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Determination of the criteria for the transition of the tribosystem to disastrous wear

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KEYWORDS

Friction pairs
Specific work of friction
Electrospark coating
Acoustic emission
Intensity of wear
Stressed-deformed state

ABSTRACT

The research aimed to determine changes in the frictional contact during transition of the tribosystem from normal to disastrous stage of wear. The study was carried out for tribosystem steel 30ChGSA – unmodified/modified D16 duralumin alloy. The modification was carried out by applying a combined discrete coating of alloy VK8 and copper with density of 55-65% by electrospark alloying. Modifying D16 duralumin provides efficient operation of friction pairs up to 1200 N. AE signals' average power, and dispersion values are reduced by 2...4 times. An 80% reduction in wear intensity of tribosystems with combined electrospark coating is established, and the depth of propagation of plastic deformations is reduced by 2 times. The dissipative energy processes in frictional contact ensure formation of wear-resistant structures. Empirical dependences of wear intensity on loading parameters and AE signals were obtained.

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1.0 INTRODUCTION

The dominant factor determining the wear resistance of machine parts is the level of strength of their contact surfaces. When analyzing a tribosystem, an important condition for its operational state is the formation of metastable dissipative structures in the process of structural adaptation of tribocoupler elements to certain operational modes. During the formation of such structures, mechanisms are implemented that provide external friction with a minimum wear intensity of the contact surfaces. A large number of factors affect the process of external friction. The main ones include the stress-strain state, environment, mechanical and physical and chemical properties of contacting bodies, mode of operation, etc. (Zhai et al., 2021; Santhosh et al., 2021). A promising direction aimed at expanding the range of implementation of external friction in variable load-speed modes of operation of friction pairs is the application and improvement of methods and technologies of modification and near-surface strengthening of parts (Khodabakhshi et al., 2017; Azadi et al., 2022; Mordyuk et al., 2019).

The method of electrospark alloying (ESA) is one of the most rational way allowing to purposefully change the stress-strain state in the surface layer, the deformation-force parameters of the contact areas, and the nature of the contact interaction of the friction pairs. Determining the friction conditions in which electrospark coatings are characterized by effective structural adaptability and minimal wear intensity is an important part aimed at establishing the range of the working state of the coatings. The development of criteria for the transition of contact surfaces modified by electrospark alloying from normal to disastrous wear allows creating recommendations on operating conditions and functional purpose of wear-resistant electrospark coatings.

An important direction for reducing material consumption in the design of machines and mechanisms is the use of materials that meet the requirements of technological effectiveness allowing reducing the weight of parts. At the same time the materials should be characterized by high mechanical characteristics and high operational reliability. Such materials include aluminum alloys. For example, multi-component aluminum antifriction alloys for rolling bearings with a tin content of 5.4...11.0 % Sn are characterized by increased tribological properties, effective characteristics in the running-in process, high anti-seize indicators due to an increase in the probability of self-organization on the friction surface. The result is formation of secondary structures, which differ from the original alloy structure (Mironov et al., 2019).

However, the increase in usage of aluminum alloys for the production of friction pairs is hindered by low operational properties – low hardness and wear resistance of the surface. The elimination of those shortcomings is related to the improvement of the composition and quality of the surface layers by applying modern methods of strengthening such as surface processing of aluminum alloy. Cost effective and efficient way in terms of improving the operational properties of heat-sensitive materials is electrospark alloying, which ensures the application of protective surface layers with improved properties in terms of hardness, wear resistance and corrosion resistance without changing the properties of the base material (Barile et al., 2022; Pliszka et al., 2018).

Application of this method allows creating coatings with high contact integrity, as well as porous coatings characterized by high wear resistance (Velichko et al., 2017; Burumkulov et al., 2014). For example, during electrospark alloying of aluminum surfaces using an Al-Sn electrode, wear-resistant and strong nanostructured coatings of increased thickness are formed due to the formation of SnO_2 nanofibers (Yurchenko et al., 2018; Yurchenko et al., 2020). The work (Al-Quraan et al., 2021) established high tribotechnical properties of discrete electrospark coatings with a density of 55-65%, which is characterized by a decrease in residual stresses in the base material.

Modern antifriction materials based on AE-alloys are obtained by alloying them or forming multifunctional coatings. At the same time, the main requirements for the developed materials should include both a favorable combination of antifriction and mechanical properties, as well as the manufacturability and cost of the process (Zlotnikov and Shapovalov, 2019). Applying surface modification and strengthening coatings expands the use of aluminum-bearing alloys and alumino-matrix composites. New aluminum antifriction alloys are used to replace bronze in various friction nodes. Such a replacement is economically justified since aluminum alloys have 2.5-3 times less density, and a unit of weight of such an alloy is, on average, 2-4 times cheaper than the replaced bronze. Aluminum alloys АК12, АК7ch и Г-AlC12 strengthened by micro-arc oxidation technology are widely used for the manufacture of bearings (Kuznetsov, et al., 2022), AlSi6Cu2 alloy is used for the most heavily loaded parts of the internal combustion engine (Nedić and Globočki, 2005).

An important area in studying the quality of the created by electrospark coatings is establishment of criteria that determine the loading range of their performance. Based on the changes in basic tribotechnical indicators such as coefficient of friction, temperature in the zone of frictional contact, thickness of the lubricating layer, specific work of friction, it is not always possible to predict the onset of catastrophic wear (Mnatsakanov et al., 2021; Dykha et al., 2020; Mikosyanchyk et al., 2019; Voitov et al., 2020). The acoustic emission method, which is characterized by high sensitivity to elastic-plastic deformations in frictional contact, can be attributed to informational methods for determining the range of performance of a tribotechnical couple. On the basis of the spectrum of changes in the amplitude of the AE signal, spread of the recorded signals, and AE energy parameters, it is possible to predict the dominance of normal or disastrous wear processes (Filonenko and Stakhova, 2020; Hase et al., 2016).

The main sources of AE signals generation during friction include the intensification of deformation processes, the initiation and propagation of cracks in the coating or on the surface of coating-base, and structural phase transformations in the most loaded zones of the actual contact area of friction pairs (Löhr et al., 2006; Zaman et al., 2021). Those processes are accompanied by the accumulation of deformation energy. Irreversible changes occur in the frictional contact when the critical level of this indicator is reached leading to disastrous wear of the tribocombination elements.

Establishing the regularities of the transition of electrospark coatings from normal to catastrophic wear based on the analysis of acoustic emission signals is a relevant direction in the way of predicting their ultimate performance, which allows for the development of recommendations for the use of modified surfaces in a certain loading and speed regime.

