formed soft coating does not provide reliable protection of the base material. Despite the fact that the zone of distribution of plastic deformations in the base is reduced by 2 times, the depth of their localization is to 15 µm.

The hard electrospark coating VK8 provides an increase in microhardness of the surface layers of the metal by 20 times. However, the presence of a negative gradient of mechanical properties in depth reduces its wear resistance, on average, by 4 times as compared with that of D16. In the process of friction, the formed coating VK8 is hardened, which leads to an increase in the stress state in the coating and is the main prerequisite for reducing the intensity of relaxation processes in the friction-activated surface layers of the metal.

The formation of a combined electrospark coating VK8+Cu eliminates the above mentioned disadvantages of individual coatings separately. Its high wear resistance is due to the implementation of a positive gradient of mechanical properties in depth and the localization of deformation processes in the coating. The presence of copper on a hard surface provides effective structural adaptability of the combined coating under friction thanks to relaxation of internal stresses such as softening of the coating by 1.25 times as compared with the VK8 coating and reduces the probability of formation of local stress concentrators via increasing the coating continuity (Figure. 11).

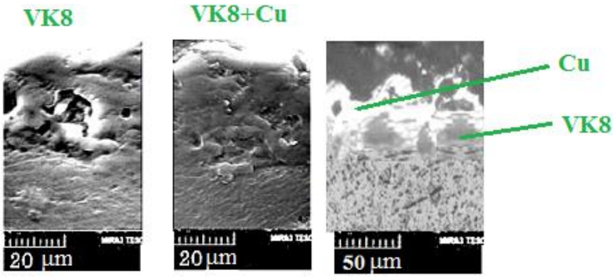


Fig. 11. Optical-microscopic images of cross-sections of D16 duralumin samples with electrospark coatings after tribological tests.

The continuity of the combined coating VK8 + Cu doubles as compared with the coating VK8 thanks to filling the imperfections of the hard coating VK8 with copper, which contributes to localization of normal and tangential stresses in the soft component of the combined coating.

Thus, the analysis of the studied electrospark coatings has shown the advantages of a combined coating from hard (VK8) and soft (Cu) materials, which provides an increased wear resistance of the modified surface of duralumin D16 due to a positive gradient of mechanical properties in depth and effective resistance to plastic deformation in the base material.

4. CONCLUSION

On the basis of the calculations and experiments, conclusions were drawn as follows:

1. According to the results of modeling the stress-strain state of coating-base, the advantages of discrete coatings with a continuity of 55 - 65% have been established. They are: the increase in the coating continuity from 20 to 60% for materials VK8, Cu, VK8 + Cu causes decrease in equivalent stresses by 1.95, 1.14, and 1.81 times in single coating and by 1.52, 1.33, and 1.65 times in the base, respectively. For a coating continuity of over 65%, an increase in the level of maximum stresses is observed due to the increase of residual stresses in the coating and tangential stresses in the plane of adhesion contact.
2. The optimal operable state of discrete ESD coatings with a continuity of 55 - 65% has been determined, which is characterized by the minimum both wear and averaged AE power owing to reducing the stress-strain state of the coating-base while optimizing the continuity of coating, the distribution of contact loads, and formation of the optimal surface geometry.
3. Increase the wear resistance of aluminum alloy D16 modified with combined VK8 + Cu coating is reached thanks to the localization of equivalent stresses in the coating elements, a 100 MPa decrease of equivalent stresses in the base, and the relaxation of stress under friction, which is due to the combination of reological properties of hard VK8 alloy with a fracture toughness of 13.2 $MPa \cdot m^{1/2}$ and of plastic copper material with a fracture toughness of 100 $MPa \cdot m^{1/2}$.
4. Analysis of the rheological-kinetic mechanism of ESD coating wear with taking into account the coating-base fracture toughness makes it possible to estimate and predict the localization of fracture and deformation processes under friction. Evaluation of rheological parameters of the base material and coating allows to establish the latent processes of mechanical deformation changes in the base (for material D16 + Cu) and on the surface (for material D16 + VK-8) of the studied friction pairs.
5. The combined coating from hard (VK8) and soft (Cu) materials on duralumin D16 has demonstrated effective antiwear characteristics thanks to the existence of a positive gradient of mechanical properties in depth of the coating-base and localization of deformation processes in the coating.

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