ELIMINATION OF IRREGULARITIES AND DEFECTS ON STEEL SURFACES THROUGH ELECTRO SPARK SURFACE MODIFICATION WITH ALUMINUM ALLOYS

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Abstract

The surface roughness of the parts has a significant influence on their performance properties and it is crucial for the friction force and wear of the bodies. Therefore, in practice it is often necessary to perform finishing treatment to reduce the macro, micro and meso- roughnesses - grinding, honing, lapping, polishing and more. In this study are examined the possibilities of reducing the roughness and the traces of the previous machining of steel surfaces by electro-spark deposition (ESD) with low-melting aluminium alloys. The roughness of the steel surfaces obtained after different milling modes after subsequent electrospark coating was investigated. Dense and uniform coatings with different surface microgeometry are obtained, which to a different extent erase the traces of the preceding processing. The examination of tribological characteristics showed a significant increase in the wear resistance of the coated surfaces. The process parameters and materials for ESD at which coated surfaces have simultaneously the lowest roughness and the highest wear resistance have been determined and optimized.

Keywords: *coatings, electrical spark deposition, electrodes, wear resistance, roughness*

1. INTRODUCTION

The increasing efficiency and service life of numerous friction components, machine mechanisms, and aggregates, especially of those working in extreme and variable conditions when in the contact area are developing high temperatures, variables tensions and speeds of deformation through hardening and wear-resistance coatings is one of the most important resources of contemporary tribology, materials science, and engineering.

Most of the existing methods and technologies for applying wear-resistant coatings however are realized through complicated and expensive equipment and require high investment. Because of its simplicity and versatility, the electrical spark deposition - ESD with his accessible and portable equipment, easy technology and universality are not only more widespread, but also significantly cheaper, and fully accessible to most consumers (Gitlevich et al. 1985, Nikolenko, & Verkhoturov 2005, Ivanov, Verkhoturov & Konevtsov 2017, Penyashki & Kostadinov 2013).

Compared to existing methods and technologies ESD has the following advantages: simplicity and availability of technology, high strength of the bond of the coating to the substrate - one of the strongest bonds with the substrate material compared to other methods - at the level of the strength limit of the material itself; insignificant heating and deformation of the base material; ecological compatibility; low costs for materials and energy; simplicity of technological operations, possibility for operation without additional processing, possibility in a wide range for change of the properties of the metal surfaces.

The method is based on the use of pulsed plasma discharges with controlled energy in the air. As a result of the electrospark discharges, melting and evaporation of particles from the laminating electrode (anode) occurs, which at extremely high-speed strikes and stick to the surface of the substrate (cathode). The material eroded by the electrode is transferred to the substrate in a vapor, liquid, and solid (softened) phase. The same is mixed with the locally melted micro spot of the substrate to form a surface layer of a mixture of the two materials, new compounds and phases derived from their chemical interaction and from the reactions with the materials from the environment.

The ratio between these phases and the size of the single portions of applied anode material depends on the processing energy and the type of anode and cathode material (Gitlevich et al. 1985, Verkhoturov & Nicolenko 2010, Ivanov, Verkhoturov & Konevtsov 2017). A new relief coating with ultrafine structure and particle sizes up to the nano-level is formed. The formation of a hardened surface layer and coating at ESD is a result of complex plasma-chemical, thermal, and mechano-thermal processes occurring on the local surface areas of the workpiece under the influence of the energy of a spark discharges. The formed layer gives the product different from the initial state surface properties, which are controlled in a wide range by changing the parameters of the spark discharge and the composition of the electrode material. The short duration of the electrical impulse of -5-200μs leads to an extremely fast hardening of the deposited material, which results in a new structured coating showing unique tribological and corrosion efficiency.