2.0 PURPOSE OF RESEARCH

The purpose of the research is to establish the mechanisms of resistance of tribocoupler elements, and to evaluate AE signals under the conditions of a gradual increase in load during the transition of the tribosystem from the normal to the disastrous stage of wear.

3.0 METHODS AND MATERIALS USED IN THE RESEARCH

Samples of 30ChGSA steel, and unmodified and modified D16 duralumin were selected for research as in Table 1, and in Table 2.

Table 1: The chemical composition in % of the material is 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

Table 2: Chemical composition in % of the alloy D16.

Al	Mn	Cu	Fe	Si	Ni	Ti	Zn	Mg
90,8 - 94,7	0,3 - 0,9	3,8 - 4,9	< 0,5	< 0,5	< 0,1	< 0,1	< 0,3	1,2 - 1,8

The surface layer of samples made of D16 material was modified by applying a combined discrete coating of VK8 hard alloy (carbide WC – 92%, Co – up to 8%, DIN standard: HG30) and copper using the electrospark alloying method. The density of the discrete coating was 55-65%. The thickness of the combined coating is 2...2.5 microns. The strengthening process at the Elyton-22 installation is carried out manually with the help of an electromagnetic vibrator with a replaceable alloying element electrode. The Elyton-22 installation has eleven strengthening modes corresponding to the strength of the technological current. The specific amount of material transferred to the treated surface depends on the energy released in the inter electrode gap during one pulse. Processing modes are chosen depending on the requirements for the strengthened surface - roughness, density, thickness, and porosity of the applied layer. The "softer" processing mode makes layer thickness smaller but increases the quality of the applied coating. With "rough" modes, the thickness of the layer increases, but the quality of the coating deteriorates. The combined coating was applied at an operating current of 0.7-0.8A. To obtain a uniformly strengthened layer of the combined coating of the required roughness and density, further surface treatment was carried out by surface plastic deformation followed by finishing treatment. In result the roughness of the contact surfaces was within Ra = 0.5...0.7 μm.

Research on the tribosystem's anti-scratch resistance was carried in two schemes:

1. According to the first scheme, the sample made of steel 30ChGSA was stationary, the sample made of modified/unmodified D16 duralumin rotated: D16+VK8+Cu / D16 (moving) – 30ChGSA (stationery);
2. According to the second scheme, the sample made of modified/unmodified duralumin D16 was stationary, the sample from steel 30ChGSA rotated: 30ChGSA (moving) – D16+VK8+Cu / D16 (stationery).

Tribological studies were carried out on the improved mass production friction machine 2070 SMT -1 according to the"ring-ring" face friction scheme with the following conditions as shown in Figure 1:

1. One of the samples rotates with a frequency of 400 min^{-1}, and the other (stationary) is installed coaxially, the samples are pressed against each other with their end surfaces;
2. The minimum load was 100 N;
3. A gradual increase in the load was created until the formation of a burr or the maximum operating temperature of the lubricant;
4. The value of each subsequent level of load was 100 N;
5. Exposure time at each level of load – 10 min.

Test conditions: the friction of the contact surfaces took place with the dominance of the limit mode of lubrication in the contact, the consumption of the working fluid was 1.2 l/hour. Motor oil M10G2k (API CC, SAE 30, GOST-8581-78) was used as a lubricant. The working fluid for lubrication is supplied through the internal holes of the samples.

During the experiment, acoustic emission parameters were recorded. The average power of the AE signal, proportional to the value of the wear rate, was chosen as the information characteristic of AE for the study of the dynamics of the formation and destruction of secondary structures (average 20 msec). The method of processing acoustic emission signals during friction and wear, and measuring the intensity of wear using the AE method is described in work (Filonenko et al., 2010).

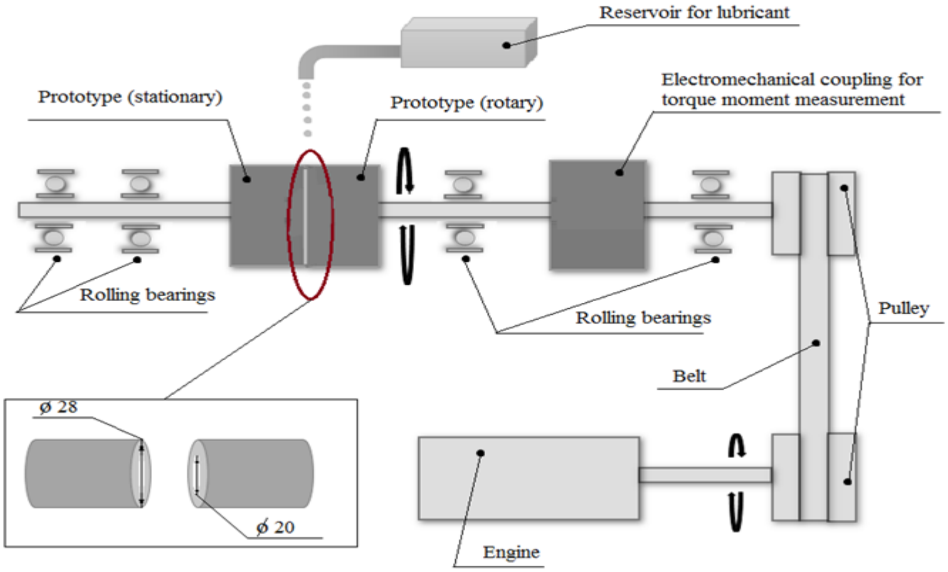


Figure 1: Friction installation scheme 2070 SMT-1.

The resulting AE signal was processed using an acoustic emission sensor made of ZTS-19 piezo ceramics, which was installed on a stationary sample on a layer of acoustically transparent lubricant. The acoustic emission sensor converts elastic displacements in the material during friction into a weak electrical signal (1 ... 10 mV). Analysis of the signal spectrum using an oscilloscope shows that the primary energy of the acoustic emission radiation is concentrated in the range of 50 ... 900 kHz. Next, the weak signal of the acoustic emission sensor is amplified by a broadband pre-amplifier. The acoustic emission signal amplification tract works according to an unchanged algorithm, and the entire measurement and information processing process is ensured by the joint operation of the specialized analog and pre-digital processing module AP08 and a personal computer (PC). Communication between the AP08 and the PC is carried out via a separate serial interface VH 485 with the help of software.

