This paper considers the technology of electrical discharge machining of steel friction pairs and reports the results of experimental studies. Analysis of the experimental studies has shown that increasing the "anode-cathode" voltage leads to a sharp decrease in the micro-hardness of the surface layer. The study has also made it possible to determine the characteristic dimensions of the structural elements, the height parameters of surface roughness. The elemental composition of the resulting surface of a steel 15KHGN2TA sample differs from the composition of coatings and the surface layers of samples modified by electrical discharge machining involving various electrodes. Under the "anode-cathode" system operation mode, a thin layer of coating with a stable modified structure forms on the surface of the cathode due to dissipative processes. It is shown that the height of surface irregularities on sections after friction is higher than on the surface sections outside the friction flow, which is associated with the formation of a friction transfer film on the samples' surface. It was established that the interaction of friction of steel samples treated by electrical discharge machining forms a thin film on the surface of friction of steel samples, which leads to a change in the relief of surfaces with an increase in the height of the micro-protrusions, as well as the structuring of the transfer film in the direction of sliding. The effect of machining steel surfaces by electrical discharge on the wear resistance of metal-polymer tribosystem was established. The implementation of the devised technology could provide a significant increase in the wear resistance of metal-polymer tribojunctions

Keywords: alloying electrode, wear resistance of metal polymers, tribojunction, electrical discharge machining, steel modification

UDC 621.1.9
DOI: 10.15587/1729-4061.2021.243374

REGULARITIES IN THE FORMATION OF WEAR-RESISTANT COATINGS ON STEEL SAMPLES WHEN MACHINING THEM WITH ELECTRICAL DISCHARGE

Dmytro Marchenko
Corresponding author
PhD, Associate Professor
Department of Tractors and Agricultural Machinery, Operating and Maintenance*
E-mail: marchenkodd1984@gmail.com

Viacheslav Kurepin
PhD, Senior Lecturer
Department of Methodology of Vocational Training*
*Mykolayiv National Agrarian University
Heorhiya Honhadze str., 9, Mykolayiv, Ukraine, 54020

Received date 24.08.2021
Accepted date 01.10.2021
Published date 29.10.2021

***How to Cite:** Marchenko, D., Kurepin, V. (2021). Regularities in the formation of wear-resistant coatings on steel samples when machining them with electrical discharge . Eastern-European Journal of Enterprise Technologies, 5 (12 (113)), 83–90. doi: https://doi.org/10.15587/1729-4061.2021.243374*

1. Introduction

Reliability and efficiency of machines and technological equipment are determined mainly by the wear resistance and durability of tribosystem parts. In the industry, depending on the operating conditions of articles, various methods of surface strengthening of steels and alloys are used. The most energy-efficient of them are such as surface plastic deformation, chemical and heat treatment, formation of hardening wear-resistant coatings (micro arc oxidation, spraying, etc.), high-energy methods (laser, ion-ray treatment, etc.), and their various combinations. All known methods of surface strengthening have advantages and specific application but do not fully meet modern requirements for the performance, versatility, and efficiency of technological processes. The most promising are the methods of surface modification of tribosystem parts with the use of highly concentrated energy flows, which include electrical discharge machining (EDM), which makes it possible to obtain coatings with high physical, mechanical, and tribotechnical properties.

Therefore, it is a relevant scientific and practical task to devise an effective method, simple enough for industrial application and economically feasible, for increasing wear resistance; this study aims to address this issue.

2. Literature review and problem statement

Combined surface strengthening methods make it possible to produce coatings with high predefined operating properties [1]. Thus, surface alloying with subsequent nitriding of low-alloyed steels makes it possible to improve the characteristics of mechanical strength above the level of properties of high-alloyed steels. Paper [2] considers the tasks of increasing the wear resistance of broaching tools by combined strengthening, including nitriding and applying a coating (Ti, Nb, Al, N). Industrial tests have shown that the combined strengthening of broaches under the proposed regimes makes it possible to increase their stability by 2–4 times compared to the non-strengthened ones.

A combination of methods of physical cathode-arc and chemical deposition from the gas phase when machining plunger pairs of high-pressure fuel pumps made of steel 25KH5MA makes it possible to obtain coatings with high hardness, wear resistance, and corrosion resistance [3]. The essence of the method is to destroy carbon-containing gas molecules as a result of their collisions with high-energy ions generated by a powerful current pulsed cathode-arc discharge on the surface of the target of graphite. Products of such interaction are deposited on the substrate and form a wear-resistant coating. It was established that the coefficient of friction of surfaces with such a coating under the conditions of maximum oiling is 0.10–0.12, and almost does not change in the presence of impurities of water and finely dispersed abrasive particles. For surfaces without coatings, the friction coefficient increases by 1.4 times in the presence of impurities.

Work [4] reports a technology of ion-radiation nitriding of gas-thermal coatings obtained by hypersonic spraying of ferrite wire steels (SV-08G2S), martensite (40KH13), and austenite (06KH19N9T) classes. It has been shown that the use of this technology ensures an increase in the wear resistance of ferrous steel coatings by 2 to 80 times; martensite steel – by 2 to 13 times; austenite steel – by 10 to 35 times.

Paper [5] reports the results of the preliminary application to the surface of the part of the alloying sublayer with concentrate by electro-spark doping, followed by its melting by an electric arc in a carbon dioxide environment. This approach, applied in [5], makes it possible to significantly change the operational characteristics of steel St3 in the right direction.

Electric-spark treatment of steel 45 with the solid alloy VK6M, chromium, and molybdenum, followed by laser strengthening, is described in work [6]. This reduces the wear intensity of coatings formed by the solid alloy by 70 %, and coatings formed by Cr and Mo, by 3.5 and 3 times, respectively, compared to untreated steel.