The method allows the application of coatings with a thickness usually of 3-100 and more μm from any and on any conductive materials, but most often used are hard-alloy composite materials based on WC, TiC and TiN. The main disadvantage of electrospark hardening is that with an increase in the thickness of the applied coating, its roughness increases, which negatively affects its performance properties. Through ESD the physicochemical and geometrical characteristics of the surface layer can be changed and modified in a given direction to give certain properties - an increase of wear- or corrosion resistance, temperature resistance, a decrease of resistance of electric contacts, increase or decrease of hardness and coefficient of friction and etc (Penyashki & Kostadinov 2013).

In this regard, the object of research is to study the possibilities for reducing surface defects and roughness obtained from previous treatments - (mechanical, "3D" printers, etc.), by creating coatings of suitable electrode materials and a comparative study of the structure, the phase composition and the tribological characteristics of the obtained coatings

2. MATERIALS AND METHODS

2.1. Materials, Equipment for ESD and deposition conditions.

Substrate. Model plates of carbon steel with 0,5%C - (steel 50) with hardness 190-210HB, with sizes 12×12×5 mm, and different roughness obtained by transverse turning are used for substrate. The chemical composition of these steels is given in Table 1.

Table 1. Chemical composition of substrate plates

Element, %	C	Cr	Si	Mn	Ni	Mo	W	Ti	Cu	V	P	S
steel 50	0.47-0.55	up to 0.25	0.17-0.37	0.5-0.8	up to 0.25	-	-	-	up to 0.25	-	up to 0.04	up to 0.04

A hand-held apparatus with vibrating movement of the electrode “Hardedge” (Fig.1) with the following parameters performs the ESD: short circuit current - 0.2÷2A, Voltage - 80V, Capacity - 1.5-20μF, oscillation frequency of the vibrator - 100 Hz. The individual layering modes are numbered from 1 to 6 in order of increase of pulse energy. In this work was used regimes with single pulse energy $E_i=C.U^2/2=0.01\div0.065J$. The individual layering modes are numbered from one to six in the order of increase of pulse energy given in Table 2.

Fig. 1. Device for Manual electrical discharge deposition with vibrating electrode "Carbide Hardedge" created by Aids Electronics Ltd - England, USA

Table 2. Regimes for ESD whit vibrating electrode

№ of regime	1	2	3	4	5	6
Capacity, µF	1.5	3.5	5	7	10	20
Single pulse energy, J	E_1≈0.005	E_2≈ 0.01	E_3≈0.02	E_4≈0.025	E_5≈0.032	E_6≈0.065

2.2. Coating materials

It is recommended that aluminum electrodes be used to increase the corrosion resistance, wear resistance and heat resistance of a number of steels (steel 08, St. 3, U10A, HVG) and titanium alloys (VT0, VT2) (Nikolenko, Verkhoturov & Syui 2015, Nikolenko & Verkhoturov 2005, Cadney et al. 2009, Milligan, Heard & Brochu 2010, Mukanov et al. 2019). In (Milligan, Heard & Brochu 2010, Mukanov et al. 2019), the prospects of using electrodes made of aluminum and silumin Al-Si for the ESD treatment of tungsten-containing hard alloys were shown.

The use of electrodes of low-melting alloys of aluminum (Al) with silicon, Al-Si as a result of plasma discharges will make it easier to melt and penetrate the melt and fill the scratches obtained after machining. Composite materials of Al-Si alloy were selected for electrodes to provide both high wear resistance, much higher amount of transfer from the liquid phase and obtaining new additional wear resistance in the process of forming the coatings.

2.3. Methodology of measurements.

- The surface roughness Ra, µm and thickness B, µm of the resulting coatings are measured by using profilometer - AR-132B and Pocket Leptoskop 2021 Fe. A VT-300 digital microscope monitored density, uniformity and morphology of coatings. The results are derived from arithmetical mean, standard deviation and confidence interval of 15 parallel measurements. Sharply diverging values are rejected by the method of Grubbs.

- The initial indicative determination of the surface hardness of the coatings was performed with hardometer Al 150A.