Simulation of the stress-strain state of the frictional contact was carried out using SolidWorks software under static conditions. An analogue of duralumin D16 – an alloy of grade 2024 (AISI USA standard), an analogue of 30ChGSA steel – 41CrMo4 steel (DIN17212 standard, Germany) were chosen as materials for modeling tribo-coupling elements. The main indicators of materials are indicated in the Table 3.

Table 3: Mechanical and physical properties of triboelements during modeling.

Material	**Parameters**						
	Yield strength, MPa	Tensile strength, MPa	Elastic modulus, GPa	Poisson's ratio	Mass densty, g/cm^3	Shear modulus, GPa	Thermal expansion coefficient, 1/Kelvin
2024 Alloy	75.82	186.12	73	0.33	2.8	28	$2.3 \cdot 10^{-5}$
1.7223 (41CrMo4)	760	980	190	0.28	7.8	79	$1.1 \cdot 10^{-5}$
Alloy VK8	1500	1660	600	0.196	14.6	250	$5.0 \cdot 10^{-6}$
Copper	258.64	394.38	110	0.37	8.9	40	$2.4 \cdot 10^{-5}$

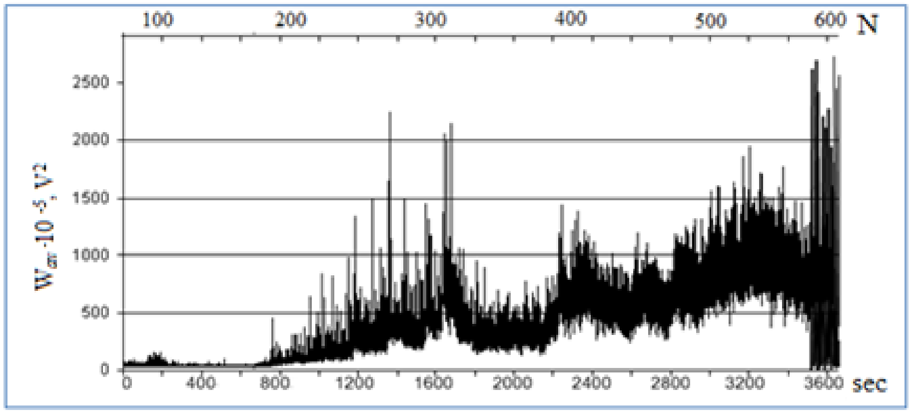
4.0 ANALYSIS OF THE MAIN RESULTS AND DISCUSSION

The obtained results of the average power of AE signals (W_{av}), and the value of its spread ($W_{av\pm}$) for the tribosystems under study are indicated in the Table 4 and in Figure 2.

The analysis of the average power of AE signals is based on the principles that the source of AE is plastic deformation, and the work spent on plastic deformation is correlated with the energy characteristics of AE (Landis and Baillon, 2001; Landis and Baillon, 2002; Kravchuk and Landis, 2018).

Table 4: AE parameters in the conditions of stepwise load increase.

	Load, N						
	100	**200**	**400**	**600**	**800**	**1000**	**1200**
Parameter	D16 – 30ChGSA (moving triboelement D16)						
W_{av}, V^2	0.005	0.00425	0.00925	0.0141	-	-	-
W_{av} ±,V^2	0.0005	0.00275	0.00575	0.0139	-	-	-
	D16+VK8+Cu – 30ChGSA (moving triboelement D16+VK8+Cu)						
W_{av}, V^2	0.004	0.0065	0.005	0.0076	0.01075	0.01375	0.0125
W_{av} ±,V^2	0.002	0.0035	0.0025	0.0044	0.00725	0.00775	0.0055
	30ChGSA – D16 (moving triboelement 30ChGSA)						
W_{av}, V^2	0.005	0.006	0.005	0.0106	-	-	-
W_{av} ±,V^2	0.0025	0.0035	0.003	0.0104	-	-	-
	30ChGSA – D16+VK8+Cu (moving triboelement 30ChGSA)						
W_{av}, V^2	0.0005	0.00165	0.00235	0.00515	0.0025	0.0036	0.00515
W_{av} ±,V^2	0.00025	0.00115	0.00145	0.00335	0.0015	0.0024	0.00335


100
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N
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$W_{av} \cdot 10^{-5}$, V2
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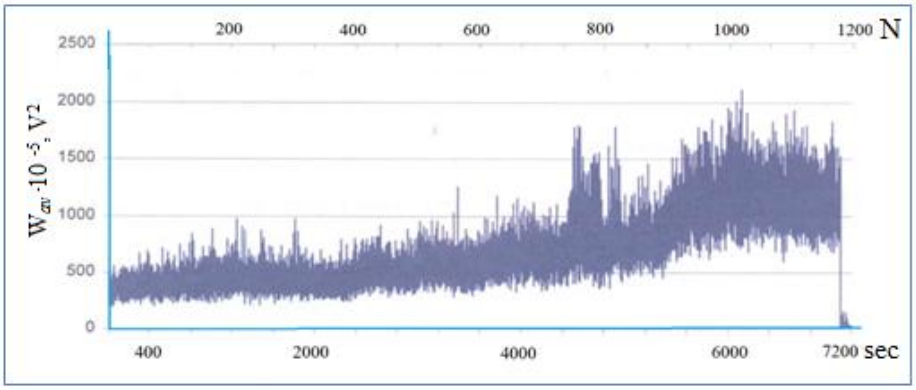
A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7200
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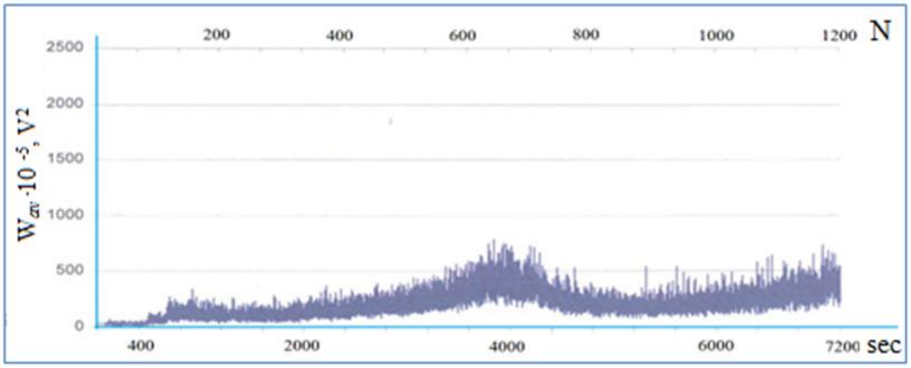
B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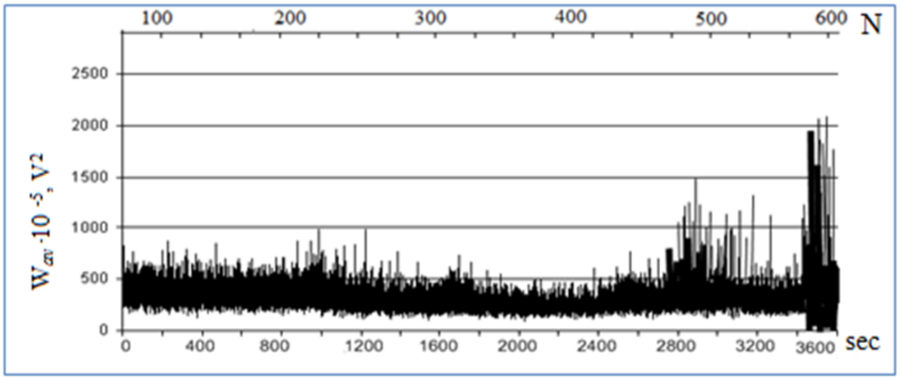
C



