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Ministry of Education and Science of Ukraine
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New Process for Forming Multicomponent Wear-Resistant Nanostructures by Electrospark Alloying Method

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Abstract— **The work is intended for discussing a problem of improving wear resistance of sliding friction pair parts. There are considered the processes of strengthening surfaces by highly concentrated flows of energy and substance, i.e. those being provided by the method of electrospark alloying (ESA). It is shown the ESA method allows creating macro-micro- and nanostructures to enhance operational properties of friction surfaces. There are represented the results of research and development of a process for protecting steel products from abrasive and other types of wear by applying wear-resistant coatings, made of refractory and wear-resistant metals, to the wear surfaces with the use of the ESA method, and enlarging thickness of increased hardness areas. The coatings formed by the ESA method in the sequence of C → Al → T15K6 have the largest area of increased hardness (of 320 to 360 µm), the maximum microhardness of the surface layer (10,000 MPa) and the smallest surface roughness (7.5 µm).**

Keywords— electrospark alloying, nanostructures, carbon, aluminum, wear resistance, microhardness, roughness

I. Introduction

Improving reliability and durability of dynamic equipment operating at high speeds, loads and temperatures, as well as under conditions of corrosive, abrasive and other types of working environment exposure remains an urgent problem and requires an integrated approach.

Modern strengthening technologies provide numerous methods for improving structures and properties of part surface layers, and each of those methods has optimal areas of application, advantages and disadvantages.

The promising methods of strengthening surfaces and modifying thereof are the methods based on processing materials by concentrated flows of energy and substance (CFES).

The results of analysis of the CFES influence on the formation of the microstructures and the surface properties, as well as on the course of processes occurring on conditions of friction and wear of metals are represented in the works of A.D. Pogrebnyak [1-3], V.V. Litvinenko [4], G.I. Kostyuk [5, 6] and others. Strengthening metallic materials by the concentrated flows of energy and substance (CFES) in their various combinations makes it possible to intensify existing technological processes of surface treatment and to obtain results unattainable with traditional technologies.

As for implementation issues and challenges, recently, multilayer multicomponent and nanocomposite (nanostructured) coatings have become the basis for creating surfaces having various functional purposes and improved characteristics depended thereof, such as hardness, wear, corrosion and heat resistance, fatigue strength, etc. [7-10].

The development of technological civilization initiates both the development of new high-energy technologies and the optimization of already known ones intended for processing materials. Among the modern methods of surface treatment by concentrated flows of energy and substance (CFES), there is electrospark alloying (ESA) method, which allows obtaining surface structures with unique physical, mechanical and tribological properties at nano level.

Despite the undeniable advantages of the ESA method, such as high adhesion strength of alloyed layer and base material, the possibility of applying any conductive materials to a surface to be strengthened, low energy intensity of the process, environmental friendliness, ease of performing the technological operation, etc., the method has some drawbacks. They concern such problems as increasing surface roughness, reducing fatigue strength and limiting the thickness of the applied layer, which often restrain the application of this method for a wider range of machine parts and tools.

The numerous papers of Ukrainian [11–13] and foreign [14–18] scientists are devoted to improving the technology of electrospark alloying. Improving the reliability and durability of machine and equipment parts operating under difficult conditions (abrasive wear, high temperature, aggressive environment, etc.) is an actual technical problem of great importance.

II. Problem Formulation. Analysis of Major Achievements and Publications

Possessing wide possibilities for creating certain structures, phase and chemical compositions in part surfaces, the electrospark alloying method allows improving their operational properties. Formation of surface structures and properties thereof, as well as investigation of laws of surface friction and wear after processing surfaces by the ESA method are research subjects by such scientists as B.N. Zolotykh [19], B.R. Lazarenko and N.I. Lazarenko [20], G.V. Samsonov [21], A.D. Verkhoturov [22], A.E. Gitlevich [23], I.A. Podchernyayeva [24], V.V. Mikhailova [25] et al.