-The microstructure of the coatings have been studied by optical microscopy on cross-sectional sections by metallographic optical microscopy (Neophot 22, Carl Zeiss Jena).

- The phase identification, the distribution of elements in the surface layer and microstructural analysis of the coatings along with the interface region were performed with the support of an X-ray diffractometer Bruker D8 Advance in cobalt "Kά" and Cu radiation tube, an optical microscope, and an electron microscope "Bruker"; by scanning electron microscopy (SEM) and transmission electron microscopy.

- The tribological properties and wear resistance of the coatings are investigated by comparative tests of friction with tribotester type "Thumb -disk" under dry surface friction with hard-fixed abrasive particles. The wear characteristics test method consists in measuring the mass wear m of the samples for a specific friction path L (friction cycles) under constant conditions - load P and glide speed V.

Calculated are the following wear characteristics:

- Mass wear - $m = m_o - m_i$, mg

-Specific wear (i_s): the ruptured mass of friction from the surface layer for normal load P=1N per friction path L=1m and nominal contact area Aa=1mm^2: $i = m / S$, mg/Nm

- Wear intensity - the amount of wear per unit of friction work: $i = m / S$, mg/m

- Wear resistance ($I = 1/i = S/m$), m/mg, Reciprocal value of the wear intensity

Table 3 gives the experimental conditions for testing the wear of the test coatings.

Table 3. Parameters of the experiment in studying the wear of the tested ESD coatings

№	**Parameter**	**Value**
1	Normal load	P = 5 N
2	Nominal contact area	A_a = 2.25 cm^2
3	Nominal contact pressure	P_a = 2.22 N/cm^2
4	Speed of rotation	n = 212 min^{-1}
5	Distance between the axis of rotation and the center of the contact site	R_c = 34 mm
8	Sliding speed of the contact center site	V_c = 0.8 m/s
9	Ambient temperature	T^o = 20^{o}C
10	Abrasive surface	Corund P 320

3. RESULTS AND DISCUSSION

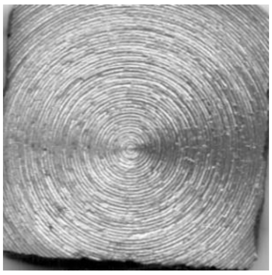
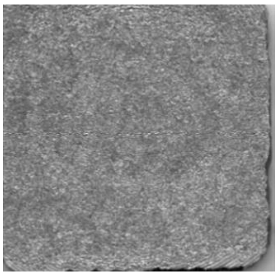
3.1. Coating characterization - Roughness Ra and thickness δ, structure and micro-hardness of coatings

Initially, in a wide range of values of technological parameters with each of the tested electrodes were applied coatings on steel substrates. The obtained results show that the increase of the energy of the impulses (in the direction from mode 3 to mode 6 - Table 2) leads to an increasing in the thickness of the obtained coatings, but significantly increase and their roughness and unevenness.

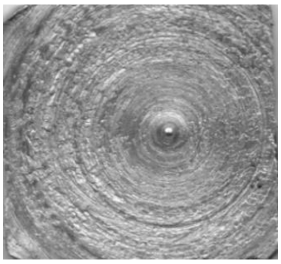
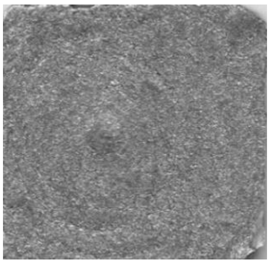
After visual comparative evaluation of the uniformity, density, roughness, grain size, porosity of the coatings deposited at modes with different puls-energy, were selected conditions suitable for ESD in which are obtained dence, uniform and fine-grained coatings.

The results obtained show that ESD coatings in most cases do not need further processing. They have improved geometrical characteristics – high density and uniformity, lower roughness, and lower scratches and bumps than those of the initial surface. The maximum thickness at which is obtained a relatively uniform coating with surface roughness up to Ra=3÷4μm is in the range of 10÷15 μm at regime № 5 with pulse energy E_5≈0.032J.