D

Figure 2: Kinetics of changes in the average power of AE signals under the conditions of stepwise load increase: A – friction pair D16 – 30ChGSA (moving triboelement D16); B – friction pair D16+VK8+Cu – 30ChGSA (moving triboelement D16+ВК8+Cu); C – friction pair 30ChGSA – D16 (moving triboelement 30ChGSA); D – friction pair 30ChGSA – D16+VK8+Cu (moving triboelement 30ChGSA).

It was established that for friction pair with unmodified duralumin D-16 (moving and stationary triboelement) the operational state remained in the load range of 100...600 N, seizing and burring of the tribocoupler elements were recorded at the load of 600 N. Under the conditions of gradual increase in the load, the intensity of wear of the D16 – 30ChGSA tribosystem increases intensively from $9 \cdot 10^{-8}$ at 100 N to $1.4 \cdot 10^{-3}$ at 600 N, for tribosystems 30ChGSA – D16 at 100 N this parameter is $1.5 \cdot 10^{-6}$, at 600 N – $8 \cdot 10^{-5}$, which indicates slower wear of tribocoupler elements.

The kinetics of changes in AE signals correlates with the intensity of wear of the tribosystems under study. For D16 – 30ChGSA, the growth of the average power of the AE signals was determined to be 9.4 times, and the value of their dispersion increased by 27.8 times with a stepwise increase in the load from 100 to 600 N. AE signals for the 30ChGSA–D16 tribosystem grow less slowly, as well as the intensity of wear: Wav increases by 2.1 times, and $W_{av}\pm$ by 4.2 times when the load increases from 100 to 600 N.

Since in the experimental conditions, the friction processes occur in non-equilibrium conditions (increasing load, increasing temperature of the lubricant in the frictional contact zone), these factors cause the tribosystem to leave the equilibrium state according to two mechanisms - either destructive processes are initiated and the intensity of wear increases, or the accumulation algorithm is implemented of primary energy in secondary dissipative structures during the self-organization of the tribosystem, which ensures a decrease in the rate of wear.

Table 5 shows the experimental results of changes in the friction coefficient, lubrication mode, temperature, and wear rate for the studied tribosystems with a movable triboelement made of steel 30ChGSA.

Table 5: Tribotechnical characteristics of the contact under the conditions of stepwise load increase.

Indicators	**Load, N**		
	400	**600**	**800**
	30ChGSA – D16		
Friction coefficient (*f*)	0.1	0.1…0.3	–
Lubrication mode (λ)	1.1 (marginal)	0.5 (semi-dry)	–
Temperature, ^{0}C	43	92	–
Wear rate, g/min	$2.52 \cdot 10^{-5}$	$2.83 \cdot 10^{-4}$ …$3.9 \cdot 10^{-3}$	–
	30ChGSA – D16+VK-8+Cu		
Friction coefficient (*f*)	0.17	0.17	0.17
Lubrication mode (λ)	3.2 (elastohydrodynamic)	2.8 (mixed)	2.5 (mixed)
Temperature, ^{0}C	30	64	74
Wear rate, g/min	$5.7 \cdot 10^{-6}$	$4.3 \cdot 10^{-5}$	$5.3 \cdot 10^{-5}$

For the tribosystem 30ChGSA – D16 under the conditions of a gradual increase in the load, a decrease in the anti-friction characteristics of the contact due to the transition from the limit to the semi-dry lubrication mode was recorded, which leads to a sharp increase in the temperature in the frictional contact, micro-seizing, and intensification of the wear of the tribo-coupling elements. At 600 N, in the 8th minute of operation, there is a 3-fold increase in the friction coefficient, a 13-fold increase in the wear rate, and an increase in noise due to the formation/rupture of micro-areas of adhesion of the contact surfaces. Under a gradual increase in the load at 600 N, a semi-dry lubrication mode is implemented, and the boundary films are destroyed. In such conditions, the process of mechanochemical oxidation of duralumin D16 dominates, caused by intense plastic deformation of the surface layers of this alloy, which is characterized by lower hardness compared to steel 30KhHSA. As the thickness of the oxide film increases in non-equilibrium thermodynamic conditions, internal stresses in it increase, and the film peels off. Since the microhardness of the oxide layers of the D-16 alloy, according to (Vasiliev, et al., 2014), can reach 10...12 GPa, these wear particles act as a hard abrasive for the surface of steel 30XHSA with microhardness of the surface layers at 7..9 GPa. In such conditions, the processes of catastrophic wear dominate, which are characterized by a decrease in the anti-friction properties of the tribosystem 30ChGSA – D16 and an increase in the rate of wear of dissipative structures.

Signs of catastrophic wear are the destruction of the boundary layers of the lubricant, the formation of areas of micro seizure in frictional contact with subsequent micro destruction, and cohesive separation in the area of the surface layers of D16 duralumin, which indicates the transition to internal friction as shown in Figure 3.