Having summarized the studies of the above mentioned authors, it is possible to single out the following processes occurring during the electrospark alloying: the process of transferring material to the surface of a part from the alloying electrode occurs through the formation of mechanical mixtures, solid solutions and chemical compounds; while performing the process of the surface enrichment with the elements of the alloying electrode, there is an abnormally high diffusion of the transferred material under the action of highly concentrated energy flows; the process of ultrafast quenching at short-term heating to a high temperature with a discharge of electric current is followed by instantaneous cooling; the process of plastic deformation occurs with a local pulse pressure impact on the material; the process is accompanied with creating extremely non-equilibrium structures with fine grains, high heterogeneity in composition, structure, and the process occurs when the material is subjected to localized pulse pressures and temperatures, as well as thermal stresses; the processes of nitration, carburization and oxidation take place under environment conditions [26].

Today the investigations conducted by the specialists are primarily focused onto the development and improvement of new equipment for the ESA method, the creation of new electrode materials and the study of the structures and properties of coatings. But now, there is lack of information on applied technologies for the use of the ESA method. Therefore, it should be noted there is a problem which is rather relevant in modern conditions.

In paper [27], to attract attention to the use of the electrospark alloying method for repair purposes, there was considered the fact of applying a new process [28] for creating thick-layer coatings by the ESA method to restore worn parts operating under sliding friction conditions. The above said application is based on investigating the well-known publications devoted to the causes of electrospark coating limited thickness [29] and the ways to increase thereof [30]. Testing the coatings was carried out on the example of restoring the worn parts of the power cylinders friction pairs with wear and local defects of more than 300 microns depth. There has been well established the advantage of БрКМц3-1 (BrKMts3-1) bronze on applying so called "hilly" relief coatings. There was determined the range of the optimal electrical modes for the ESA method with the pulse energy of 0.6 to 1.3 J, the pulse-repetition rate of 250 Hz and the specific time for the ESA method of 42 to 53 s/ cm^2.

It should be noted that in the course of performing the ESA method, a strengthened surface layer having a modified structure and properties can be formed both as a result of diffusion provided, for example, with the use of a graphite electrode as a tool to saturate the surface with carbon and to perform a kind of carburization with the help of the ESA method (CESA) [31], and also at applying coatings of refractory wear-resistant metals or their combination with soft antifriction metals [32].

In addition, while performing the ESA method, for example, with aluminum, the surface layer of the product, depending on the discharge energy (Wu), can be modified not only by diffusion (under 'soft' alloying conditions), but also owing to the occurrence of joint effect, namely, because of forming a diffusion layer and also creating a coating by transferring aluminum to the surface. It has been found that with increasing the amount of carbon in the alloyed surface and also with enhancing the discharge energy in the course of the process of aluminization by the ESA method, there is raised microhardness, continuity, thickness of increased hardness zone and roughness of the obtained surface layer [33].

In papers [34-36], there are described the processes for increasing the thickness of strengthened surface layers of 12X18H10T steel and ХН58МБЮД nickel alloy at applying combined electrospark coatings (CEC) consisting of ВК8 hard alloy and copper, which were formed in the sequences of ВК8→Cu→ВК8 and ВК8→ВК8→Cu, respectively. The methods are used to increase the wear resistance of the working surfaces of the pulse and seal rings for the turbopump units of the liquid rocket engines, and those consist in that before applying the CEC, there is produced the process using the CESA method. At the same time, the increased hardness zone is enlarged by the thickness of the CESA layer.

Thus, it should be noted that the thickness of the increased hardness zone of the surface layer is essential for parts of friction pairs at occurring abrasive and other types of wear, and the problem of increasing such a thickness remains relevant.

The aim of the work is to increase the efficiency of the electrospark alloying method to protect steel products from abrasive and other types of wear by applying wear-resistant coatings to the wear surfaces and enlarging the thickness of the increased hardness zone, due to preliminarily performing the CESA method and applying aluminum by the ESA method.

III. Research Methods

To study structure and perform measurements of surface layer microhardness, the thin sections made of 12X18H10T steel and having dimensions of 10x10x8 were used after processing them for 1.0 min. by the CESA method. The process of alloying occurred on different conditions at the Элитрон-52А (Elitron-52A) unit equipped with a manual vibrator and at the ЭИЛ-9 (EIL-9) mechanized unit at the discharge energy range (W_p) of 0.5 to 6.8 J.