An experimental study into the process of micro-arc cementation of steel articles in powder environments was carried out in [7]. The use of coal powder intensifies the process of diffusion saturation with carbon and the formation of a diffusion layer, 0.3 mm deep, occurs within 2–3 minutes, which reduces the cementation process by hundreds of times.

A study of cementation in the plasma of the electrolyte of reverse polarity is reported in [8]. It has been shown that electrolyte-plasma treatment, at a temperature of 850 °C with a duration of 3–6 minutes, leads to the formation of a modified layer, 30–40 μm deep, in steel, consisting of ferrite (-Fe) grains, on the borders of which iron carbides are located (Fe_3C). The micro-hardness value of the surface layers of steel modified by electrolyte-plasma cementation is 7,500 MPa.

In modern repair technology, a promising direction is the combination of electrical impact on the surface with machining or strengthening by electro deforming treatment [9]. In [10], the experimental data were analyzed from studying the micro-hardness of surface layers of carbon steels subjected to electromechanical strengthening with impact. The author of work [11] also considered some distinctive features of the thin structure of the strengthened surface layer ("white layer") of material obtained in the region of pulse temperature-force influence.

An effective way to strengthen carbon steels is also processing, combining the effect on the strengthening surface of the spark discharge and subsequent plastic deformation with simultaneous alloying [12]. Surface treatment is possible both by an eccentrically installed electrode and by a rotating disk-electrode with rollers that perform the functions of breaking and closing the anode-cathode circuit during surface deformation. When the circuit is closed, the alloying material is transported to the treated surface and its leveling with an electrode. In this case, the alloying material fills the dents and scratches on the surface of a workpiece, changing its topography, formed after the passage of the electrode, and increasing micro-hardness.

The authors of [13] investigated one of the promising methods for increasing wear resistance – combined friction-electric treatment with high-energy influence through the intermediate environment – a modifier containing a surfactant (SAS). In [1, 14], the influence of surface modification of steel samples by dispersed modifiers in a mixture with SAS (glycerin) and combined processing modes on the micro-hardening of the surface layer and wear resistance of steel-bronze friction pair were studied. Molybdenum disulfide, copper, bronze were used as modifiers.

Therefore, it is important to study the influence of structural steel EDM on the structure, element and phase composition, mechanical and tribotechnical properties of the modified surface layer. The research and the practical implementation of the results could ensure increased wear resistance of machined parts.

3. The aim and objectives of the study

The purpose of this work is to establish patterns in the formation of wear-resistant coatings on the steel substrate using a method of electrical discharge machining, which improve the wear resistance of steel parts of friction units in machines. This would provide an opportunity to provide a significant increase in the wear resistance of metal-polymer tribojunctions.

To accomplish the aim, the following tasks have been set:

– to investigate experimentally the influence of the chemical composition of the electrode material (anode) on the structure and phase composition of coatings formed on steel samples;

– to examine by the method of contact atomic-force microscopy the influence of the composition of alloying electrode (AE) material and EDM modes on the dimensions of the structural elements of the formed coatings and the roughness parameters of the machined surface;

– to investigate the dependences of micro-hardness and tribotechnical properties of coatings on the composition of AE material and the energy modes of EDM.

4. The study materials and methods

The structural alloy steel 15KHGN2TA was used as the object of our experimental research as it is widely used for the manufacture of gears, axles, bushings, car gear shafts, multipurpose tracked and wheeled machines, and other types of equipment [1, 15]. To increase the mechanical properties of the 15KHGN2TA, chemical-thermal processing with subsequent heat treatment is used, which greatly complicates and increases the duration of the technological process of manufacturing parts.

Samples were machined at the EDM installations of models IMEI-02-2-IMES and IMEI-1001-IMES that enable the following technological modes: anode-cathode voltage, U=40–160 V; charge capacity of capacitors, C=34–240 μF.

The surfaces of steel samples were treated with different AE. Standard electrodes of T15K6 grade were used (TiC – 15 %, Co – 6 %, WC – 79 %); IMKH21 electrodes (WC-Co – 50 %, Ni-Cr-B-Si – 50 %); SH21 electrodes with mineral raw materials based on scheelite concentrate (TiC – 60 %, Ni-Cr-Al – 30 %, SHLC (scheelite concentrate $CaWO_4$) – 10 %). The choice of alloying electrodes was made on the basis of earlier studies.

The research methodology included the study of the influence of the material of the alloying electrode and technological modes of machining on the micro-hardness and thickness of the coatings formed with EDM. The micro-hardness of the formed surface layers was determined by the micro-hardness meter PMT–3M at a load on the indenter of 0.49 N.

We studied the structure and phase composition of the modified surface layer of steel 15KHGN2TA after EDM by X-ray phase analysis of the starting and modified samples at the D8 ADVANCE (Bruker) diffractor in a monochromatized Cu-K_α radiation in the region of angles of 5°...120° in increments of 0.050 and accumulation time of 10 s/point.

Using the NTEGRA Prima scanning probe microscope (NT-MDT, Russia) under the mode of contact atomic-force microscopy (k-ASM), the microrelief was studied, and the characteristic dimensions of the structural elements of the surfaces of the starting samples and the samples modified by EDM with various electrodes were determined. In addition, we investigated the modified coatings formed by the IMKH2 electrode under different modes after friction and wear tests [1, 16]. Mathematical post-processing of the obtained results was carried out with the help of the modular program Gwyddion (Czech Metrology Institute).

To study the elemental composition of the initial surface of steel 15KHGN2TA and the surface layers modified by EDM with different electrodes, we used the raster electron microscope Jeol JCM–5700 with the detector Shimadzu EDX–720HS (Japan). X-ray energy dispersion spectrometer was used for coatings formed by the IMKH2 electrode under different modes after tribotechnical tests. Additionally, the JEDML JCXA–733 "Superprobe" (Japan) microchemanalyzer was used.