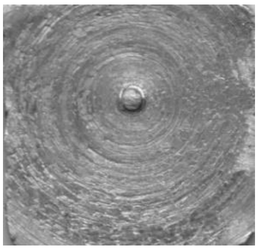
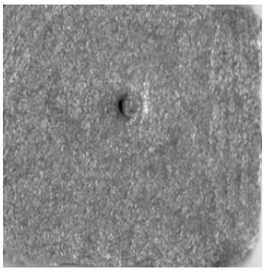
On the substrates with different roughness are obtained similar in structure coatings - Fig. 2. The results obtained show that ESD coatings in most cases do not need further processing. They have improved geometrical characteristics – high density and uniformity, lower roughness, and lower scratches and bumps than those of the initial surface. The maximum thickness at which is obtained a relatively uniform coating with surface roughness up to Ra=3÷4μm is in the range of 10÷15 μm at regime № 5 with pulse energy E_5≈0.032J.

a)Sample 1 - before ESD after tourning b) Sample 1 - after ESD

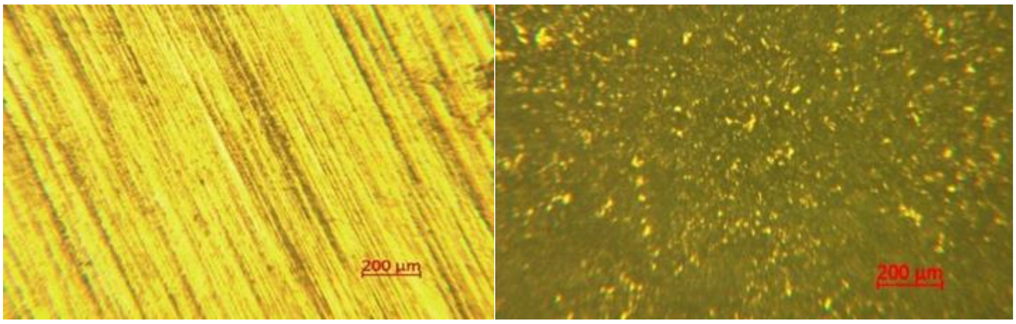
c) Sample 2 - before ESD after tourning d) Sample 2 - after ESD

e) Sample 3 - before ESD after tourning g) Sample 3 after ESD

Fig. 2. General appearance of st.50 plates with different roughness before and after ESD with Al-12%Si electrode

Coatings applied to ground steel surfaces after finishing machining turning, milling, and grinding significantly, change the morphology of the surface - Fig. 3, but their roughness is higher than that of uncoated plates. Despite the higher values of roughness, the wear resistance of the coating retains its higher values than those of the substrate (Penyashki & Kostadinov 2013, Penyashki et al. 2016).



a) the initial sanded surface b) the surface after ESD

Fig. 3. General appearance of initial sanded surface (a) and the same after ESD

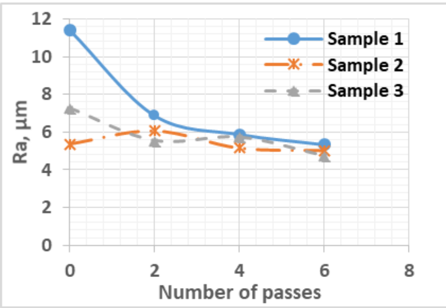
Homogeneous, dense and adherent coating layers with good repeatability of the qualitative characteristics have been obtained during ESD experiments. It is evident that the coatings form on the surface of the steel a heterogeneous structure with a specific relief. In this structure are, differentiate electroerosion craters and the smooth sections between them.

Table 4 shows the change in the roughness parameters Ra, Rz, Rt Rq, and the dispersion of uncoated samples 1, 2, 3 (Fig. 2a,c,e) and the same samples at ESD with two, four, and six passes of the electrode. The layering was performed with an electrode Al-12% Si in mode 4, Table 2 (E_4≈0.025J).