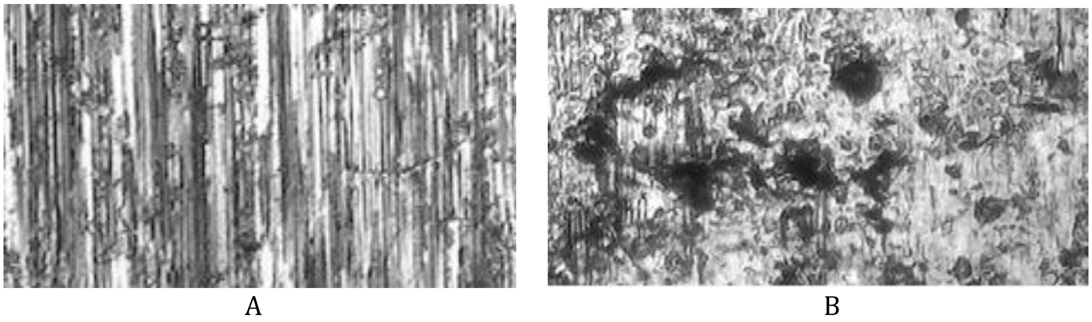


Figure 3: Surface of D16 duralumin: A – original surface, B – after working under step load conditions (×478).

Modification of duralumin D-16 with a discrete combined coating of hard alloy VK-8 and copper provides an expansion of the load range, in which the tribosystem 30ChGSA – D16+VK8+Cu maintains a normal working condition. One of the main mechanisms of this process is an increase in the bearing capacity of the lubricating layer - in tribocontact, elastohydrodynamic, or mixed lubrication regimes dominate. The formed lubricating layer in the frictional contact ensures a decrease in the temperature increase in the contact zone of tribosystem elements, and reliable separation of friction pairs by a layer of lubricating material causes an effective decrease in the rate of wear of the contact surfaces. According to (German et al., 2015; Al-Quraan T. M. A., 2023), one of the main prerequisites for reducing the wear rate is self-organization in tribosystems, which is accompanied by the formation of dissipative structures.

Since the appearance of AE signals is due to a certain stress-strained state of the contact surfaces, the depth of localization of equivalent stresses according to Mises was evaluated in the SolidWorks software.

On the basis of the obtained modeling results, it was defined that the value of the maximum equivalent stresses according to Mises in the surface layers of unmodified D16 duralumin does not depend on the contact kinematics (moving or stationary triboelement D16 in the studied tribocoupling with the counter body of 30ChGSA steel) and makes 10: 31: 62 MPa, respectively, for the load 100, 300 and 600 N. However, the contact kinematics significantly affects the depth of propagation of the stress-strain state in the near-surface layers of D16 duralumin, which is, on average, 1.3 times higher for the friction pair D16 – 30ChGSA as shown in Table 6 and Figure 4.

Table 6: The depth of localization of the stressed-strained state in the near-surface layers of D16 duralumin.

Parameter	**Load, N**		
	100	300	600
Depth of localization for D16 (moving triboelement), μm	0.21	0.64	1.27
Depth of localization for D16 (stationery triboelement), μm	0.17	0.5	1.0

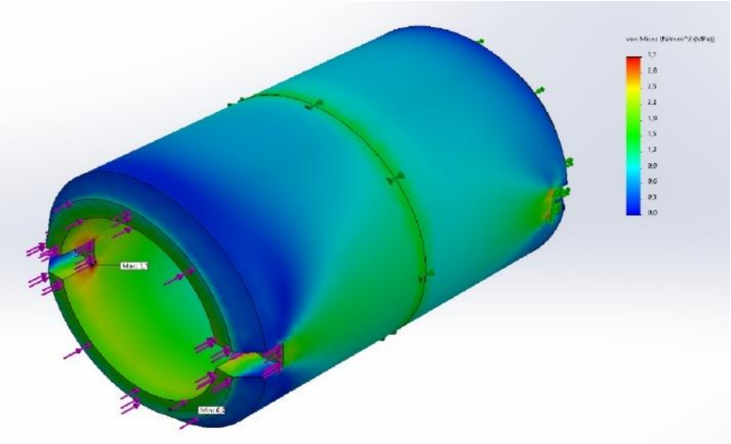
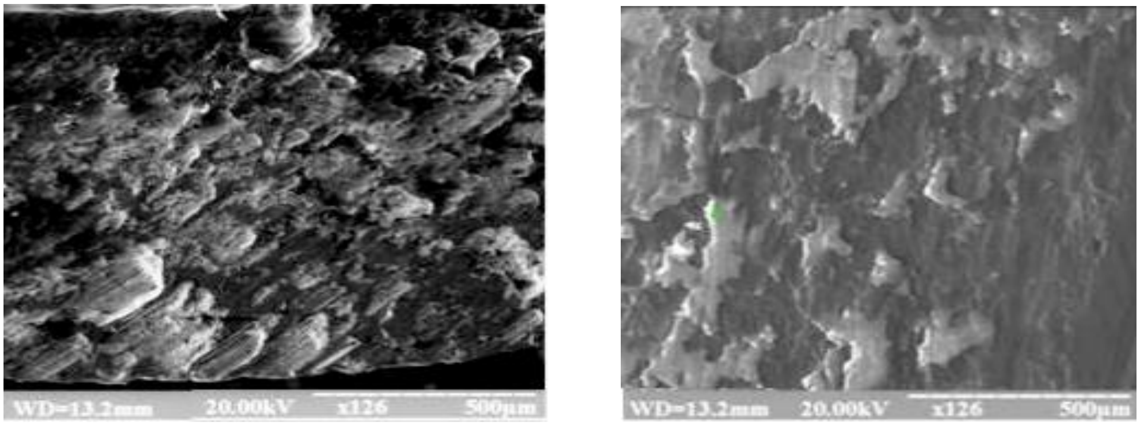


Figure 4: Modeling of the stress-strain state of the tribosystem D16 - 30ChGSA.

As mentioned above, greater indicators of wear intensity and AE signals are established for this system. According to the simulation results, it was determined that in the conditions of a stepwise increase in the load from 100 to 600 N, the depth of intense strained stress localization increases by 6 times for the stationery/moving triboelement D16. Thus, an increase in the load in the frictional contact leads to the intensification of plastic deformations, the generation and development of defects, which is registered by the appearance of AE signals with large amplitudes and their dispersion values, indicating the transition of the tribosystem to disastrous wear.

Electron microscopic studies of the surface of the friction tracks of unmodified and modified D16 duralumin with a combined electrospark coating revealed significant differences in the topography of the surface after friction under step load conditions. For unmodified duralumin D16, an uneven topography with severe damage was established on the friction track, indicating a great depth of deformation processes during the load increase. The prerequisite for the development of the intensification of the setting processes is the destruction of the fragile oxide film when the load increases to 600 N. The temperature in the frictional contact increases to 90^0C, the formation of a juvenile surface with subsequent setting, which is accompanied by catastrophic adhesive wear of the duralumin sample as shown in Figure 5(A). The results of the electron microscopic examination of the surface of the modified duralumin D16+VK8+Cu showed that during friction, the formation of peculiar thin-film protective structures is observed, the destruction of the surface is not established, which indicates a small depth of propagation of deformation processes as shown in Figure 5(B). The main prerequisite for preventing seizure when using modified duralumin is the presence of a discrete coating of VK8 hard alloy, which perceives the load and prevents the propagation of plastic deformations in depth. The uniformity of load localization on the surface of modified duralumin is ensured by the presence of copper in the combined coating, which acts as a soft matrix that redistributes the load over the entire friction contact surface.