We studied the characteristics of tribotechnical properties at a special installation designed on the basis of a desktop drilling machine according to the "finger-disk" friction scheme at contact pressure P=2.66 MPa and slip speed V=1.20 m/s.

5. Results of experimental studies into the modification of steel samples using the technology of electrical discharge machining

5. 1. Results of studying steel samples for the structure and phase composition of coatings

Radiographs of the starting surfaces of samples (Fig. 1, *a*) show that 15KHGN2TA steel contains four intense peaks that belong to a solid solution of type CrFe.

Fig. 1, *b–d* shows the radiographs of the samples' surfaces modified by EDM with various electrodes. Decoding the coating radiographs revealed that electric-spark treatment with a standard T15K6 electrode leads to the formation of titanium carbide (TiS) in the surface layer, as well as the phases of $(CrTi)_2O_3$ and FeO in insignificant quantities (Fig. 1, *b*). At the same time, almost no peaks from the initial material are observed, which indicates the absence of the mixing between material of the alloying electrode and the base. The surface layer formed by EDM with electrode SH2 contains phases the phases of CrFe, FeC, CrTiC, and Cr_2O_3 (Fig. 1, *d*).

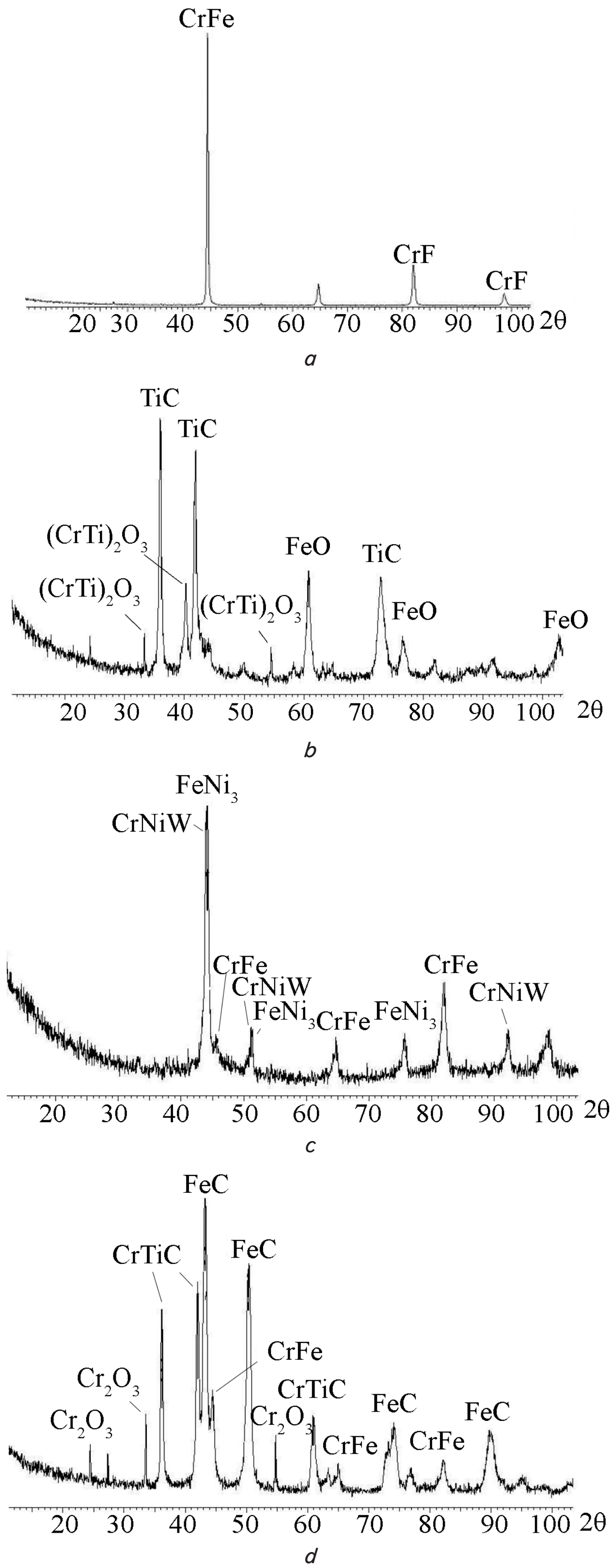


Fig. 1. Radiographs of the surface layers of 15KHGN2TA steel samples: *a* – non-machined sample; *b* – sample machined with the alloyed electrode T15K6 under modes U=160 V, C=34 μF, t=4 min; *c* – sample machined with the alloyed IMKH2 electrode under modes U=80 V, C=60 μF, t=3 min; *d* – sample machined with the alloyed electrode SH2 under modes U=80 V, C=120 μF, t=4 min

Radiograph analysis also showed that in the surface layer modified by the IMKH2 electrode, intense peaks corresponding to complex intermetallides are observed: $FeNi_3$, CrNiW (Fig. 2, *c*), as well as spears from the substrate (CrFe). The result of EDM with the alloying electrode IMKH2 is the formation on the surface of the samples of a layer, which is a mixture of intermetallides. The formation of intermetallides with the participation of iron, chromium, and nickel is a consequence of micrometallurgical processes occurring on the cathode as a result of mixing and chemical interaction of electrode components with the base material. At EDM of 15KHGN2TA steel using the IMKH2 electrode, micro-alloying elements ensure the formation of a protective environment that prevents the formation of oxides in the surface layer.

Charts in Fig. 2 demonstrate that with the increase in the energy modes of EDM: voltage – from 80 V to 160 V; capacity – from 34 μF to 240 μF, the thickness of the coatings increases with any AE material. At the same time, when using the electrode T15K6, the thickness of the coating is increased by 48.6 %; when using the IMKH2 electrode – by 75 %; when using the electrode SH2 – by 83.3 %.