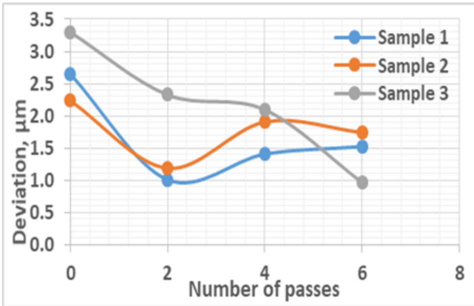
Fig. 4 a, b, c) displays the change in the average value of the roughness Ra of coatings and his dispersion and coefficient of variation (Table 4). The figure shows that at ESD the initial roughness of the samples decreases. The variance and the coefficient of variation also decrease. As the number of electrode passes increases, the roughness of the coatings continues to decrease but more slightly. The above trend is most pronounced in sample 2, which has the highest initial roughness and unevenness. At sample 1, the trend is maintained but is less pronounced, but at sample 3, which has the lowest initial roughness, in the second pass of the electrode the roughness of the coating increases slightly, and in the 4th and at the 6th pass decreases slightly, and its values are close to the initial ones. Moreover, for each number of electrode passes, the values of the roughness of the coatings at all three samples are close to each other, regardless of the different initial roughness of the uncoated samples.

This shows that ESD can be successfully used to reduce the initial roughness when it is higher than a certain value - in this case at Ra≥ 6-7µm. After applying a coating to a surface with an initial roughness of Ra≥6µm, all height and step parameters of roughness decrease on average 1.15 to 1.5 times compared with the roughness parameters of the initial surface. The coefficient of variation and the dispersion after ESD in the second pass of the electrode also decrease, but in the following passes, they increase slightly. Therefore, ESD can also be used to reduce scattering and for leveling the relief of the original surfaces.

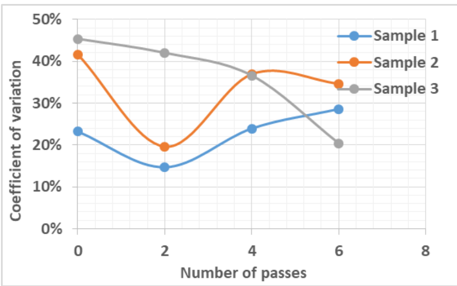
The thickness of the coatings also increases, with each subsequent pass the increase is less than that of the previous one. The increase is more pronounced until the third pass of the electrode.



a)



b)



c)

Fig. 4. Change in average roughness (Ra), dispersion, and coefficient of variation after ESD with 2, 4, and 6 electrode passes.

Table 4. Roughness and dispersion of the coatings after 2, 4 and 6 electrode passes.

№ Sample		Without coverage				ESD with two pass				ESD with four pass				ESD with six pass			
		Ra	Rz	Rq	Rt	Ra	Rz	Rq	Rt	Ra	Rz	Rq	Rt	Ra	Rz	Rq	Rt
Sample 1	Avg.	11.40	34.58	11.22	41.46	6.87	20.11	6.87	21.2	5.87	16.61	5.84	17.7	5.33	15.07	5.48	15.61
	Dispersion	2.65	9	2.75	17.47	1.01	4.34	1.35	4.86	1.41	3.98	1.25	4.86	1.52	4.31	1.55	4.71
Sample 2	Avg.	5.37	15.11	5.40	16.17	6.05	17.11	5.88	17.6	5.16	15.41	5.41	16.2	5.03	14.22	4.90	11.66
	Dispersion	2.24	6.32	2.10	7.43	1.19	3.36	0.81	3.82	1.91	6.0	2.05	6.75	1.74	4.92	1.52	6.31
Sample 3	Avg.	7.27	20.56	7.01	21.35	5.54	19.68	6.80	20.7	5.73	19.02	6.47	20.1	4.73	13.1	4.98	14.58
	Dispersion	3.30	9.33	3.11	9.76	2.33	8.45	2.98	9.14	2.10	8.84	2.43	9.99	0.97	2.91	1.02	3.47