The surface of a thin section was oriented perpendicular to the surface being alloyed. To exclude edge effect in the course of alloying, the end face of a specimen had been milled by the depth of at least 2 mm before preparing the thin section thereof. To prevent crimpling of the layer, the edge of the specimen was fastened with a counterbody in a clamp. To identify the structure, the thin section was subjected to chemical etching in a reagent.

After manufacturing, the thin sections were examined with the use of the Neofot-2 optical microscope, where the layer quality and continuity and also the thickness and the structure of the underlayer zones, namely the diffuse zone and the heat-affected zone, were evaluated. At the same time, there was carried out a durametric analysis to determine microhardness distribution in the surface layer along the depth of the thin section beginning from the surface thereof. The microhardness measurement was performed using the PMT-3 microhardness tester by means of indenting a diamond pyramid under the load of 0.05 N. The roughness was measured by reading and processing profilograms with the use of the profilograph-profilometer measuring device of 201 model, "Kalibr" plant production. To study the distribution of the elements and carbon along the depth of the layer, the local X-ray spectroscopic analysis was performed using the Joel JSM-5400 scanning electron microscope equipped with the microanalyzer of the ISIS 300 Oxford Instruments.

IV. Research results

Fig. 1 shows the microstructure (a, b) and the distribution of the microhardness in the surface layer (c, d) of 12X18H10T steel at processing by the CESA method with the discharge energy (W_u) of 3.4 J.

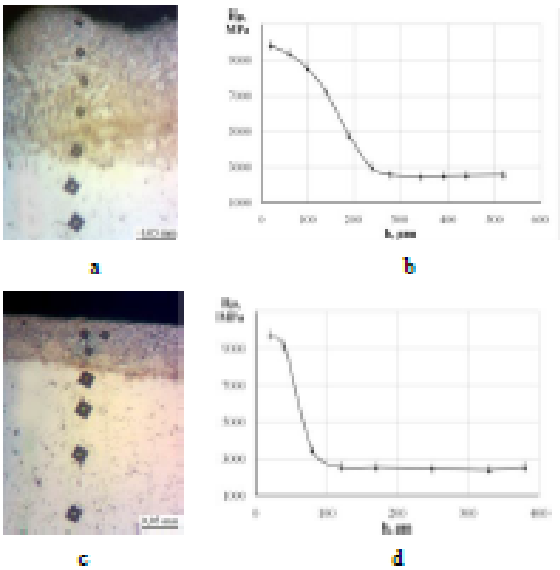


Fig. 1. Microstructure (a, b) and microhardness distribution (c, d) of the surface layer of steel 12X18H10T at processing it by the CESA method with W_u = 3.4 J

The layer is not uniform, and it is of 160 µm (a, c) to 90 µm (b, d). On average, the depth of the increased hardness layer is ~ 100 µm.

Fig. 2 represents the results of the electron microscopic studies, that is the area of the surface layer of 12X18H10T steel after processing it by the CESA method with W_u = 3.4 J, as well as the distribution of carbon and other elements, that is chromium, iron, nickel and titanium, which are the parts of the steel, along the depth of the layer.

