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APPLICATION OF ELECTRIC DISCHARGES IN IMPULSE IN MICRO AND NANO-TECHNOLOGY

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Abstract: The results of experimental investigations on the application of electrical discharges in impulse at micro- and nano- surface strata formation are presented in this work. The possibility of meniscuses extraction is demonstrated. It provides the increasing of cathodes active surface area up to 8 times and the increasing of thermo-electronic emission capacity up to 10 times. The surface oxidation occurs at nano-scale depths under the regime of "cold" electrode spots action. The oxide pellicles increases by 10 times the resistance to corrosion of pieces made of construction steel.
Key words: meniscus, oxide pellicle, electrical discharges in impulse, surface, thermo-electronic emission

1. INTRODUCTION

Electrical discharges in impulse have found a wide technological application: dimensional processing via electro-erosion [1], powder and compact materials deposit formation, graphite deposit formation accompanied by chemical-thermal surface treatment [2], etc.
A series of papers have recently appeared [3, 4, 5]. They review the physics of pulsed electric discharges plasma channel interaction with electrode surfaces and from the point of view of new scientific hypotheses offer new fields for their application as concentrated sources of energy.
The new hypotheses treat the interaction of the electric discharges plasma channel with the electrode surfaces via electrode spots:
-electrode spots by the character of interaction with the electrode surfaces were classified into "cold" and "warm", the first are used to maintain on the surface irregularities and dirt and causes thermal interactions on the surface processed without submitting it to melt and the "warm" appear in the first and cause the surface to melt and vaporize [2];
-electrode spots are migratory and they are moving the electrode surfaces at certain speed: the "cold" at 75...100 m/s (seventy-five....one hundred meters per second) and the "warm" – at about 30 m/s (thirty meters per second), [ ];
-we submitted a new hypothesis crater formation mechanism based on electro-capillary waves developing on the surface of the liquid metal in the electric field of electrical discharge pulse;
-erosion craters were found to differ greatly electricity between them [2] as follows: the first have smooth spherical surface, the rough and the second are centered round a conical meniscus (the meniscus located in the center of the crater can cause its formation).
Theoretical and experimental studies of the process of taking material from the electrode surface at interaction with the plasma channel formed by the pulsed electrical discharges and understanding the mechanism of erosion is important to design new processing methods, as well as to design new devices and equipment for surface treatment of parts with high productivity and broadening the scope of the electrical discharges in impulse applicability as a concentrated source of energy.
Direct measurement of anodic and cathodic voltage drop is impossible for a small size of the gap. Electrode erosion was determined by weighing samples before and after processing. This allowed us to determine the ratio of the anode voltage drop and the cathode by the ratio of masses of material drawn:

$$\frac{-\Delta m_a}{\Delta m_k} = \frac{-U_a}{U_k} \qquad (1)$$

where Δma, Δmk – are respectively the mass of material taken from the anode and the cathode; Ua, Uk – voltage drop at the anode and cathode. To take into account that the gap is covered by the same current and the electrodes are made of the same material.
It was supposed that electrode patches are some point sources of heat and electric fields (fig. 1). They are located at a certain height in relation to the electrode surface. This is confirmed experimentally by the spherical form of craters that are formed on the electrode surfaces.

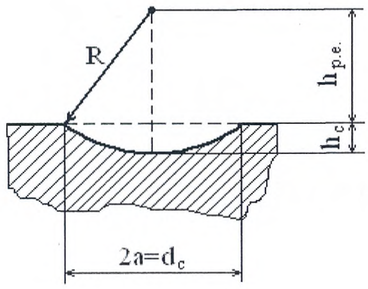


Fig. 1. General view of an erosion crater formed by a singular electrode spot

To determine the height at which cathodic and anodic spots are located we deduced the following relation:

$$h_{pe} = \frac{a^2 - h_{cs}^2}{2h_{cs}} \qquad (2)$$

R - spherical calotte radius;
a - radius of the crater;
h_{cs} - spherical calotte height;
h_{pe} - height of the electrode spot on processed surface.

2. MATERIALS AND METHODS OF EXPERIMENTAL INVESTIGATIONS

In order to realize the experimental investigations we have used the generator of current impulses induced from a voltage block at a high tension of 12 kV and the current being of 0,3 mA [2].
The modifying of metal surfaces with formation the cone meniscuses is realized using two electrodes made of the same material: the one (the tool-electrode) has a cylindrical form with a 1 mm diameter, another electrode has a plane surface [3].
When processing plane surfaces both the piece and the tool-electrode were made of steel C45 under the form of a cylinder with a 10 mm diameter; they were placed in the device of the tool machine with their active surfaces being parallel while the electrical discharges scanned the processed surface via the migration of the plasma canal on these surfaces for one cycle of processing [2, 3].
The analysis of the morphology and chemical composition of the processed samples was done with the help of the electronic microscope of the type TESCAN.