A B

Figure 5: Topography of the friction track of duralumin D16 (A) and duralumin D16 modified by combined electrospark coating (B) after friction under conditions of stepwise increase in load.

An assessment of the numerical energy indicators during the transition of the tribosystem from normal to disastrous wear was carried out based on the assumption that energy of plastic deformation, according to (Casiez et al., 2014; Filonenko, 2015), correlates with the amplitude characteristics of AE signals according to the following ratios in Equation (1):

$$E = \int_0^t |U(t)^2|\, dt, \qquad (1)$$

Where U –amplitude of AE signal, t – time.

It was defined that for the tribosystem D16 – 30ChGSA with each step increase in the load, there is a sharp increase in energy by 4...12 times, which indicates intensive plastic deformation processes in the near-surface and surface layers of the friction pairs as shown in Table 7.

Table 7: Energy of AE signals.

Friction pairs	**Load, N**						
	100	**200**	**400**	**600**	**800**	**1000**	**1200**
D16– 30ChGSA	$8\cdot10^{-8}$	$8.8\cdot10^{-8}$	$4.5\cdot10^{-6}$	$1.6\cdot10^{-5}$	-	-	-
30ChGSA– D16	$1.1\cdot10^{-7}$	$1.08\cdot10^{-7}$	$1.28\cdot10^{-7}$	$8.8\cdot10^{-6}$	-	-	-
D16+VK8+Cu– 30ChGSA	$7.2\cdot10^{-7}$	$1.2\cdot10^{-7}$	$1.3\cdot10^{-7}$	$2.9\cdot10^{-7}$	$6.5\cdot10^{-6}$	$9.2\cdot10^{-6}$	$6.5\cdot10^{-6}$
30ChGSA-D16+VK8+Cu	$1.1\cdot10^{-8}$	$1.6\cdot10^{-7}$	$2.9\cdot10^{-7}$	10^{-7}	$3.2\cdot10^{-7}$	$7.2\cdot10^{-7}$	10^{-7}

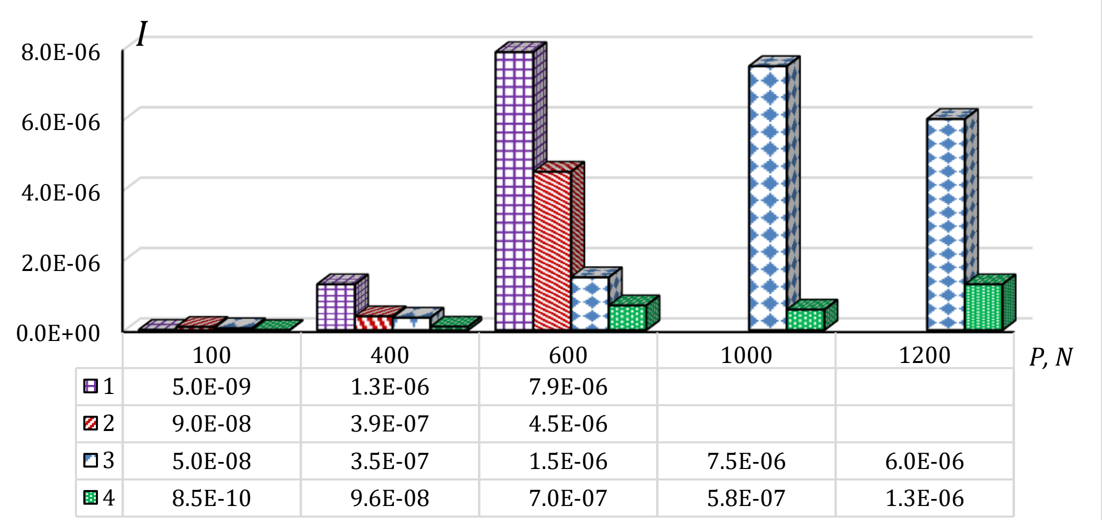
Based on the numerical energy values for signals corresponding to different types of destruction presented in the study (Stankevich, 2015): plastic deformation processes are characterized by the release of energy of about $10^{-11}...10^{-7}$ J, while destruction processes are accompanied by a large number of pulses with energy of about 10^{-11} to 10^{-7} J.

Thus, for the tribosystem D16 – 30ChGSA, the transition to disastrous wear occurs with an increase in the load of 400 N and above, which is registered by the intensification of AE signals, increase in the average power of AE signals, their spread, and an increase in the energy of destruction up to $1{,}6{\cdot}10^{-5}$ during friction pair adhesion. For the tribosystem 30ChGSA – D16, which is characterized by higher wear resistance, up to 600 N the energy of plastic deformation is on average at the level of $1{,}1\ 10^{-7}$ J, the processes of structural adaptation, formation of metastable secondary structures, and mechanisms of normal wear are realized. At 600 N, there is a 60-fold increase in energy indicators that indicates the transition of tribosystem to disastrous wear. The similar changes registered in the AE signals specified for the D16 - 30ChGSA tribosystem.

Duralumin D16 was modified with a discrete combined electrospark coating of the VK-8 alloy and copper to increase the wear resistance of tribosystems and expand the loading range of their operational state.

For tribosystems D16+VK-8+Cu – 30ChGSA and 30ChGSA – D16+BK-8+Cu, a doubling of the load range has been established before the first signs of adhesion. The signs of adhesion appear while the load is gradually increased up to 1200N. Wear intensity of tribosystems decreases with a modified combined electrospark coating on D16 duralumin at 600 N compared to tribosystems with unmodified D16 by 5.5 times and by 6.5 times for friction pairs where triboelement D16+VK8+Cu is moving and stationary as shown in Figure 6.

A further increase in the load up to 1200 N leads to an increase in the intensity of wear by 4 and 1.9 times for tribosystems with a moving and stationary triboelement D16+VK8+Cu, respectively.