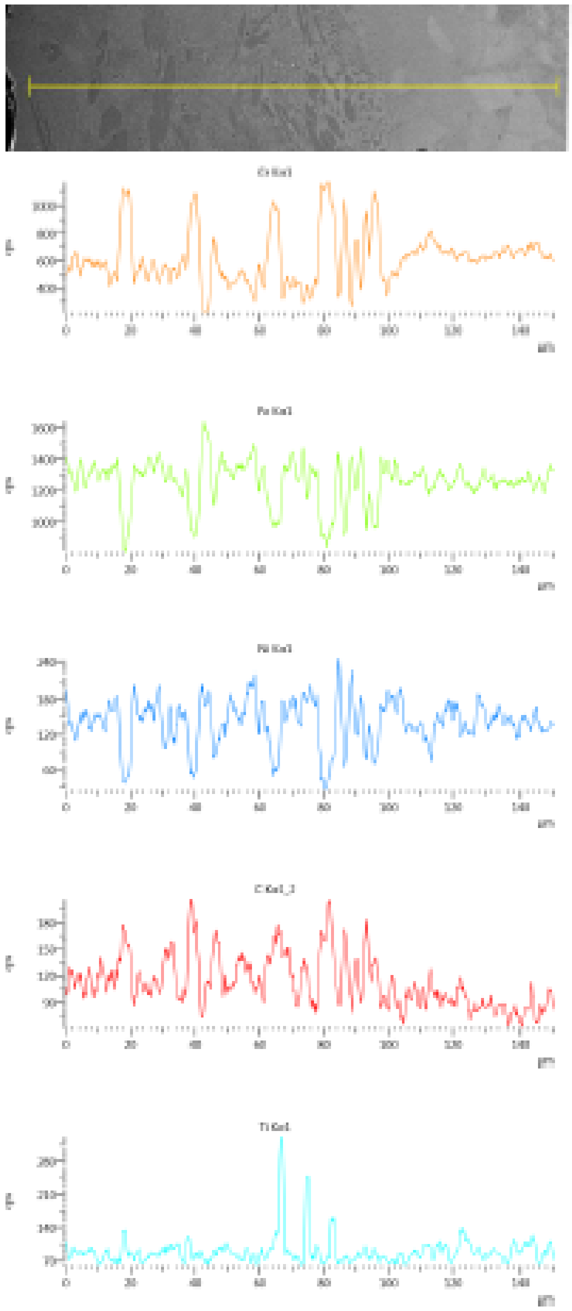
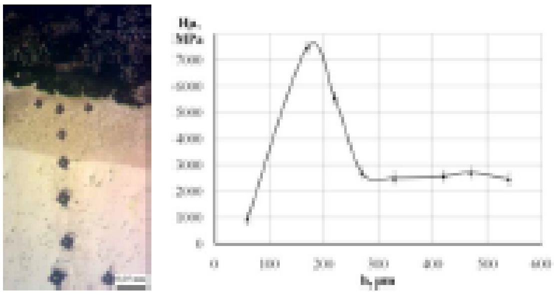


Fig. 2. Distribution of the elements in the surface layer of 12X18H10T steel after processing it by the CESA method.

From the figure, it can be seen that the increased carbon content in the surface layer is maintained up to 100 μm, which fact is consistent with the data of durametric studies (Fig. 1).

Fig. 3 shows the microstructure (a) and the distribution of the surface layer microhardness (b) of 12X18H10T steel after processing it by the CESA method and doing it with aluminum by the ESA method with W_u = 3.4 J. The layer is rather massive, but not uniform. The thickness of the layer having a modified structure is ~ 170 μm. At the same time, on the surface, there is an uneven soft, crumbly and porous layer, the thickness of which is of 70 to 100 μm in various areas, and the microhardness is of 1000 to 2500 MPa. Under this layer, there is a layer of a higher microhardness (up to 7500 MPa) having a depth of 80 to 120 μm.



a b

Fig. 3. Microstructure (a) and distribution of microhardness (b) in the surface layer of 12X18H10T steel after processing it by the CESA method and further doing it with aluminum by the ESA method.

Fig. 4 shows the area of the surface layer of 12X18H10T steel after processing it by the CESA method and doing it with aluminum by the ESA method with W_u = 3.4 J, as well as the distribution of aluminum, iron, chromium, nickel, carbon and titanium. The results of the local x-ray and microscopy microanalysis indicate that in the course of processing by the ESA method, aluminum diffuses into the steel substrate by the depth of 100 μm. The content of the elements (Fe, Cr, Ni, Ti) comprised into 12X18H10T steel in the surface layer is minimal, and at a distance of 80 to 100 μm starting measurement from the surface, it corresponds to the steel grade composition.