3. RESULTS AND THEIR ANALYSIS

A physical model of the electro-erosion phenomenon was developed based on the experimental research [2]. It includes the following phases with formation of three types of craters (fig. 2): ignition of electric discharge pulse forming a conductive channel; development of the plasma channel and electrode surface melting; perturbations of the liquid metal surface with formation of semicircular meniscuses; two or more channels are simultaneously formed for high intensities of discharge currents in the gap.

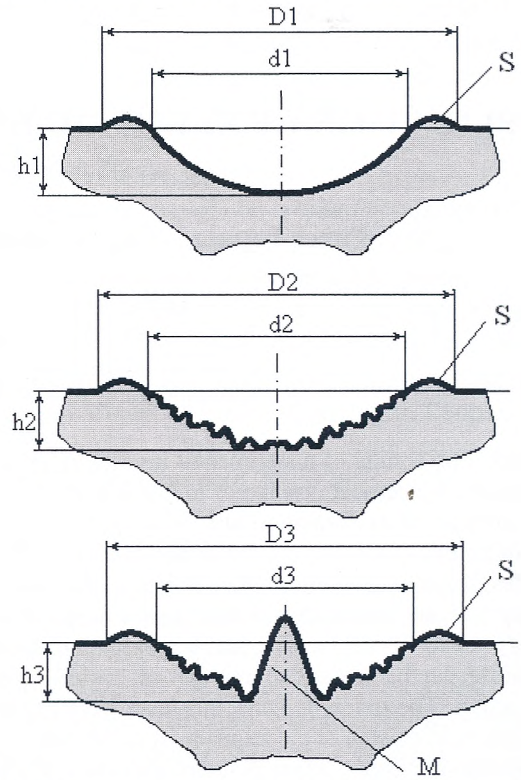


Fig. 2. A general view of craters that can form under a singular impulse electrical discharge: (D_1, D_2, D_3) – diameters of craters with concentrical wave of material surplus; (d_1, d_2, d_3) – diameters of three tipes of craters by zero line; (h_1, h_2, h_3) – crater heights; M – meniscus; S – wave of material surplus [2]

Two or more meniscuses (they can merge because of Lorentz forces through which the parallel currents in the same direction interact) are extracted from electrode surfaces; under the action of electric field due to surface electric charge distribution a droplet formation by draining the electrified liquid in the direction of electric field action occurs; if the surface tension is exceeded by the electro dynamic forces, the drop that is on the meniscus surface will break and will transfer to the opposite electrode surface or will be expelled from the gap; in the droplet formation and rupture, a semispherical meniscus becomes a conical meniscus with an angle on the top between 88...92 (as we can see an example of the extracted meniscus at fig. 3) degrees; when the electric discharge terminates, if the material extracted as meniscus succeeds in crystallizing during the flow in the reverse direction, then it keeps its shape and dimensions. If the material fails to crystallize, under the action of surface tension, and/or gravity force, it drains in the opposite direction, sliding on the surface of the semispherical crater, it is expelled from it and it crystallizes on the surface in the form of concentric wave.
Different experimental investigations have been done on extracting and freezing meniscuses from different materials (see table 1).

Having analyzed the results presented in table 1 (the constant values: the value of the interstice – S=0,2mm, the voltage drop – U=21V and the number of discharges - one) we may notice that the energy necessary for melting the surface and the length of the excited wave, as well as the height of the produced meniscuses, depend on the physical-thermal properties of the electrode material.

Fig. 3. Meniscus extracted from the electrode surface made of W(90%)+Re(10%). The anode is located in the down position. The energy regime of impulse generator: the size of the interstice S = 0.2 mm, the capacity of condencer battery C = 100 μF, the voltage on the condencer battery U_c = 60V, impulse duration t = 100μs

Table 1. Some experimental results on extracting the meniscus surfaces made of different material

Material	Height of meniscus H_m, [μm]	Length wave λ, [μm]	Energy W_s, [J]	Number of electrical discharges	Gap size S, [mm]	Voltage on interstice U_s, [V]
Niobium	0.06	0.36	0.58	1	0.2	21
Copper	0.03	0.36	0.26	1	0.2	21
Zirconium	0.03	0.52	3.17	1	0.2	21
Titan	0.02	0.06	1.03	1	0.2	21
Tungsten	0.02	0.06	18.72	1	0.2	21

The practical application of the meniscuses aiming at modifying the surface micro- geometry has proved that one meniscus causes the increase of the surface area processed about 8 times. The surfaces with meniscuses applied in building cathodes for electron canons provide an increase of the thermo-emission current by 10 times under constant functioning conditions (fig. 4) [3].

It was demonstrated that in the regime of plasma channel interaction with the processed surface (specimen made of steel C45) via "cold" electrode spots and the analysis of their after-processing chemical content they contained a considerable percentage of C, N, O, Fe. Out of these elements Fe and C are found in the material used to make the piece, while O and N are implanted in the piece material from the working medium (air).

The morphology of surface strata is shown in fig. 5.

