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Investigation of the electrospark coating, alloying and strengthening technology

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Introduction. The work objectives were the analysis and application of the technology of electrospark deposition of wear-resistant metal coatings on cutting tools or machine parts for their hardening or dimensional restoration.

Materials and Methods. The technology, device and principle of operation of the modernized installation intended for electric spark application of wear-resistant metal coatings with composites T15K6, VK8 and VK6 are considered.

Results. To determine the parameters of the upgraded electrospark alloying plant, experiments were carried out on hardening of polished samples made of steel 45 with hard alloy T15K6 with dimensions of 25×25×25 mm. As a result of using the experiment planning method, the possibility of selecting and adjusting the installation parameters was confirmed. The following parameters were selected for hardening samples made of steel 45 with hard alloy T15K6: current I = 1-2–A, voltage U = 40-75 V, capacitor bank capacity = 60–100 µF.

Discussion and Conclusions. The use of carbon dioxide as a protective medium enables to increase the number of passes and, accordingly, the number of coating layers to twenty, to obtain a total thickness of up to 0.3 mm with a dense structure without oxides. Coatings of this thickness make it possible not only to strengthen, but also to restore the dimensions of worn machine parts. The parameters of the technological modes of electrospark alloying significantly affect the intensity of coating application and the quality of the resulting surface. A rise in the electrical parameters causes an increase in the intensity of each individual discharge and, within certain limits, contributes to an increase in the amount of the transferred coating material, as well as to deeper transformations of the coated surface in the discharge zone. Thus, an electrospark alloying plant equipped with monitoring and diagnostic tools, as well as with a protective gas supply system, can be used for hardening and restoring machine parts and cutting tools.

***Keywords*:** electrospark alloying, machine parts, cutting tool, hardening, wear resistance coating, restoration of machine parts.

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Introduction. The introduction of technology for manufacturing machine parts and cutting tools with high mechanical characteristics is an important component of mechanical engineering in general and the production of metal-cutting equipment in particular. The basic requirements for this technology are accessibility, cost-effectiveness, and efficiency.

The materials used for manufacturing machine parts and cutting tools, as a rule, do not fully meet the requirements of operation, so they must be made of high-quality structural materials. But in this case, their production can be very expensive. In addition, it is also impossible to guarantee full satisfaction of operational requirements in this case. These problems are sufficiently eliminated through applying coatings with a thickness of fractions of a millimeter to several millimeters to the working surfaces of machine parts and tools of various functional purposes [1−4].

The quality of such coatings is evaluated, as a rule, according to several specific criteria, on the basis of which a complex criterion is formed. Studies using the experimental planning method [5], in turn, enable to establish the relationship of quality criteria and the parameters of the coating process [6], optimize these parameters, and predict the properties of bimetal compositions [7].

Coating layers can have various chemical compositions and structural-phase states that differ from the base material. Coating materials provide high performance properties or a set of properties to the working surfaces of cutting tools or machine parts [5, 8−18]. In addition, a small amount of expensive materials is consumed on thin coatings, which gives a high economic effect when they are used in production practice.

Currently used various metal parts (bearings, shafts, axles, drills, turning tools, milling cutters, etc.) require increasing their wear resistance and strength. One of the inexpensive ways of applying thin metal coatings to their working surfaces is the electric spark processing method — electric spark alloying (ESA) [1−4]. In addition, this technology can be used to restore steel parts of machines with minor wear of their working surfaces — up to 0.2 mm.

Materials and Methods. ESA enables to harden the cutting tool and restore the steel parts of machines with wear-resistant composites such as T15K6, VK8, VK6, and coatings of other composition [8−18]. This technology allows increasing the hardness, wear resistance, corrosion resistance of metal surfaces and provides a good bond with the base material. ESA is implemented on relatively simple equipment, whose performance does not depend on the hardness and other physical characteristics of the materials used.