With sequential alloying of the steel according to the scheme of C → Al → T15K6 at Wu = 3.4 J, the formation of a massive layer having a thickness of 320 to 360 μm and a maximum microhardness on the surface of 9000 to 10000 MPa is observed. The results of metallographic studies indicate that a significant amount of carbides and other chemical compounds are formed in the coating, which apparently result in significant strengthening of the surface layer.

The results of the x-ray microscopy microanalysis indicate (Fig. 6) that, as a result of sequential processing by the CESA method and further doing it with aluminum and the electrode-tool of T15K6 hard alloy with the use of the ESA method at W_u = 3.4 J, aluminum diffuses by the depth of 320 μm, but its content decreases, tungsten as the main element of T15K6 hard alloy - by the depth of 270 μm, and carbon does it by up to 270 μm. Processing by the ESA method according to the described technology allows to enlarge the diffusion zones of carbon and aluminum and also

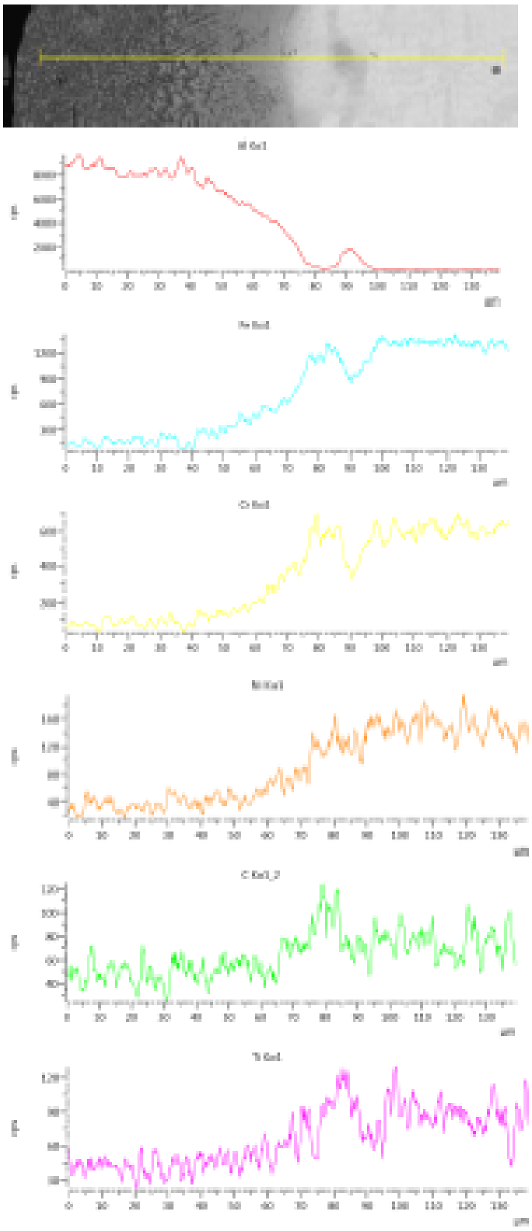
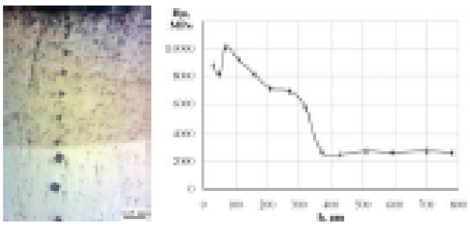


Fig. 4. Distribution of the elements in the surface layer of 12X18H10T steel after processing it by the CESA method and further doing it with aluminum by the ESA method.



a b

Fig. 5. Microstructure (a) and microhardness distribution (b) in the 12X18H10T steel surface layer after processing it by the CESA method and further doing it with aluminum and the electrode-tool of T15K6 hard alloy with the use of the ESA method.