	100	400	600	1000	1200
▦ 1	5.0E-09	1.3E-06	7.9E-06		
▨ 2	9.0E-08	3.9E-07	4.5E-06		
◈ 3	5.0E-08	3.5E-07	1.5E-06	7.5E-06	6.0E-06
▩ 4	8.5E-10	9.6E-08	7.0E-07	5.8E-07	1.3E-06

Figure 6: Intensity of wear (I) of tribosystems in conditions of stepwise load increase (P): 1 – tribosystem D16 – 30ChGSA; 2 – tribosystem 30ChGSA – D16; 3 – tribosystem D16+VK8+Cu – 30ChGSA; 4 – tribosystem 30ChGSA – D16+VK8+Cu.

The calculated indicators of the energy characteristics of AE signals indicate that for the tribosystem D16+VK8+Cu – 30ChGSA the stage of intensive wear is at a load of 800…1200 N – energy indicators reach (6,5…9,2)·10^{-6} J. That corresponds to the energy of destruction shown in Table 7. However, during the experiment, there was no adhesion or burring of the contact surfaces. Presumably, the increase in energy indicators of tribocontact is caused by the intensification of dissipative processes in the surface layers of the contact surfaces leading to formation of modified structures in the surface layers of friction pair materials, which are characterized by increased specific work of wear (Mironov et al., 2019; Mikosyanchik and Mnatsakanov, 2017). For tribosystems 30ChGSA – D16+VK8+Cu, no significant change in the energy characteristics of tribocontact was established, which indicates the implementation of wear mechanisms far from disastrous ones.

The analysis of AE signals indicates a decrease in the stress-strain state of the frictional contact and the intensity of the flow of plastic deformations for tribosystems with modified duralumin. At each level of load, the values of the average power of the AE signals and their dispersion values decreased by 2-4 times shown in Table 2.

The main prerequisite for reducing the degree of plastic deformations in frictional contact is presence of a combined discrete electrospark coating, that is characterized by effective damping properties both due to the copper film covering up to 80% of the surface area of the modified duralumin D16 during the process of structural adaptation of the tribosystem, and due to the discrete layer of hard alloy VK8, which provides localization of stresses in the coating and prevents the spread of plastic deformations in the softer D16 duralumin base (Al-Quraan et al., 2021).

The results of simulations on the depth of localization of plastic deformation; using SolidWorks software, indicate a decrease in this parameter, on average, by 2 times for triboelement D16+VK8+Cu, compared to the unmodified D16 surface shown in Figure 7.

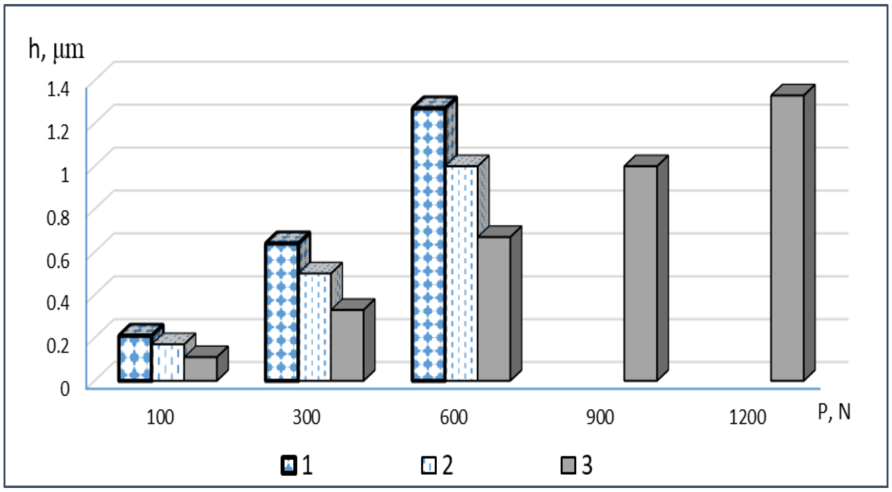


Figure 7: Results of modeling of the influence of load (P) on depth of localization of the stress-strain state in near-surface layers (h): 1 – D16 (moving triboelement), 2 – D16 (stationery triboelement), 3 – D16+VK8+Cu moving and stationary triboelement).

The modification of duralumin D16 with a discrete combined coating provides a redistribution of stresses in the formed coating due to the formation of wear-resistant dissipative structures, providing an increase in tribosystem wear resistance and expansion of the operational range under conditions of a gradual increase in load. Based on the analyzed experimental data on the wear resistance of tribosystems under study, the empirical dependences of intensity of wear on the linear load (N/l, N/mm^2), average power of the acoustic emission signals (W_{av}, V^2), spread of the average power of the acoustic emission signals (W_{av}±, V^2), operating time (t, min) and friction path (L, m) as shown in Figure 8 and in Figure 9.

$$I = \left(\frac{N}{l} \cdot W_{av} \cdot W_{av\pm}^{0,5} \cdot t^{0.5}\right)/L \tag{2}$$

Where N– load, H; l – contact length, mm.