The experimental dependences of the micro-hardness of coatings on 15KHGN2TA steel samples on the anode-cathode voltage and discharge capacity of capacitors were analyzed in [1, 17]. It was established that the increase in energy processing modes differently affects the nature of changes in the micro-hardness of coatings when changing the material of the alloying electrode (Fig. 3, 4).

The highest values of the micro-hardness of coatings (NV 900...1,080) were obtained when using IMKH2 and T15K6 electrodes. The greatest effect of increasing the micro-hardness is provided when using EDM with the IMKH2 electrode, with a voltage of U=140 V and a capacity of C=120 μF. When applying the electrode T15K6, the maximum micro-hardness was obtained at voltage U=120 V and capacity C=150 μF. Further increase in the anode-cathode voltage leads to a sharp decrease in the micro-hardness of the surface layer [1, 17].

The quantitative chemical composition of the initial (unmodified) sample and coatings on the steel samples machined with electrodes T15K6, SH2, and IMKH2, is given in Table 1.

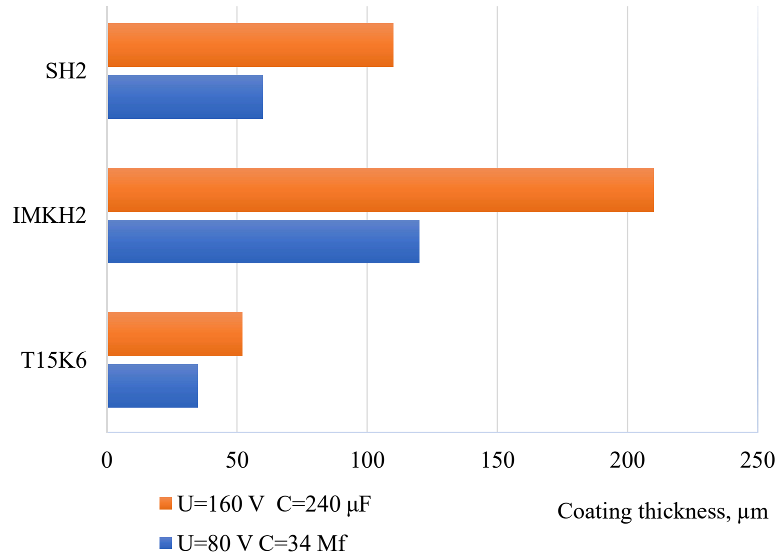


Fig. 2. The thickness of coatings on 15KHGN2TA steel samples with various materials of electrodes

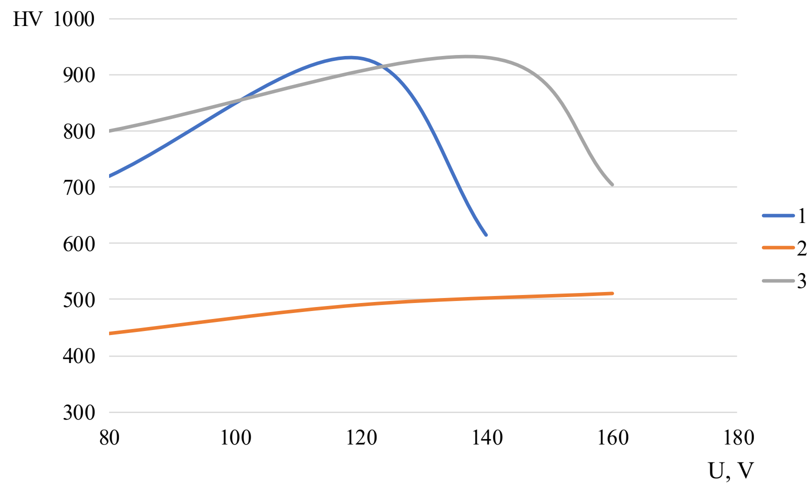


Fig. 3. Dependence of the micro-hardness of surface layers of samples modified by electrical discharge machining with various electrodes on anode-cathode voltage at C=34 μF: 1 – T15K6; 2 – SH2; 3 – IMKH2

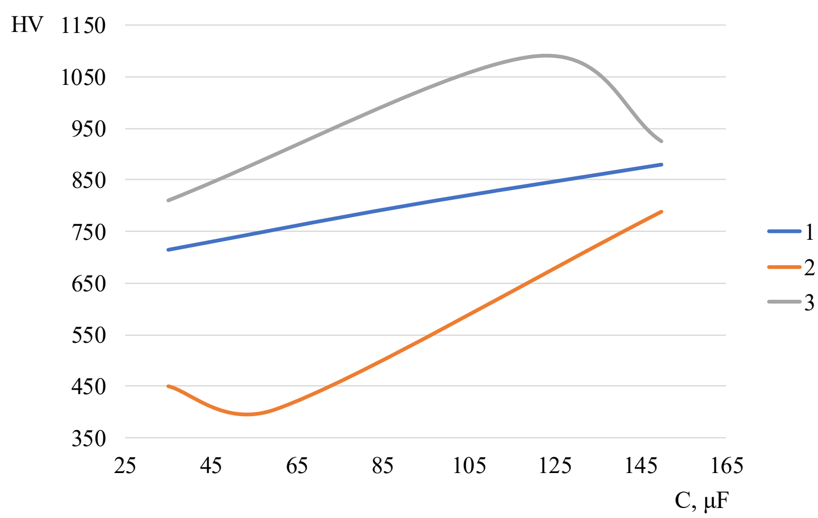


Fig. 4. Dependence of the micro-hardness of surface layers of samples modified by electrical discharge machining by various electrodes on discharge capacity at U=80 V: 1 – T15K6; 2 – SH2; 3 – IMKH2

Table 1

Elemental composition of coatings on 15KHGN2TA steel samples

Sample	Chemical element, %							
	Fe	Cr	Mn	Ni	Si	Ti	W	O
Steel 15KHGN2TA (starting)	95.3	1.09	1.95	1.66	–	–	–	–
Coating AE T15K6	54.87	–	–	–	–	12.34	32.8	–
Coating AE IMKH2	23.73	14.39	–	58.02	3.86	–	–	–
Coating AE SH2	47.05	–	–	7.32	–	29.56	–	16.07

5. 2. Results of studying the influence of the material of alloying electrodes and the modes of electrical discharge machining

We studied the influence of EDM on the topography of coatings formed by EDM under the modes of U=80–160 V, C=34–240 µF in k-ASM regime (Fig. 5–7).

