Testing of the mathematical model application of the wear coating electro-spark method

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Abstract. The paper presents a metallographic investigation of samples of high-speed steel and structural steel with hard alloy coatings applied by electro-spark alloying. Metallographic investigation shows that there is a transition layer between the samples and their coatings where impurities of an electrode alloy material in the structure of the base material can be detected. This indicates that the technological process of the coating is accompanied by diffusion of the materials of the cathode and anode in the transition layer. Microhardness testing shows that the coating can be divided into two layers. The top layer consists of a reinforcing material of the electrode and the base material. It has high hardness, which decreases with the penetration of the coating into the sample because the coating and the base material is mixed. Also, there is the second transition layer, which has hardness lower than the hardness of the base material, i.e., in fact, a secondary temper layer. This layer is a result of high temperature exposure of the process of hardening. Metallographic investigation shows that physical-mechanical properties of the coating can be controlled by varying coating mode.

1. Introduction
Performance of automatic lines and production lines depends on the stability of their cutting tools. Breakage of tools and scheduled replacements increase downtime and reduce an equipment utilization rate.

Nowadays, the use of cutting tools made of high-speed steel does not meet increased requirements in mass production. On the other hand, the use of geometrically complex, composite cutting tools made of different hard alloys, ceramics and artificial super hard materials on technical procedures significantly increases their cost.

There are a significant number of methods of hardening using wear-resistant coatings. One of them is electro-spark alloying (ESA). Its advantages towards other hardening processes are:

1) a simplicity of the process flow diagram; 2) an implementation of the process in air; 3) after regrinding of the tool, re-coating is implemented without removing the old coating; 4) a possibility of coating of local zones of the working surfaces of parts. [1]

The process of electro-spark alloying is well studied. This method was developed almost a century ago and its physics has been described by many scientists [2, 3, 4]. Study of each coating material applied on a certain base material brings novelty towards the information about the method, as that enables to apply the analysing materials and coating modes in manufacture to obtain desired results fast. [5, 6, 7]
2. Description of the study

We developed a mathematical model of the process of coating by electric-spark alloying [8], in which one of the conditions is melting of the material of both electrodes that is an indicator of mixing of the electrode materials and inseparability of the coating from the base material. A resulting system of equations derived from the mathematical model is the following:

\begin{align}
W &= \frac{2\pi \cdot \lambda \cdot S_E \cdot T_P}{\eta \cdot F(k)}; \\
W &= \frac{\pi \cdot \rho \cdot L_{FE} \cdot d^3}{4 \cdot \eta \cdot p} \cdot h \cdot \nu; \\
W &\leq W_{max}; \\
W &\geq W_{min},
\end{align}

where \(W\) – the power of the generator; \(S_E\) – the cross-sectional area of the electrode; \(L_{FE}\) – the latent heat of melting of the electrode; \(T_P\) – the melting temperature of the electrode; \(\nu\) – the speed of the electrode; \(h\) – the height of the alloying electrode; \(\eta\) – the efficiency factor of the pulse generator.

In order to control the physical-mechanical properties, parameters and quality of the coating, previous metallographic investigations were analysed.

Research of the authors [9, 10, 11] shows that in most cases a layer emerged on the surface has the following properties: the thickness is 20-50 micrometres, the hardness is 2-2.5 times higher than the hardness of the base material, while the continuity of the coating is 60…90%.

High hardness of the emerged layer, significantly exceeding the hardness of the electrode and the base material for ESA of titanium by aluminium and nickel, is caused by a formation of a number of compounds (intermetallic compounds) between the anode and cathode, and also compounds of titanium with nitrogen and oxygen (nitrides and oxides).

Hence, we stated problems, first, to determine by metallographic investigation a relationship between the power of the generator, the speed of the alloying electrode and the thickness of the coating, and, second, to identify a presence of the transition layer, indicating ongoing diffusion processes and a microhardness distribution of the top layer of the sample with coating.

The process of hardening and its intensity can be judged by an influence of a condition of the top layer of the treated material on the modes.