Until now, various models of the process have been proposed, which to one degree or another explained individual experimental data [1−4]. Figure 1 shows a model of the ESA technology, which is designed for high voltages and small values of the short-circuit current ($I_{к.з}$ < 10–20 A). Providing that the short-circuit current $I_{к.з.}$ > 10 A and the no-load voltage of the power supply $U_{x.x}$ < 50 V, it will be required to refine such a model, since due to the low potential between the electrodes, the interelectrode gap in this case should be significantly reduced.

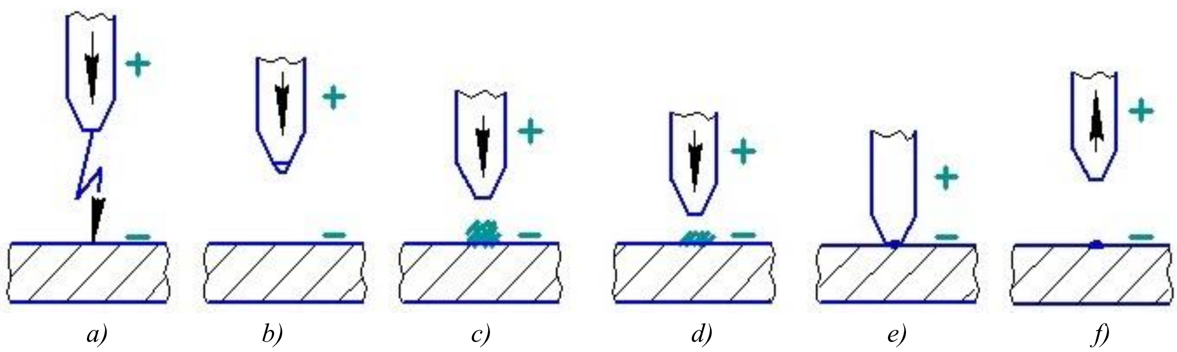

Fig. 1. Electric spark alloying model: *a)* moment of the interelectrode gap breakdown; *b)* detachment of a molten metal drop from the anode; *c)* explosion of a drop of molten metal; *d)* deposition of molten anode metal on the cathode; *e)* contact of electrodes (mechanical shock of the anode on the cathode); *f)* separation of electrodes

As the movable electrode (anode) approaches the cathode (substrate), the electric field strength increases. At a certain distance, the voltage reaches a value at which a spark discharge occurs, and a through conduction channel is obtained. An electron beam from the cathode (substrate) passes through this channel, hits on the anode surface in a focused manner (Fig. 1 *a*), and the current density increases. The electrons abruptly release the accumulated kinetic energy, which is converted into thermal energy released in the surface layer of the anode. At the point of the electric discharge breakdown, the anode melts, a drop of molten metal separates from it and moves to the cathode (Fig. 1 *b*), ahead of the moving anode.

The falling drop, breaking away from the anode, heats up to a high temperature, boils and explodes. The current circuit in the channel is interrupted, the compressive forces of the electromagnetic field disappear. The metal particles, formed after the explosion of the drop, are no longer focused by the electromagnetic field and fall on the substrate with a wide front (Fig. 1 *c*), and when they reach the cathode, they are welded with it, partially penetrating into its surface (Fig. 1 *d*). Following the molten metal of the electrode, the electrode-anode itself moves. In the meantime, the capacitor bank has time to charge, and the electric field strength in the interelectrode gap will increase accordingly. This is followed by a mechanical shock of the electrode on the surface of the substrate, while the electrical circuit is closed.

The anode material in the presented ESA model is transferred in the liquid crystal state, starting from the moment of the interelectrode gap breakdown and until the anode comes into contact with the cathode surface. In the liquid crystal state, the mesophases of a substance are characterized by anisotropic properties and combine the rheological properties of liquid bodies (fluidity) with the properties of solid crystals (anisotropy of physical properties). In the mesomorphic state, the fluidity of a substance is limited since there is a certain ordering of the arrangement and mutual orientation of its molecules, which approaches the ordered arrangement of the structure of solid crystals. A second pulse passes through the particles of the anode material lying on the cathode that have not cooled down. Pulse discharges have a high current density — up to 10^5–10^6 A/mm^2.