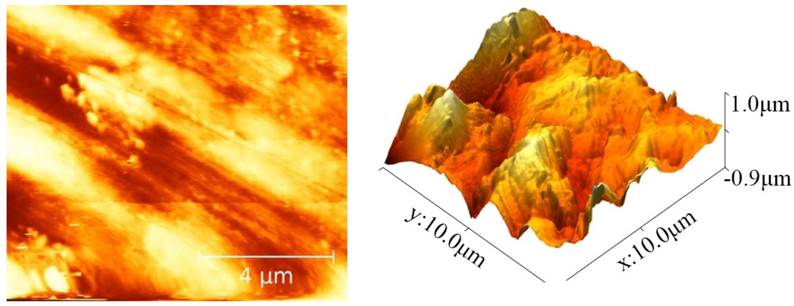
Our study has also made it possible to determine the characteristic size of the structural elements (D), the height parameters of the surface roughness: the arithmetic mean deviation of the profile (Ra), the depth of the largest depression (Rv), and the height of the largest protrusion (Rp) of the profile of sample surfaces (Table 2).

The roughness values of the surfaces studied show that the parameters of *Ra, Rp,* and *Rv* vary depending on the material of the electrode. The parameters are increased in the following order: initial state of the surface→machining with the electrode T15K6→machining with the electrode SH2→machining with the electrode IMKH2 (Table 2). At the same time, the *Ra* parameter increases by 1.5–3.9 times. The largest increase in the roughness parameter *Ra* to 6.3, and the R_P parameter to 538.3 nm, is observed when using the electrode IMKH2. This may be due to a higher level of energy action in the EDM involving this electrode.

The obtained values (Table 2) of the characteristic dimensions of the structural elements of the surface show that in the modified samples, compared to the initial state, they decrease by 8–13 times. The minimum dimensions of the parameter D were obtained when machining with the electrode SH2 [1, 18].

In order to study the effect of frictional interaction of polymer counter-specimen with metal samples after EDM on the topography of friction surfaces, we studied the friction surfaces at the atomic-force (k-ASM) and raster electron microscopes (Fig. 8, 9).

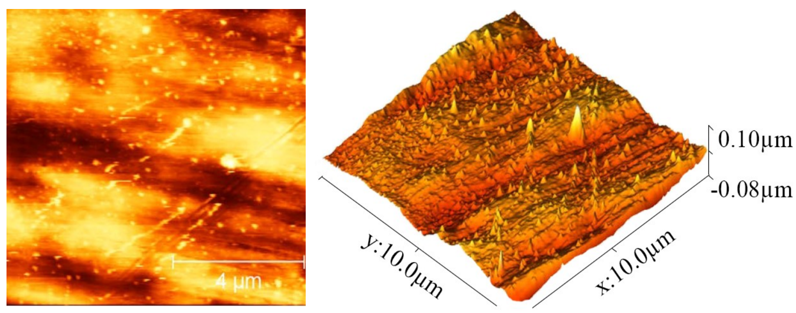
Images of the surfaces of samples acquired from contact atomic-force microscopy show that the topography of surfaces on the friction path and beyond the track differ (Fig. 8). Fig. 8 shows that the height of surface irregularities in areas after friction is higher than on areas of the surface outside the friction path. This may be due to the formation of friction transfer film on the samples' surface.



2D 3D

a *b*

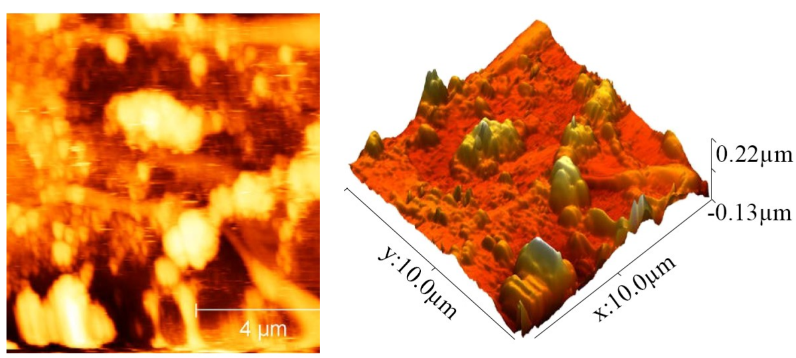
Fig. 5. Topography of the sample surface treated with the electrode T15K6 under the modes of U=120 V; C=34 µF (E=0.25 J): *a* – two-dimensional plane; *b* – three-dimensional plane



2D 3D

a *b*

Fig. 6. Topography of the sample surface treated with the electrode SH2 under the modes of U=80 V; C=150 µF (E=0.48 J): *a* – two-dimensional plane; *b* – three-dimensional plane



2D 3D

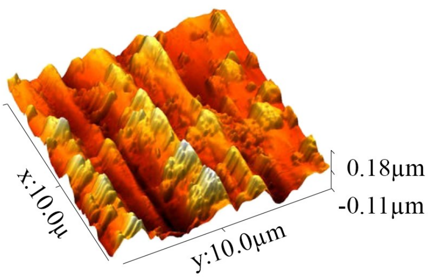
a *b*

Fig. 7. Topography of the sample surface treated with the electrode IMKH2 under the modes of U=160 V; C=240 µF (E=3.07 J): *a* – two-dimensional plane; *b* – three-dimensional plane