It is noteworthy that the roughness of the coatings applied on all three samples (Fig. 4a)) is close, especially at the 4th and 6th electrode passages, and is within the scattering despite the significant differences in the values of the initial roughness of the samples. This allows us to conclude that regardless of the different initial roughness of the steel surfaces, with an increasing number of electrode passes, the differences in the values of the roughness of the applied coatings gradually decrease and after the second pass the roughness of the coatings becomes almost the same.

After the process of ESD in the modes with low energy of the pulses is observed reduction in the parameters of surface roughness, but the obliteration of the deep scratches and traces of the cutting edges of the tool is partially and only in some cases it is full. To reach a complete obliteration it is necessary to use modes with higher energy, but in these cases, the roughness of the coatings will also be higher. In these cases, too a decrease in the initial roughness is observed, but in a lesser extent, but a further increase in the energy of the pulses can lead to a lack of changes in the initial parameters of the surface roughness.

Figure 5 shows the microphotography of general appearance of the coated surface and the relief of coatings from Al-12%Si applied by vibration ESD on 50 steel.

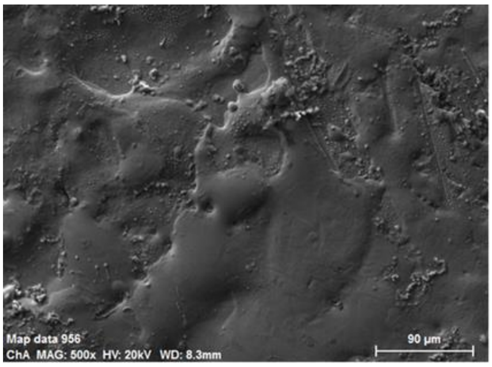


Fig. 5. Microphotography of coatings from Al-12%Si applied by vibration and ESD on 50 steel

The images of the microstructures obtained on the surface of the coatings indicate the formation of a coating from a melt. The sections with a structure similar to amorphous are observables and distinguishable.

The coating layers produced by the ESD with 4 passes of the electrode applied in mode №4 -Table.2. is shown in Fig. 6.

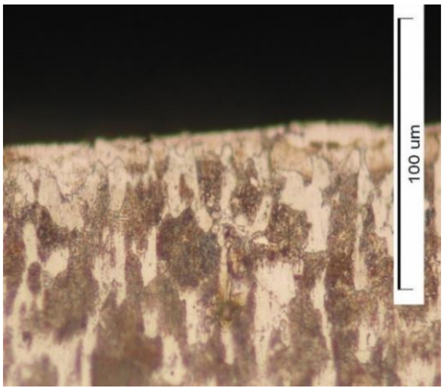


Fig. 6. Cross-section microphotographs of microstructure of coatings applied by ESD on steel 50 at regime 4-Table 2 with 4 passes of the electrode

The ESD coating - Fig. 6 represents a white uniform layer with a thickness about of 12-15 microns. The coatings have a compact and uniform microstructure with a low degree of porosity, and certain degree of mixing with the substrate is observed along the boundary.

Microscopic unevenness is observed in different locations on the surface of the coatings in the cross-section. However, are seen a uniform, equal, dense layers, without visible microcracks and gaps, snugly connected with the substrate.

The hardness of coatings applied by vibration ESD with the Al-Si varies too widely and reaches up to 1.6-2.5 times higher values than those of the substrate and exceed the values of the corresponding initial hardness of the aluminum electrodes.

Based on the results of the tests are selected two operating modes with ESD- (regime 3 and 4) – Table2.