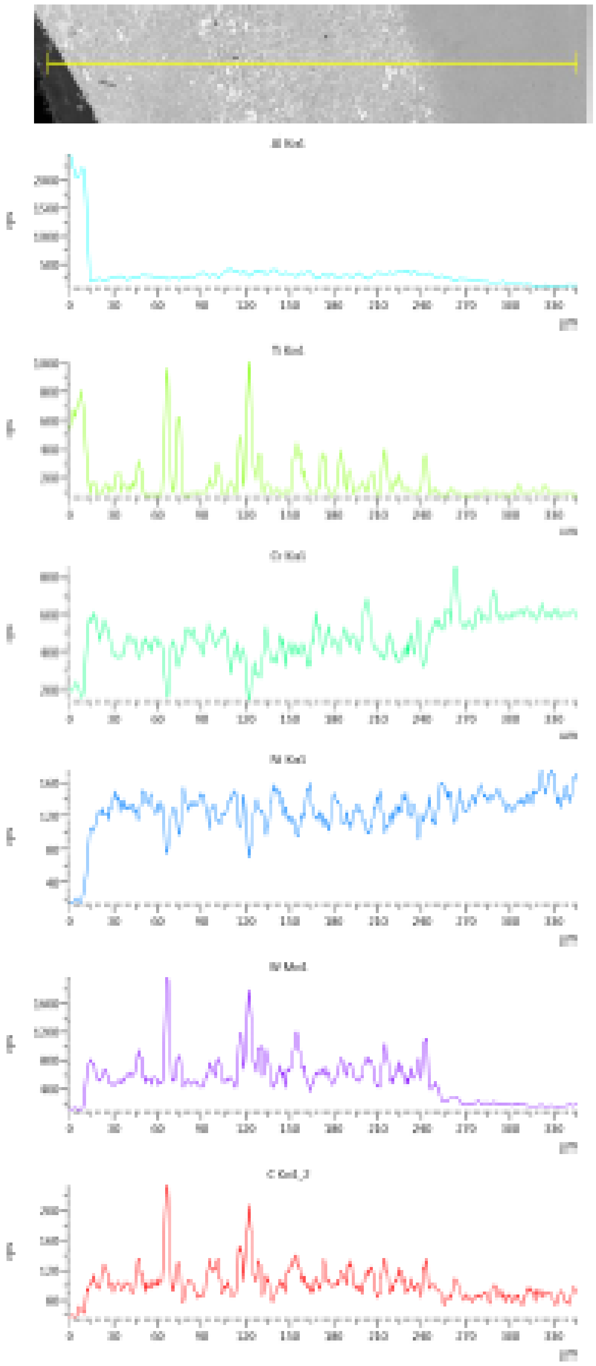
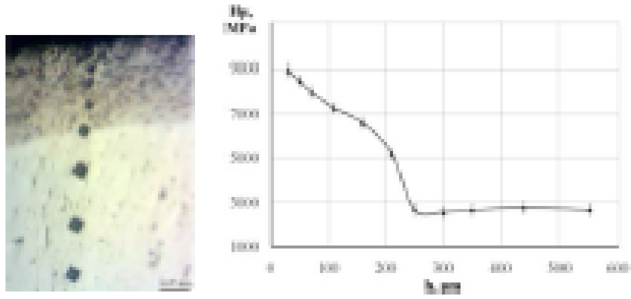


Fig. 6. Distribution of the elements in the surface layer of 12X18H10T steel after processing it by the CESA method and further doing it with aluminum and the electrode-tool of T15K6 hard alloy with the use of the ESA method.

to increase the hardness and thickness of the strengthened layer.

The results of the studies show that, when processing by the ESA method under the scheme of C → T15K6 (without the ESA by aluminum), it is impossible to achieve the required microhardness values (Fig. 7). On the surface, it is equal to 9000 MPa, and as deepening, it gradually decreases to the microhardness value of the substrate, that is about of 2500 to 2600 MPa. The thickness of the increased hardness layer is of 200 to 220 μm, which is 100 μm less than that as a result of processing by the ESA method in the sequence of C → Al → T15K6 (Fig. 5). The continuity of the layer is ~ 100%.