Table 2

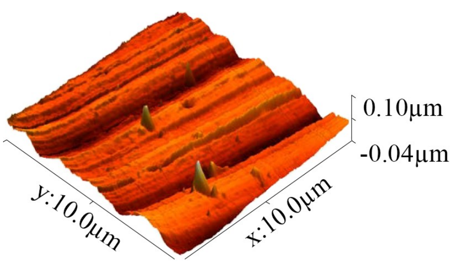
Surface parameters of starting and modified samples

Sample/Parameter	The characteristic size of the structure *D*, nm	*Ra*, µm	The height of the largest protrusion of the profile *Rp*, nm	Depth of the largest depression of the profile *Rv*, nm
Steel 15KHGN2TA (starting)	2,000–2,500	≈1.6	379.0	344.8
Coating AE T15K6	200–250	≈2.5	477.3	378.5
Coating AE SH2	150–200	≈3.2	504.1	485.7
Coating AE IMKH2	250–300	≈6.3	538.3	484.4



friction path

a



beyond the friction path

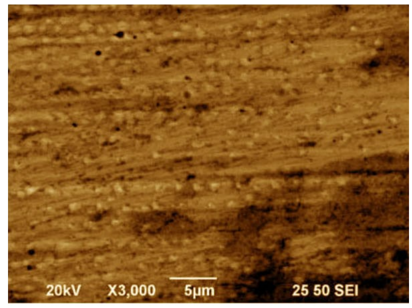
b

Fig. 8. Topography of the surface of the sample of steel 15KHGN2TA, machined with the electrode IMKH2 (U=120 V; C=150 µF; t=4 min/cm^2), after friction and wear tests: *a* – friction path; *b* – beyond the friction path

5. 3. Results of studying the micro-hardness and tribotechnical properties of coatings of steel samples

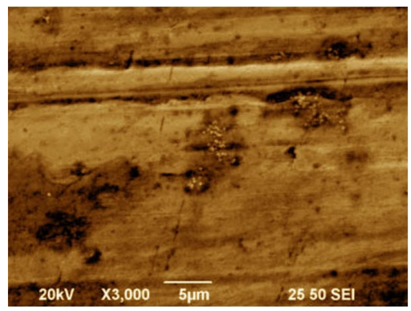
Fig. 9 shows the images of surfaces after tribotechnical tests acquired by raster electron microscopy. The surface areas of the samples on the friction path differ markedly from the surface areas outside the track. On the friction path, a polymer film of friction transfer (FT) structured in the direction of sliding is clearly visible. On the site next to the friction path, there is an island coating without FT film [15]. Thus, it was established that during the friction interaction of steel samples exposed to EDM, a thin FT film is formed with polymeric counter-cracks on the friction surface of steel samples. This leads to a change in the topography of surfaces with an increase in the height of micro irregularities and the structure-formation of the transfer film in the direction of sliding.

We estimated the tribotechnical properties of structures formed on a steel basis at EDM by the rate of the wear of polymer counter-samples at sliding friction over the modified surface of steel samples [18, 19]. Steel samples were machined with an IMKH2 electrode. In order to obtain a clear idea of the effect of the level of energy action on the wear resistance (wear rate) of a friction pair, we built $J=f(E)$ dependences based on the test results (Fig. 10).



friction path

a



beyond the friction path

b

Fig. 9. The surface of the sample made of steel 15KHGN2TA, machined with an IMKH2 electrode (U=120 V; C=150 µF; t=4 min/cm^2), after friction and wear tests: *a* – friction path; *b* – beyond the friction path

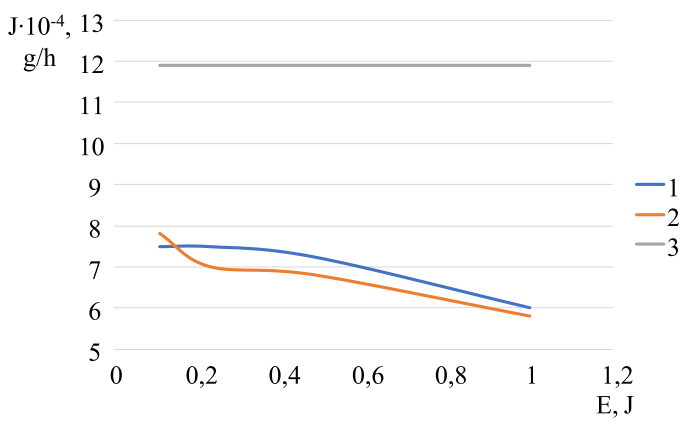


Fig. 10. Dependence of the wear rate of polymer counter-samples on pulse energy during the electrical discharge machining of samples made from steel 15KHGN2TA: 1 – samples with the duration of electrical discharge machining of 4 min/cm^2; 2 – samples with the duration of electrical discharge machining of 5 min/cm^2; 3 – sample tempered without electrical discharge machining

The dependences in Fig. 10 of the wear rate of polymer counter-samples make it possible to conclude that with an increase in pulse energy when steel samples are exposed to EDM, the wear rate of a polymer counter-sample is reduced by 1.2–1.3 times. At the same time, the increase in the duration of EDM has a slight impact on the wear rate of polymer counter-samples (by ~3 %). It was also shown that the wear rate of a metal-polymer friction pair with samples modified by EDM is less than this parameter in a pair of friction with a tempered sample, by about 1.6–2 times.