Metallographic observation of the samples coated by a hard alloy, which properties can be found in table 1, was conducted to study the interaction of the coating with the sample material, to analyse a connection between the generator power, the electrode speed and the thickness of the coating and also to determine a thermal effect of ESA on the top layers of the sample material.

| Table 1. Electrode properties. |
|--------------------------------|
| The chemical composition of the electrode | Density, [g/sm³] | Hardness, [HRA] | \(\sigma\), [kg/mm²] |
|------------------------------------------|-----------------|----------------|------------------|
| TiC-Cr3C2-10Ni                          | 5.37-5.38       | 92.5-93.0      | 90-100           |

The coating was applied by the machine Elitron-22A with various powers, shown in table 2.
Table 2. Modes of coating by ESA.

| Coating mode | 1  | 2  | 3  |
|--------------|----|----|----|
| Intensity of the current I, [A] | 0.5 | 0.8 | 1.3 |

The prepared samples were cut into EDM machine in the direction perpendicular to the coating belt, and then each sample was poured by quick-hardening plastic in a ring. Next, the sample was smoothened, polished and processed in ten percent nitric acid solution. After neutralization and washing, all the samples were studied by a metallographic microscope "Neofot 32" and the electron microscope "AxioTec" by "Zeis".

The micro hardness of metallographic sections was determined by the Knoop method on a hardness tester "Lits minilout 2".

Figure 1 demonstrates the results of metallographic observation of the coated samples by the electron microscope at two magnifications 1000 times. It is seen that, under the nonerodible layer of the coating with a thickness of 5...15 micrometres, there is a transition layer with a thickness of 10...20 micrometres which depends on the generator power and speed of the electrode.

Figure 1. Image of a metallographic section of a high-speed steel sample with coating (×1000 magnification).

A similar effect is recorded by the authors of [12, 13, 14]. There, it is indicated that physico-mechanical properties of the top layer of the cathode change significantly during the process of ESA. In order to optimize the ESA and predict the properties of the hardened layer it is necessary to know the dependence of the phase state, chemical state, stress state of the top layer and its hardness, surface roughness, durability and heat resistance on the electrode material.

During the ESA, a layer of a modified structure is formed on the surfaces of the anode and cathode, which remains "white", i.e. its structure cannot be identified, under the exposure of the enchains that used to detect the microstructure of electrode material. Similar layers were observed on the surface of the material subjected to grinding, turning, milling, electro-mechanical treatment, shot peening, on friction surfaces and after an exposure to high-concentrated energy fluxes. The formation of "white" layers occurs at high local temperatures and pressures is common to all these cases. However, the intensity of an impact of the ESA on the top layer distinguishes considerably from the above-mentioned
processes (the pressure of the shock wave is 0.1 Pa, the temperature is 5...40 ×10³ ºC). High speed heat removal leads to the fact that the temperature quickly drops to the melting point and the corresponding phase transformations within a layer with a thickness of an order of several micrometres. [15, 16, 17] As a result, crystallization, phase transformation, diffusion and chemical interactions accompanying the ESA lead to the formation of extremely unstable structures with very small grains, high heterogeneity in composition, structure and properties [18]. Thus, the hardness of the deposited layer, in most cases, slightly exceeds the hardness of the cathode at the ESA of steels and titanium alloys of refractory metals and compounds. [19, 20]

3. Summary
The presence of the transition layer, where the inclusions of the coating in the base material can be detected, indicates that the technological process of coating is accompanied by the diffusion of the materials of the cathode and the anode in the transition layer.

Figure 1 shows that a penetration of ions and molecules of the coating, which have higher temperatures and, correspondingly, higher energies, into the base material occurs along the boundaries of base material grains. That is the weakest element in the metal and less energy is required to penetrate into these elements. Similar processes happen in the opposite direction; however, due to the fact that particles of the base metal are less heated, and, therefore, have a lower energy, the depth of their penetration into the coating is minor. Data from metallographic observations indicates that mutual diffusion of the components of the layer and the base material determines the bond strength of the coating and the base material at ESA.