During mechanical contact of the mobile electrode and the substrate, the particles of the electrode material are welded to each other and to the surface of the substrate, which is heated, and the electrode material diffuses into it. Together with the diffusion process, chemical reactions occur between the materials of the electrode particles and the substrate. The mechanical shock of the movable electrode forges the heated coating material (Fig. 1 *d*), increasing its uniformity and density. Thus, a coating with an alloying effect is formed on the surface of the substrate that is firmly connected to it (Fig. 1 *e*). Then the next cycle begins, and the electrode moves up.

The coating process in ESA occurs under the influence of the following factors:

— gravity, under the influence of which a drop of molten metal rushes from the anode to the cathode when they are open;

— mechanical vibration of the electrodes;

— electrical polarity, under the influence of which ions of the coating material settle on the substrate.

An important characteristic of coating with the help of ESA is the bond strength of the coating and the base, which provides reliable and long-term operation of the cutting tool or part. During the formation of the coating and while ensuring the connection of the coating and the base, the interaction of the liquid phases of the electrode materials occurs. A chemical bond is formed between them, volumetric processes of diffusion of the anode into the substrate in the solid phase develop, intermetallides are formed.

Physical and chemical transformations in the surface layer of the substrate occur at high temperatures and high-speed plastic deformation. Interaction of the anode and substrate materials, crystallization of the molten anode material on the substrate surface, and diffusion in its surface layer occur under nonequilibrium conditions. High temperatures in the interelectrode gap and alloying elements of the electrode make it possible to increase and dope the surface of the substrate, improving its physical and chemical properties. Therefore, ESA can be used to restore complex-shaped machine parts and alloying cutting tools.

ESA advantages:

— spot heating, in which there is no deformation of the substrate (base);

— local (spot) coating, including on complex-shaped substrates;

— possibility of alloying the surfaces of machine parts and cutting tools.

Physical and mechanical properties of the surface of the tool or part being processed can be varied through changing the material of the electrodes. At the same time, the composition of the coating and its physico-chemical properties may differ significantly from the alloying material of the anode, and the alloyed base material.

After ESA processing, the steel base consists of three areas: the white layer, the transition zone, and the basic material. The thin white layer contains refractory compounds with a fine-grained structure, which are formed under conditions of fast heat dissipation. In the transition zone of the steel base there is a diffusion layer, a heat-affected zone, and a transition layer. The diffusion layer is a martensitic-carbide structure. The heat-affected zone is an austenitic-martensitic-carbide structure. The transition layer has an austenitic-sorbitol-martensitic structure. An austenitic structure is formed on the interface of ferrite carbide phases under rapid cooling and during diffusion saturation of steel with air nitrogen if the ESA is carried out without the use of a shielding gas. It should be taken into account that the less nitrogen penetrates into the transition zone, the more martensitic structures will be formed under cooling. The transition layer is followed by the structure of the base, which is not subject to changes. The thickness and structure of the zones depend on the process conditions, the composition of the coating and base materials, as well as the composition of the environment.

The performance of the ESA process, the quality of the coating, the grain size of the base can be adjusted through changing the borehole and the frequency of electrical discharges. For electrodes, it is recommended to use materials with high hardness and wear resistance, for example, tungsten and titanium carbides, gray or white cast iron, hard alloys based on titanium carbide with various bonds based on molybdenum, nickel, intermetallides and steel. It should be noted that the microhardness of the hardened layers obtained on hardened steels is significantly higher than on non-hardened ones. This is due to the active influence of the base materials on the formation of the coating.

The ESA electrical parameters determine the degree of hardening, the purity of the coating surface, and the performance of the process. The electrical modes used can be conditionally divided into coarse, medium, and fine. They cover a significant range of power required for both finishing and rough ESA processes. Rough modes are characterized by a voltage of 100-200 V and a large capacity of the capacitor bank (100-300 μF). Medium modes are implemented through reducing the capacitance of the capacitor bank to 90-100 μF or by reducing the voltage at the same capacity. Fine modes can be obtained through reducing the voltage to 10-30 V or by reducing the capacitance of the capacitor bank to 0.5-10 μF. Accordingly, the short-circuit current increases or decreases.