3.2. *Phase Composition of Coatings*

The results of X-ray analysis showed that at ESD with Al-Si electrodes the main phases in the coating composition are: martensite α- Fe, austenite γ-Fe, Al. The characteristic diffraction peaks of the substrate (α-Fe, γ-Fe) are present for all coated samples. They are broadened and displaced, which indicates the presence of superdispersed to an amorphous structure, solid solutions, crystal defects, and internal stresses (Penyashki et al. 2016). In small quantities (with a low intensity of peaks) and traces of Fe_3Al, FeAl, Fe_3Si, AlN, Si_3N_4, Al_2O_3, Fe_2O_3, Fe_3O_4 are registered and observed. The registered traces of Al_2O_3, as well as the traces of AlN and SiN, show that during the transfer process aluminum and silicon reacted with oxygen and nitrogen from the air, forming highly wear-resistant compounds.

The obtained results of X-ray diffraction analysis shows that the white layer is a mixture of disequilibrium heterogeneous finely grained martensitic-austenitic structure, saturated with modified ultra-disperse anodic components, solid solutions, intermetallic compounds and metastable (Penyashki et al. 2016) amorphous- like phases, whose part increases with increasing of energy for ESD.

3.3. Scanning Electron Microscopy Analysis of Coatings

Figure 7 show some of the results obtained by SEM analysis the distribution of the elements in coatings deposited by Al-12%Si electrodes via vibration ESD on 50 steel.

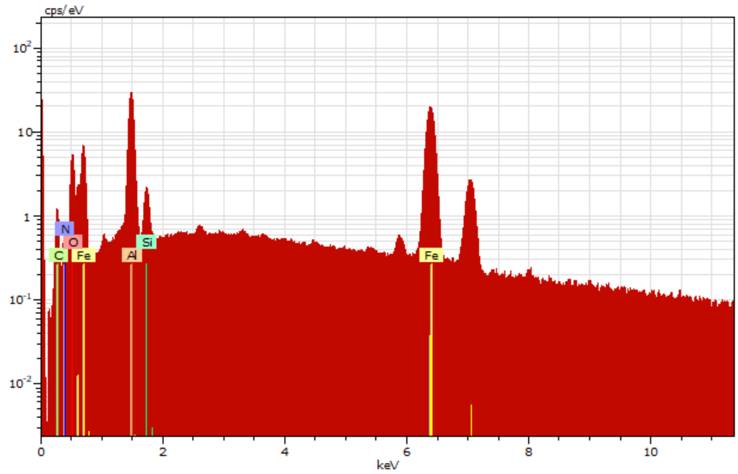


Fig. 7. Elemental composition of the coating deposited by Al-12Si electrodes on 50 steels

According to the data from the X-ray phase analysis and the CEM analysis, it can be judged that the elements of the substrate and the electrode material form new compounds both with each other and with the oxygen and nitrogen from the air. The quantitative microanalysis, of the coatings– Fig.7, detects the presence of Fe, Al, Si, C, F, N.

The distribution of Al and Si repeats that of O_2 and N, which confirms that Al and Si are present in a bonded form in the form of oxides and nitrides. Based on the data obtained, it can be concluded that the part of elements, that are not involved in the formation of oxides and nitrides, form a solid solution and intermetalides with the iron. The formation of a glass-like metal matrix- Fig.5 in the form of a solid solution is confirmed by the distribution of Al, Si, and Fe. In the course of the study, it was found that the distribution of Al and Si to some extent repeats the distribution of Fe, indicating that those elements form a solid solution.

The summary of the data obtained shows that the short pulse duration at ESD process causes extremely fast overcooling and solidification /rapid curing/ of the deposited onto the substrate melted particles from the electrode, resulting in the formation of a homogeneous in structure and heterogeneous in composition coatings with a fine super dispersed and amorphous structure.

3.4. Wear resistance of the coatings obtained

In Fig. 8 are given the results of the comparative experimental studies of the tribo-technical properties of the resulting coatings.