6. Discussion of results of the experimental study into steel samples modification using the technology of electrical discharge machining

In determining the mechanism of formation of coatings of different phase compositions, depending on the chemical composition of AE, X-ray phase analysis of surfaces of the modified samples was carried out. Our results of the experimental studies into steel samples modification using the technology of their electrical discharge machining confirmed that the phase composition of coatings is determined by the chemical composition of AE [20]. It was established that the thickness of the formed coating depends on the chemical composition of the material of the alloying electrode and the energy modes of EDM. Thus, the largest thickness of the coating is formed when using the electrode IMKH2, which is 4 times more than when applying a standard electrode T15K6. Increasing the energy modes of EDM leads to an increase in the thickness of the coating regardless of the AE material, which makes it possible to recommend EDM using the electrodes T15K6, IMKH2, SH2 to increase the wear resistance and restore worn surface parts of friction units in machines. It was established that the micro-hardness of coatings depends on the modes of EDM and AE material. The experimental dependences of coating micro-hardness on the voltage and discharge capacity of capacitors are of an extreme nature with highs at voltage U=120–140 V and discharge capacity C=120 μF [21].

Charts (Fig. 2) for the thicknesses of coatings on steel samples with various materials of electrodes also show that when EDM involves the electrode IMKH2 based on tungsten carbide with the additives of components forming unlimited solid solutions with the base material, the largest coating thickness (210 μm) is obtained. This can be explained by the fact that the introduction of boron and silicon into the AE composition slows down the formation of oxide films in the created structure, which has a positive effect on the solidity and increases the thickness of the coating. In addition, the introduction of boron reduces the erosion resistance of AE, as a result of which the mass carrier of the electrode material to the treated surface increases. The use of the SH2 electrode also leads to the formation of coatings exceeding the thickness of coatings formed by the T15K6 electrode, by 1.7–2 times [1, 22]. This is due to the fact that the mineral raw materials (scheelite concentrate) in the composition of the electrode material creates a protective atmosphere in the EDM zone, preventing the burnout of erosion particles and contributing to the intensification of the mass transportation of the electrode material. The results of studying [1, 17] steel samples in terms of the structure and phase composition of coatings make it possible to use EDM to restore the worn surfaces of precision friction pairs in the range to 100 μm.

The results of analyzing the chemical composition of samples (Table 1), machined with the electrodes T15K6, SH2, and IMKH2, show that the element composition of the initial surface of the sample of steel 15KHGN2TA differs from the composition of coatings and surface layers of the samples modified by EDM with various electrodes. The modified samples did not reveal the presence of a series of 15KHGN2TA steel elements: chromium, manganese, and nickel, when machined with the electrode T15K6; chromium and manganese when machined with the electrode SH2; manganese and titanium when machined with the electrode IMKH2. At the same time, the presence of tungsten (AE T15K6), oxygen (AE SH2), and silicon (AE IMKH2) was established, which can be explained by the erosion of alloying elements and their low concentration in steel, as well as the interaction of electrodes elements with steel.

A method of contact atomic-force microscopy was used to determine a significant (by 8–13 times) reduction in the characteristic size of the structural elements (D) in coatings formed by EDM using various electrodes, compared to the initial (unmodified) surface. It was also established that at EDM, surfaces with high roughness parameters (*Ra, Rv, Rp*) are formed, characteristic and commensurate with similar surface parameters obtained during pure machining [23]. At the same time, as a result of EDM using the IMKH2 electrode, there is the largest increase in the roughness parameter *Ra*, by 3.9 times, which is explained by a higher level of energy action when applying this alloying electrode [24].

The joint effect of voltage and discharge capacity in EDM causes a decrease in the wear rate. To improve the wear resistance of a friction pair, it is necessary to increase the discharge capacity and anode-cathode voltage.

Therefore, the further direction of research is to establish optimal modes for EDM using the method of planning a factor experiment and statistical treatment of data to be obtained. And to study the impact of EDM modes for steel surfaces on the wear resistance of the metal-polymer tribosystem.

7. Conclusions

1. We have investigated the relationship between the physicochemical processes of energy mass transportation and the formation of modified structures in a surface layer and the wear-resistant coatings on the surfaces exposed to EDM. The greatest effect of increasing the micro-hardness is demonstrated when EDM involves the electrode IMKH2 with a voltage of U=140 V and a capacity of C=120 μF. When machining with the electrode T15K6, the maximum micro-hardness was obtained at voltage U=120 V and capacity C=150 μF.

2. The regularities of the process of surface modification of 15KHGN2TA steel and the formation of wear-resistant coatings reflecting the influence of the chemical composition of the material of electrodes and processing modes on element and phase compositions, thickness, micro-hardness, and wear resistance of formed coatings have been established. The largest increase in the roughness parameter *Ra*, to 6.3, and the parameter *RP*, to 538.3 nm, is observed when machining using the electrode IMKH2.

3. We have established the experimental dependences of the wear rate of metal-polymer friction pairs on the technological modes of EDM of steel parts. This mechanism, elucidated on the basis of tribological studies, could make it possible to achieve the specified parameters for the wear resistance of friction pairs. With an increase in pulse energy at EDM of steel samples, the wear rate of a polymer counter-sample decreases by 1.2–1.3 times.