The disadvantages of the ESA technology include the limited thickness of the applied coating layers and the significant roughness of their surfaces. Let us consider the disadvantages with specific examples.

Example 1. The installation operates in rough mode: the capacity of the capacitor bank C = 200 μF, the short-circuit current $I_{к.з.}$ = 3 A, voltage U = 150 V, vibration frequency of the vibrator with the electrode is 100 Hz. Assume that the capacitor bank is charged to 99 % of the power supply voltage. In this case, the charging time of the capacitors is 0.05 s. However, since the vibrator closes the electrodes every 0.01 seconds and a discharge occurs, the voltage on the capacitors has time to rise only to 65 V.

Example 2. The installation operates in soft mode: the capacity of the capacitor bank C = 4 μF, the short-circuit current $I_{к.з.}$ = 0.5 A, voltage U = 150 V, the capacitors are charged to 99 % of the voltage of the power source. In this case, the charging time of the capacitor is 0.005 s, but the vibrator will close the electrodes only after 0.01 s. In this case, the process is idle waiting for the next short circuit of the electrodes for about 50 % of the time.

One of the major causes for the limited thickness of the coating layer is the occurrence of chemical reactions between the electrode material and its environment during doping. The experimental data have shown that the greater the inertia of the environment, the higher the permissible specific duration of doping and the more coating material can be applied to the cathode. However, even in inert media, with an increase in the duration of doping, a decrease in the amount of material deposited on the cathode is observed.

The application of vacuum to eliminate the influence of chemical elements of the protective environment on the composition of the coating will require a significant complication and increase in the cost of electric spark alloying installations. Therefore, the use of a protective environment, e.g., carbon dioxide for ESA is preferable.

To study the ESA technology, an upgraded EFI-25 installation was used (Fig. 2). The basis of its power part is a single-phase transformer with increased scattering, a selenium rectifier, and a capacitor bank. The primary winding of the transformer is powered from a single-phase AC network of industrial frequency with a voltage of 220 V through 5A fuse and a two-pole switch. The installation rectifier is full wave. The cathode (the processed part) is grounded.

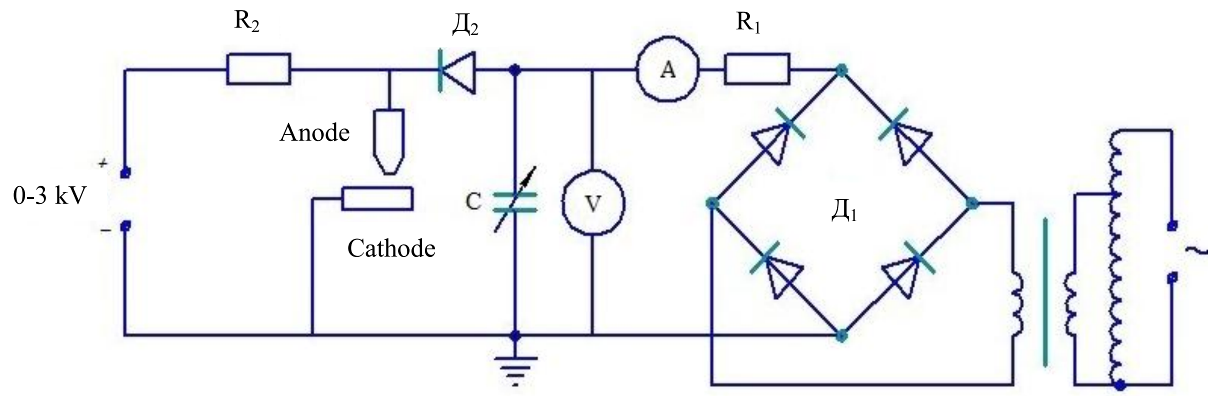

Fig. 2. Electric circuit of the power supply of the interelectrode gap of the electrospark alloying installation: $Д_1$ — selenium rectifier; C — capacitor bank; R_1 — ballast resistance; R_2 — current limiting resistance; $Д_2$ — valves; A — ammeter; V — voltmeter

At the output of the rectifier, the voltage changes from 15 to 220 V through switching the secondary winding. The valves separate the low-voltage and high-voltage parts of the installation, which prevents the breakdown of high voltage into the RC generator, which is designed to produce a spark discharge. The generator generates current pulses in the frequency range of 100-600 Hz. These are the optimal frequencies that are determined during experiments with different materials. The operation of the ESA installation outside this range causes performance degradation.