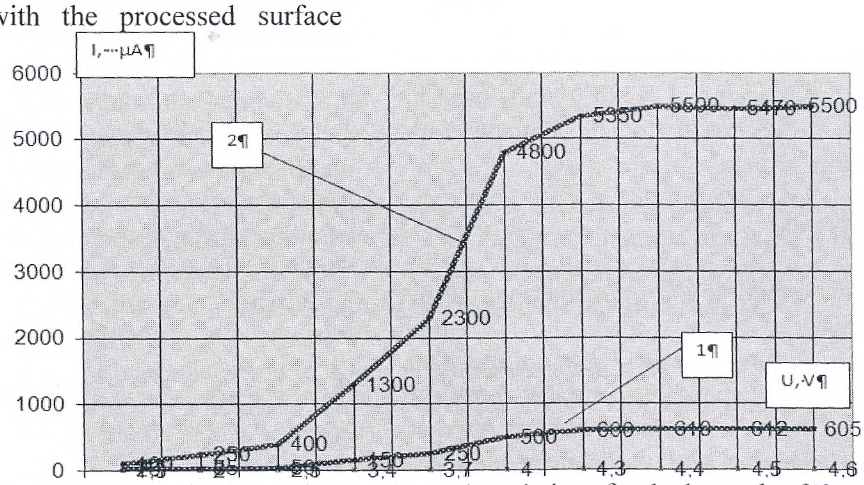
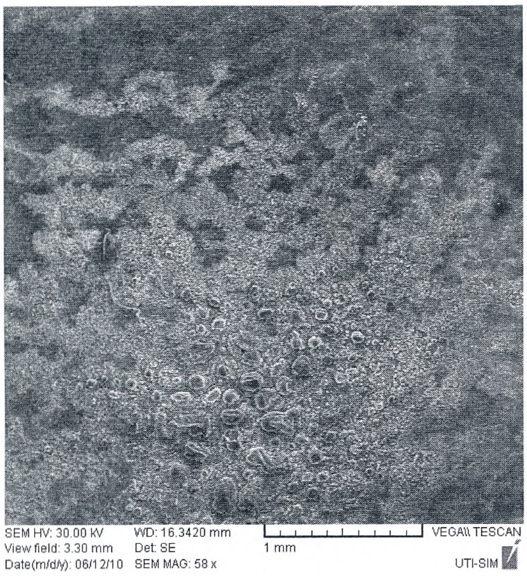
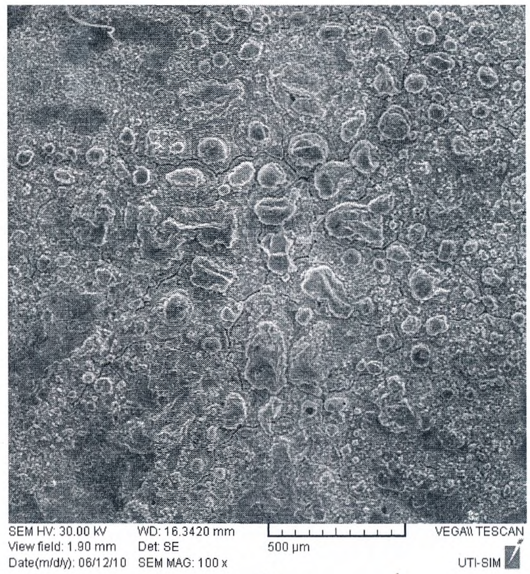


Fig. 4. Volt-amperic characterization of thermo-electronic emission of cathodes made of Tungsten: 1 – unprocessed cathode; 2 – cathode with meniscuses extracted on its active surface



a)



b)

Fig. 5. Microstructures SEM: a) 58×; b) 100×.
The processing regime: the charging voltage of the condenser battery U_c=140 V; the capacity C=600μF; the distance between electrodes S=1.5mm; the impulse frequency f =15Hz; the duration of processing τ =2min

The formation of oxide pellicles on the piece surfaces does not lead to changes in their geometry and dimensions but gives them new properties. The process of oxide pellicle formation is accompanied by surface hardening in depths up to 240 nm. The oxide formation in the amorphous state is attested in these thin strata and the amount of dissolved oxygen reaches about 59% at [4]. Experimental investigations have shown that the surface active resistance of these pellicles constitutes 10^6 Ω, the potential of corrosion increases for steel by 10 times and the speed of corrosion decreases by 2...4 times for construction steel [4, 5]. Oxide pellicle formation is performed on flat, rotating and combined, interior and exterior piece surfaces made of metal materials, for which reason it can be applied: in oxide pellicle formation on piece surfaces aiming at providing anticorrosive protection; in surface passivation of construction pieces used in the chemical industry; in manufacturing the active resistances of high values (10^6 Ω) and small dimensions (1x1x0,01mm) used in microelectronics; in the production of elements with electronic emission surface.

4. CONCLUSIONS

The results of our experimental investigations allow us to conclude that:

1. Meniscuses formation or thermo-chemical processes can occur depending on the type of electrode spots ("warm" or "cold") that interact through the plasma channel with work-piece surface.

2 Meniscuses extracted from the active work-piece surface increase their active area up to 8 times, and increase their thermo-electronic emission capacity up to 10 times.

3. Formation of oxide nano-pellicles by applying electrical discharges in impulse provides increasing the resistance to corrosion of pieces made of construction steel by 10 times.

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