a b

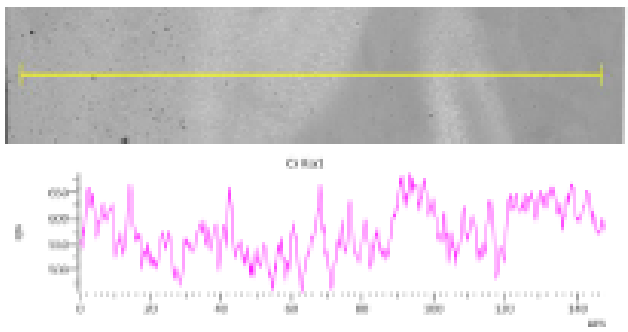
Fig. 7. Microstructure (a) and distribution of microhardness (b) of the surface layer of 12X18H10T steel after processing it by the CESA method and further doing it with the electrode-tool of T15K6 hard alloy with the use of the ESA method.

Fig. 8 represents the results of the study for the distribution of the elements included into the substrate (12X18H10T steel) and also those comprised into the composition of the electrode-tool along the depth of the layer obtained after processing it by the CESA method and further doing it by the ESA method with the electrode-tool of T15K6 hard alloy at W_u = 3.4 J. Tungsten diffuses by the depth of 125 μm, and the layer with a higher carbon content is ~ 120 μm.

The results of the metallographic and durametric studies of the coatings obtained on 12X18H10T steel are summarized in Table. 1. The studies have shown that the greatest thickness value of the increased hardness zone is observed in the surface layers formed in the sequence of CESA + ESA Al + ESA T15K6.

TABLE I. RESULTS OF METALLOGRAPHIC STUDIES OF THE SPECIMENS MADE OF 12X18H10T STEEL.

Electrode-tool material	Thickness of surface layer increased hardness zone, μm	Maximum microhardness of strengthened surface layer, MPa	Surface roughness, Ra, μm
C	90-160	9500	9.5
C + Al	80-120	7500	25.5
C+Al+T15K6	320-360	10000	7.5
C + T15K6	140-220	9000	8.5



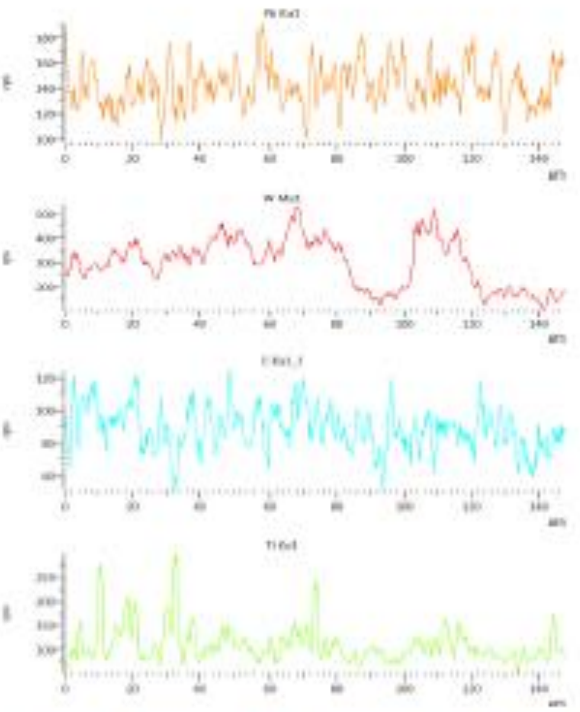


Fig. 8. Distribution of elements in the surface layer of steel 12X18H10T after processing it by the CESA method and further doing it by the ESA method with the electrode-tool of T15K6 hard alloy.

V. CONCLUSION

1. There is represented the analysis of the electrospark alloying method, which increases the reliability and durability of the equipment operating in difficult conditions.

2. There is proposed a new process for protecting steel products from abrasive and other types of wear by applying the wear-resistant coatings, made of the refractory wear-resistant metals, to their wear surfaces by the electrospark alloying method, having conducted the preliminary processes by the CESA method and the ESA method with aluminum.

3. The coatings formed in the sequence of CESA → ESA C → Al → T15K6 have the greatest zones of increased hardness (of 320 to 360 µm), the maximum microhardness of the surface layer (10.000 MPa) and the smallest surface roughness (7.5 µm).

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