Automation of the ESA process and constant monitoring of its parameters provide high productivity and obtaining a high-quality carbide coating. This is provided, in particular, by ammeter A, designed to monitor the current in the power supply circuit of the interelectrode gap, and voltmeter V — for monitoring the voltage in the power supply circuit of the interelectrode gap (Fig. 2).

An autotransformer is installed as a power source on the upgraded installation, which provides stepless voltage regulation at the interelectrode gap up to 200 V. A panel of switches of the bank capacity is installed for stepwise changing the capacity of the interelectrode discharge power source. The total capacity of the bank is 120 μF, the number of switching stages is 16.

The safety of operation at the installation is provided by a separation transformer with a transformation coefficient K = 1:1 between the transformer and the electrodes of the installation. The technological modes of operation of ESA installations for coating, alloying and hardening, mainly set the following parameters:

— voltage at the interelectrode gap;
— capacitor bank capacity;
— charging current or the percentage of charging capacitors from the circuit voltage.

Research Results. To determine the possibility of regulating the ESA parameters, which should be provided by the upgraded installation, experiments were carried out on electric spark hardening with T15K6 hard alloy of polished samples made of steel 45 with dimensions of 25×25×25 mm. The experiments were carried out without using a protective gas in the coating area; carbon dioxide was used as a protective medium. As a result, the possibility of selecting and adjusting the ESA parameters was confirmed. I = 1-2 A, voltage U = 40-75 V, 60-100 μF.

The results of experiments without using carbon dioxide have shown the following: when applying a hard alloy to the surface of steel 45 at a minimum voltage and minimum current, the surface of the material is strengthened unevenly due to the adhesion of the electrode to the treated surface; the minimum voltage causes a sharp increase in the porosity of the applied coating; the thickness of the applied layer is small and does not exceed 0.1 mm. The surface is uneven, loose, with traces of oxides, and the number of arbitrary passes of the alloying electrode, i.e., passes at which the thickness of the hardened layer increases, does not exceed eight. This is due to an increase in thermal stresses caused by local temperature drops at the interface between the cladding layer and the base, and mainly to the adhesive nature of the bonding of the cladding layer and the base. In addition, the hardness of the cladding layer is lower than the hardness of the electrode. For example, the T15K6 hard alloy plates used in the experiments had a hardness of 85−90 HRC, and in the cladding layer, this material has a hardness of 80−85 HRC.

In the next set of experiments, carbon dioxide was supplied to the coating area to prevent oxidation. This made it possible, with the same electrical parameters, to increase the number of passes, respectively, the number of coating layers applied, to twenty, and to obtain a total coating thickness of up to 0.3 mm with a dense structure and without oxides. Obtaining a coating of such thickness makes it possible not only to strengthen, but also to restore the dimensions of worn machine parts.

Discussion and Conclusions. It is possible to increase the operational characteristics of machine parts and cutting tools without compromising economic indicators through applying coatings on their working surfaces using the ESA method. The considered technology, due to point heating, in which there is no deformation of the substrate (base), and local coating, enables to restore the dimensions of complex-shaped parts lost as a result of wear. This is possible due to the use of a protective environment in the form of carbon dioxide for ESA since it provides increasing the thickness of the coating to 0.3 mm and achieving its dense structure that does not have oxides.

Values of the electric spark alloying parameters significantly affect the intensity of coating application and the quality of the resulting surface. A rise of the electrical parameters causes an amplification of the intensity of each individual electric discharge and, within certain limits, contributes to an increase in the amount of the transferred coating material and deeper transformations in the coated surface (in the discharge zone).

Thus, an electric spark alloying installation equipped with monitoring and diagnostic tools, as well as a protective gas supply system, can be used for hardening and restoring machine parts and cutting tools.

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