References

1. Alimbaeva, B. Sh., Marchenko, D. D. (2009). Poverhnostnoe uprochnenie stal'nyh detaley s pomoshch'yu tekhnologii elektroiskrovogo legirovaniya. Povyshenie nadezhnosti i prochnosti detaley pri remonte s vnedreniem perspektivnyh metodov uprochneniya: materialy mezhdunarodnoy nauchno-prakticheskoy konferentsii, 8 (09), 154–178.
2. Bayati, M. R., Molaei, R., Janghorban, K. (2011). Surface alloying of carbon steels from electrolytic plasma. Metal Science and Heat Treatment, 53 (1), 91–94. doi: https://doi.org/10.1007/s11041-011-9347-5
3. Bunshah, F. (2001). Handbook of Hard Coatings. Deposition Technolgies, Properties and Applications. William Andrew, 560.
4. Kanayev, A. T. (2008). Plasma Surface Hardening of Crests of Wheels of a Rolling Stock. Materialy IV Mezinarodnivedecko-prakticka conference VEDA TEORIE A PRAXE-2008. Praha, 56–60.
5. Meletis, E. I., Nie, X., Wang, F. L., Jiang, J. C. (2002). Electrolytic plasma processing for cleaning and metal-coating of steel surfaces. Surface and Coatings Technology, 150 (2-3), 246–256. doi: https://doi.org/10.1016/s0257-8972(01)01521-3
6. Newbery, A. P., Grant, P. S. (2009). Arc Sprayed Steel: Microstructure in Severe Substrate Features. Journal of Thermal Spray Technology, 18 (2), 256–271. doi: https://doi.org/10.1007/s11666-009-9300-y
7. Mazhyn, S., Laila, Z., Michael, S. (2012). Electrolytic-plasma cementation influence of regimes on phase structure and steel 30CrMnSi hardening. 2012 7th International Forum on Strategic Technology (IFOST). doi: https://doi.org/10.1109/ifost.2012.6357723
8. Ulianitsky, V., Shtertser, A., Zlobin, S., Smurov, I. (2011). Computer-Controlled Detonation Spraying: From Process Fundamentals Toward Advanced Applications. Journal of Thermal Spray Technology, 20 (4), 791–801. doi: https://doi.org/10.1007/s11666-011-9649-6
9. Witke, T., Schuelke, T., Schultrich, B., Siemroth, P., Vetter, J. (2000). Comparison of filtered high-current pulsed arc deposition (φ-HCA) with conventional vacuum arc methods. Surface and Coatings Technology, 126 (1), 81–88. doi: https://doi.org/10.1016/s0257-8972(00)00544-2
10. Yerokhin, A. L., Nie, X., Leyland, A., Matthews, A., Dowey, S. J. (1999). Plasma electrolysis for surface engineering. Surface and Coatings Technology, 122 (2-3), 73–93. doi: https://doi.org/10.1016/s0257-8972(99)00441-7
11. Lewis, S. R., Lewis, R., Olofsson, U. (2011). An alternative method for the assessment of railhead traction. Wear, 271 (1-2), 62–70. doi: https://doi.org/10.1016/j.wear.2010.10.035
12. Lewis, S. R., Lewis, R., Richards, P., Buckley-Johnstone, L. E. (2014). Investigation of the isolation and frictional properties of hydrophobic products on the rail head, when used to combat low adhesion. Wear, 314 (1-2), 213–219. doi: https://doi.org/10.1016/j.wear.2013.11.024
13. Bhushan, B. (2013). Introduction to Tribology. John Wiley & Sons. doi: https://doi.org/10.1002/9781118403259
14. Zaspa, Y., Dykha, A., Marchenko, D., Matiukh, S., Kukurudzyak, Y. (2020). Exchange interaction and models of contact generation of disturbances in tribosystems. Eastern-European Journal of Enterprise Technologies, 4 (5 (106)), 25–34. doi: https://doi.org/10.15587/1729-4061.2020.209927
15. Dykha, A., Marchenko, D., Artyukh, V., Zubiekhina-Khaiiat, O., Kurepin, V. (2018). Study and development of the technology for hardening rope blocks by reeling. Eastern-European Journal of Enterprise Technologies, 2 (1 (92)), 22–32. doi: https://doi.org/10.15587/1729-4061.2018.126196
16. Butakov, B. I., Marchenko, D. D. (2013). Promoting contact strength of steel by rolling. Journal of Friction and Wear, 34 (4), 308–316. doi: https://doi.org/10.3103/s106836661304003x
17. Marchenko, D. D., Dykha, A. V., Artyukh, V. A., Matvyeyeva, K. S. (2020). Studying the Tribological Properties of Parts Hardened by Rollers during Stabilization of the Operating Rolling Force. Journal of Friction and Wear, 41 (1), 58–64. doi: https://doi.org/10.3103/s1068366620010122
18. Raskin, L. G., Seraya, O. V. (2008). Nechetkaya matematika. Kharkiv: Parus, 352.
19. Hartman, K., Letskiy, E., Shefer, V. et. al. (1977). Planirovanie eksperimenta v issledovanii tekhnologicheskih protsessov. Moscow: Mir, 552.
20. Mezrin, A. M. (2009). Determining local wear equation based on friction and wear testing using a pin-on-disk scheme. Journal of Friction and Wear, 30 (4), 242–245. doi: https://doi.org/10.3103/s1068366609040035
21. Togawa, K., Arai, S., Uwatoko, M. (2012). Influence of Traction Sheave P.C.D. Difference on Sheave and Rope. The Proceedings of the Elevator, Escalator and Amusement Rides Conference, 2011, 31–34. doi: https://doi.org/10.1299/jsmeearc.2011.31
22. Dykha, A., Marchenko, D. (2018). Prediction the wear of sliding bearings. International Journal of Engineering & Technology, 7 (2.23), 4. doi: https://doi.org/10.14419/ijet.v7i2.23.11872
23. Ryu, J. B., Chae, Y. H., Kim, S. S. (2005). A Fundamental Study of the Tribological Characteristics of Sheave Steel against a Wire Rope. Key Engineering Materials, 297-300, 1382–1387. doi: https://doi.org/10.4028/www.scientific.net/kem.297-300.1382
24. Erdonmez, C., Imrak, C. (2009). Modeling and numerical analysis of the wire strand. Journal of Naval Science and Engineering, 5 (1), 30–38. Available at: https://dergipark.org.tr/tr/download/article-file/105285