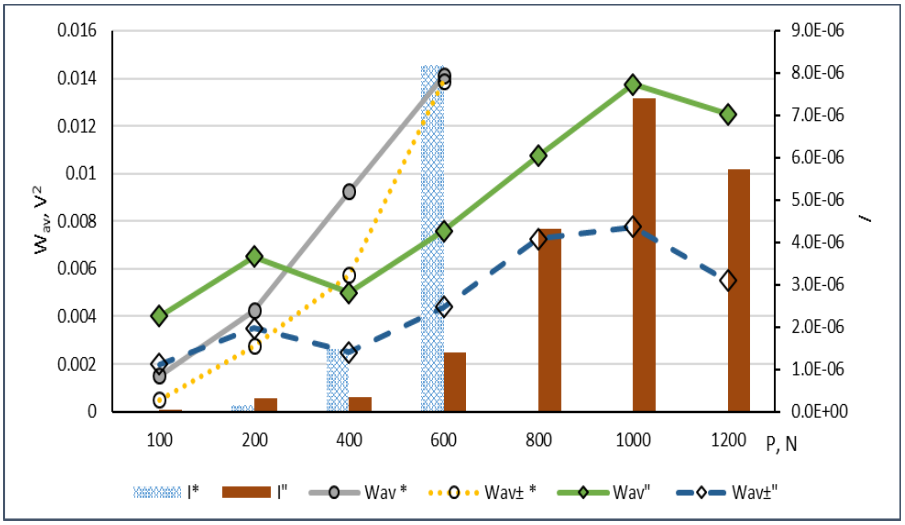
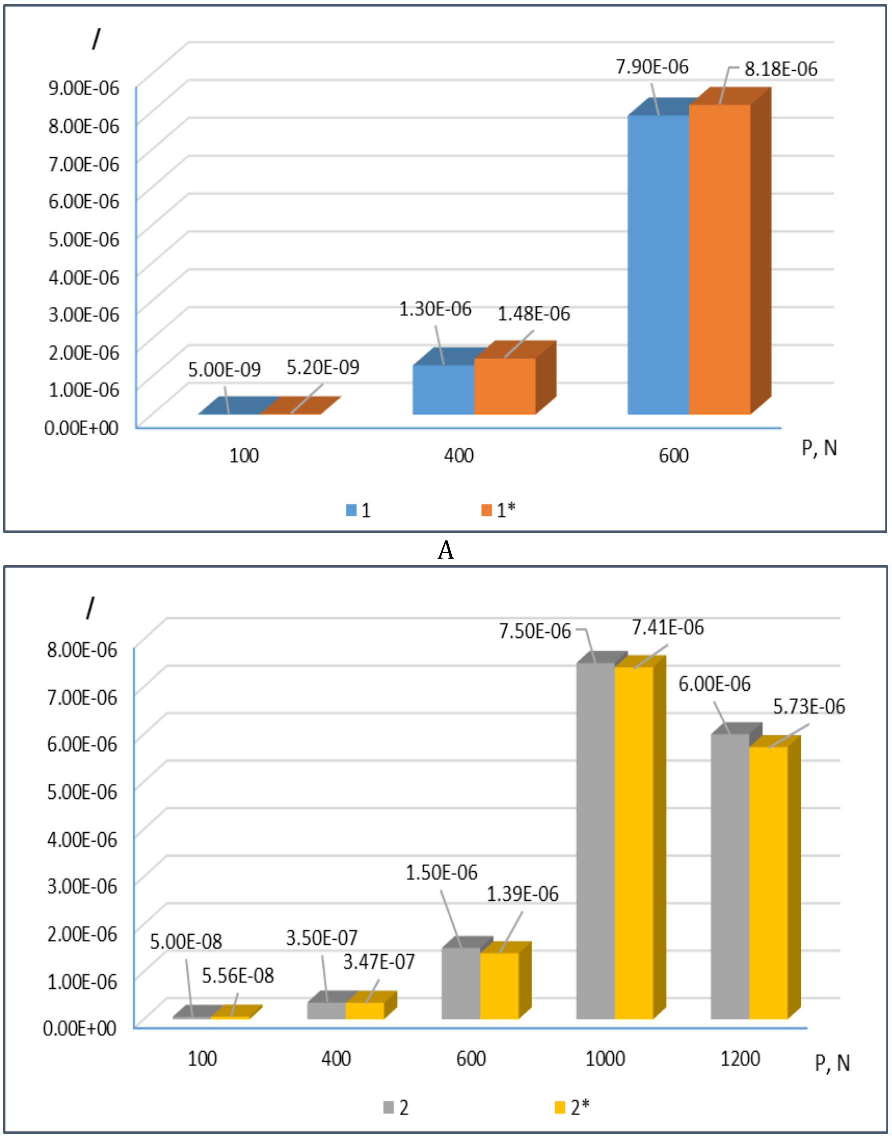


Figure 8: Calculated dependences of wear intensity (I) on the average power of AE signals (Wav) and its spread (W_{av} ±): * – tribosystem D16 – 30ChGSA; '' – tribosystem D16+VK8+Cu – 30ChGSA.



A

B

Figure 9: Experimental and empirical indicators of wear intensity (I): A) – for tribosystem D16 – 30ChGSA (1 – experimental values, 1* – according to Eq. (2)); B) – for tribosystem the D16+VK8+Cu– 30ChGSA (2 – experimental values, 2* – according to Equation (2)).

The difference between the experimental values of the intensity of wear of the tribosystems under study and the values obtained by Equation (2) is 5...15%. Based on the obtained empirical formula on the basis of the average power of AE signals, it is possible to predict the intensity of wear of the tribosystem in the optimal load range. That provides a possibility to determine the limit of the transition from normal to disastrous wear of the tribosystem at the stage of laboratory tests of triboelements.

The combined coating of the VК-8 alloy and copper obtained by the ESA method differs in structure and properties from the original D16 alloy. The reason for this is the micrometallurgical processes that occur on the treated surface in the area of action of the spark discharge as a result of the physical and chemical interaction of the transferred material with the material of the cathode and elements of the environment in the presence of pulsed thermodynamic stresses (Ivanov et al., 2017; Tarel'nyk et al., 2016).

A feature of the created combined electrospark coating is its inherent discontinuity, which provides increased wear resistance due to the discreteness of the coating structure, which is responsible for reducing residual stresses. The presence in the surface layer of discrete areas of increased hardness, optimal integrity, geometry, and depth of introduction into the surface eliminates the concentration of stresses from contact loads, and interrupts the process of crack formation, plastic deformation, and also reduces the tendency to the seizure of parts, which significantly increases the strength and operational reliability of friction pairs.

Therefore, the main advantage of discrete coatings is the ability to manage and minimize the stress-deformation state of the surface by changing the integrity and size of discrete areas on the surface of the base, by selecting materials according to physical and mechanical characteristics, ensuring increased wear resistance of electrospark coatings.

CONCLUSIONS

1. Determined the limit of operational capacity in the load range of the friction pair duralumin alloy D16 – steel 30ChGSA, which is 600 N. The criteria for the transition of the tribosystem to disastrous defined as increase in the density, amplitude and spread of the AE signals, as well as increase in the destruction energy up to (0.88….1.6)· 10^{-5} J, which manifests itself in the adhesion of contact surfaces.
2. Modification of duralumin D16 with a discrete combined electrospark coating of the VK8 alloy and copper ensures the effective performance of tribosystems up to 1200 N. Under the conditions of gradual increase in the load, the values of the average power of AE signals and their dispersion values decrease by 2-4 times, and dissipative energy processes in frictional contact ensure the formation of wear-resistant structures.
3. Based on the results of modeling the depth of localization of plastic deformations in the SolidWorks software, a 2-fold reduction of this parameter was established for modified D16 duralumin, compared to the unmodified surface. The stressed-deformed state is localized in the electrospark combined coating without spreading into the base material.
4. Based on the obtained empirical dependences of the wear intensity of tribosystems on the linear load, average power and dispersion of the average power of AE signals, operational time and friction path, it is feasible to determine the transition of the tribosystem from normal to disastrous wear at the stages of laboratory tests.

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