References
[1] Kuznetsov I S, Kolomeichenko A V and Pavlov V Z 2017 Process of mass transfer of amorphous alloys under low-voltage electric spark treatment Surface engineering and applied electrochemistry 53(4) 333-8 doi:10.3103/S1068375517040093
[2] Gertsriken D, Mazanko V, Qiao S and Zhang C 2009 Diffusion characteristic of several elements in copper during an electric spark processing under a constant magnetic field Modern Physics Letters B 23(19) 2369-76 doi:10.1142/S0217984909020527
[3] Verhoturov A D, Vlasenko V D and Konevtsov L A 2018 Investigation of the adhesive strength of antifriction coatings depending on the energy parameters of electro-spark alloying Journal of friction and wear 39(3) 232-40 doi:10.3103/S1068366618030145
[4] Kolomeichenko A V, Kuznetsov I S and Kravchenko I N 2015 Investigation of the thickness and microhardness of electrospark coatings of amorphous and nanocrystalline alloys Welding International 29(10) 823-25 doi:10.1080/09507116.2014.986892
[5] Ribalko A V and Sahin O 2003 The use of bipolar current pulses in electrospark alloying of metal surfaces Surface and Coatings Technology 168(2-3) 129-35 doi:10.1016/S0257-8972(02)00877-0
[6] Padgurskas J, Kreivaitis R, Rukuiža R, Mihailov V, Agafii V, Kriūkienė R and Baltušnikas A 2017 Tribological properties of coatings obtained by electro-spark alloying C45 steel surfaces Surface and Coatings Technology 311 90-7 doi:10.1016/j.surfcoat.2016.12.098
[7] Prokopenko G I, Mordyuk B M, Volosevych P Y, Vorona S P, Popova T V and Piskun N O 2017 Structure and properties of the 20GL steel after electric-spark alloying with nickel and molybdenum and ultrasonic impact treatment Metallphysics and Advanced Technologies 39(2) 189-208 doi:10.15407/mfint.39.02.0189
[8] Loginov N Y 2017 Study of tribological characteristics of samples with the coating made by the electric-spark method Hardening technologies and coatings 13 2(146) 67-70
[9] Mashkov Y K, Korotaev D N, Baybaratskaya M Y and Alimbaeva B S 2015 Nanostructured coatings synthesized by electro-spark machining Technical Physics 60(10) 1489-93 doi:10.1134/S1063784215100217
[10] Mashkov Y K, Korotaev D N, Baybaratskaya M Y and Alimbaeva B S 2015 Research and
optimization of technological modes of electro-spark processing details of tribosistem 
Proceedings of Dynamics of Systems, Mechanisms and Machines, Dynamics doi:10.1109/Dynamics.2014.7005682

[11] Wang Y, Yu H, Shi H, Qiu R and Zhang K 2013 Interface behavior of WC coatings on 40Cr steel by electro-spark deposition Transactions of Materials and Heat Treatment 34(8) 173-6

[12] Zhai H 2010 Phase composition and wear mechanism of the electrosparc alloyed coatings under different surrounding atmosphere Heat Treatment of Metals 35(5) 49-51

[13] Korotaev D N and Mashkov Y K 2009 Optimization of spark alloying operating parameters of tribosystem parts Journal of Friction and Wear 30(2) 106-9 doi:10.3103/S1068366609020068

[14] Wu J, Nie Z, Zhang X, Kong L and Li Y 2016 Mechanical characteristics of pump impeller blades surface produced by electro-spark deposition doi:10.3303/CET1655031

[15] Gould J 2011 Application of electro-spark deposition as a joining technology Welding Journal 90(10) 191s-7s

[16] Gould J 2010 Application of electro-spark deposition as a joining technology Paper presented at the Materials Science and Technology Conference and Exhibition 4 2700-10

[17] Gould J 2010 Application of electro-spark deposition as a joining technology AIST Steel Properties and Applications Conference Proceedings - Combined with MS and T’10 Materials Science and Technology 363-73

[18] Li Z, Gao W, Kwok P, Li S and He Y 2000 Electro-spark deposition coatings for high temperature oxidation resistance High Temperature Materials and Processes 19(6) 443-58

[19] Chen C, Wang M, Wang D, Jin R and Liu Y 2007 Study of the electro-spark alloying of la on ZM5 mg alloy. Cailiao Kexue Yu Gongyi Material Science and Technology 15(6) 823-6

[20] Zhang F, Ma L, Zhang G and Sun F 2005 Interface behavior and microstructure transformation of welded joint of 35CrMo steel by electro-spark deposition China Welding 14(1) 15-8