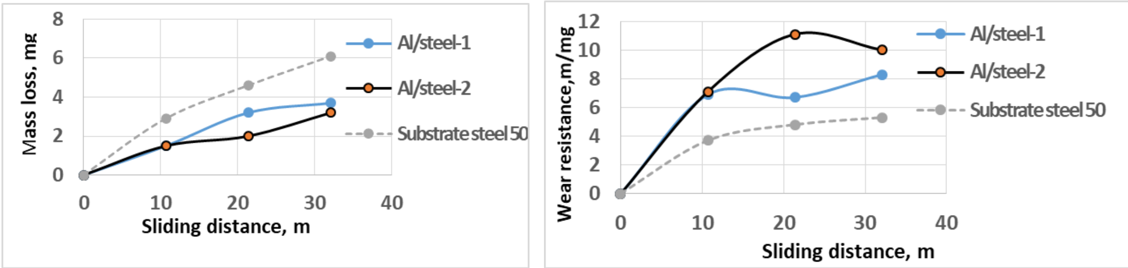


Fig. 8. Mass loss (a) and Wear-resictance (b), vs. sliding distance of tested coatings on 50 steel obtained by ESD processe of regime 3 (steel-1) and 4 (steel-2) (table 2)

From the results, it was established that the coated samples have 1.6 to 2 times lower wear than those of uncoated samples have. The lowest wear at ESD with electrode Al-12%Si samples is obtained in the pulse energy modes E_4=0.025J.

The classical surface microgeometric parameters (Ra, Rz, Rmax, tp, Sm, etc.) in this case do not reflect the actual situation of the friction contact. Coatings with higher values of Ra, Rz, Rmax have higher wear resistance than those with low roughness.

The higher roughness of the coatings obtained under regime 4 - Table2 implies a decrease in wear resistance (Kandeva 2012, Berkovich & Gromakovsky 2000), but obviously this is offset by the greater thickness and higher concentration of wear-resistant phases in the layer, as well as by the higher degree of dispersity and amorphous, i.e. the increase of the pulse energy has led to an increase in the wear resistance of the coatings.

Increased wear resistance apparently is ensured by the fine-grained and amorfous structure and of the presence of highly wear-resistant compounds in the electrical-spark coatings that allows the full benefits of each component to be utilized and to provide a higher wear resistance of the coating than that of the substrate. These coatings reduce the intensity of wear, slow down the development of wear over time, and can be used both to reduce surface defects and to increase the durability of friction steel surfaces and parts subject to abrasion wear.

CONCLUSIONS

1. The use of Al-Si alloy electrodes in ESD allows to obtain multifunctional coatings with good reproducibility and stability of the surface layer with a thickness of up to 15µm and a roughness of Ra up to 5µm. The maximum thickness at which relatively uniform coatings with surface roughness up to Ra=3 ÷ 4µm are obtained is in the range 10÷15µm at mode № 5 with pulse energy E_5=0,035J.
2. The use of ESD and electrodes of Al-Si alloy allows us to significantly improve the geometric characteristics of the surface layer of carbon steel - lower roughness, better uniformity, acceptable for practical repetition of quality characteristics, the ability to obtain coatings with a predetermined roughness and thickness through ESD modes.
3. Coatings applied on surfaces with a roughness of Ra≥6 µm make it possible to reduce both the roughness and surface defects from previous treatments (pores, cracks, traces of cutting edges, irregularities, etc.).
4. The obtained results show that in the ESD on carbon steels with electrodes of aluminum-silicon alloys allow the production of coatings with a high content of amorphous phases (metallic glass) and up to certain energy limits of the pulses allow simultaneous smoothing of surface irregularities and deep traces, and at the same time strengthen the surface and increase its durability up to two times.
5. It was found that the increased wear resistance of the obtained coatings is due to a double effect: structural changes in the thin surface layer and the formation of intermetallic compounds, wear-

resistant compounds, and amorphous phases, increase of the microhardness, and of the obliterating of the surface defects and formation of coatings with specific surface topography

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