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Peculiarity of the Tool-Electrode Wear Mechanism during Surface Machining with Electric Discharges in Pulse

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Abstract. The paper presents the results of experimental research on the wear mechanism of the tool-electrode as a result of machining metal materials by applying electric discharges in pulse. It highlights the requirements that should be followed when designing and developing the tool-electrode. It examines several phenomena noticed on the tool-electrode surface, exactly, the oxide layer formation and the modification of the micro-geometry of the tungsten tool-electrode surface. The paper presents the experimental results on the behavior of the tool-electrode made of stainless steel after the metal parts have been machined. It also presents the phases of mass transfer in the gap between electrodes.

Introduction

It is known that the wear phenomenon of the used tool-electrode occurs during machining processes, such as surface micro geometry modification (conical meniscus removal), surface oxidation (oxide film formation) [3, 4], deposit layer formation (electrical spark alloying) [4] and electro-erosion machining (obtaining orifices and shaped canals) [1, 2].

Wear during processing is due to the electro-erosion phenomenon, i.e. electrode destruction while electric current pulses pass. Metal removal is due to the local heating of electrode surfaces and to metal melting and vaporization. Electro-erosion methods can be applied to machine complex shape parts, for example, slot dies and press-forms, non cylindrical holes, etc. The electro-spark method is mainly used for precise machining of radio electronic apparatus parts; the method of electro impulses is used for spatial machining of complex surfaces.

The following requirements should be followed when designing and developing the tool-electrode [1, 2]:

- the material should be as cheap as possible;
- the production material will possess high resistance to electro-erosion;
- the production material will shape easily to confer necessary forms;
- when expensive materials are used, the tool will be bi-component (the body will be made of cheap materials while the active head will be made of expensive material).

When surface processing ends in the formation of oxide films, graphite film depositions of compact and powder materials, modification of surface micro-geometry, etc. the submitted prescriptions in relation to the construction, geometry and the composition of the used material are different for each of the machinings.

For example, for the formation of deposits from compact materials it is more important for the tool-electrode erosion to be maximized to ensure high productivity of layer formation and its quality; when the oxide films are formed [4], it is necessary that the electrode material should not influence the film composition, thus it will have a high resistance to erosion and at the same time will have a high resistance to oxidation; when powder deposits are formed [8], it is necessary to avoid the tool wear and powder particle sticking to its surface (because the size of the energy gap changes and the processing of energetic regime is violated); when graphite films are formed [6,9], (it will be made of high purity graphite), it will relatively slightly erode and it will preserve the size of the gap constant by permanently renewing the active surface.

Methodology of experimental research

Electrode-tool design takes into account several criteria depending on the specific technological process of machining: selection of the material for tool-electrode production, stamping the form and dimensions typical of the machining operation, power regime limits, parameters of fixation and positioning devices, working environment and others. The materials for the production of tool-electrodes applied in the research were Cu, steel, titanium, graphite and W + Re(10%).

In order to investigate the phenomenon of tool-electrode wear applying electric discharges in pulse we have used the experimental installation [4] that consists of two modules: the mechanical module and the electrical one. The electric module includes the RC power generator of pulses, the inducement and the command blocks.

During the research, the size of the gap between electrodes was measured using a comparator with a dial with an exactness of 0.01 mm and was permanently controlled by an MPB-2 microscope. The electro dynamic parameters (pulse duration, pulse current variation, voltage drop on the gap, and the energy released from a solitary discharge) were determined by oscilloscoping [4, 5].

The electric discharges took place in the system of electrodes made of the same material (the tool in the form of a cylindrical bar with a diameter of millimeter order, and the piece was a 20x20x3 mm plate and placed perpendicularly one towards the other, with a 0.3 - 2.5 mm gap. In all cases the anode was placed in the top position.

Results of experimental investigations

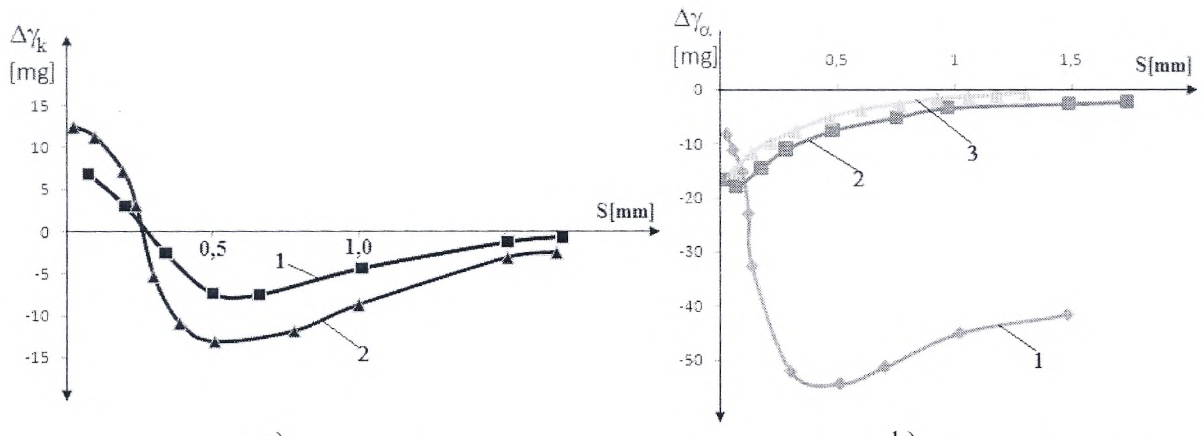
The experimental research carried out by the authors [1, 2] have proved that, in the case of dimensional processing, the growth of the voltage of the electric discharge pulse current (I) is accompanied by the growth of machining productivity. At the same time, the relative wear of tool Q, defined as the ratio between tool absolute wear (V_s) and the machining productivity (V_p), decreases [2]:

$$Q = \frac{V_S}{V_p} \cdot 10^2 \ (\%) \tag{1}$$

The higher the productivity, the lower the tool relative wear. Regarding the maximum allowed voltage there are limits imposed by the nature of the two electrodes (thermal and electrical properties), and by the possibility of rapid removal of heat that is produced in the working gap.

The quantitative assessment of the process of electrode electro-erosion (anode or cathode) for solitary discharges it is practically impossible to realize the formation of chemical bonds (oxides, nitrates, etc.) because of the reciprocal mass transfer between electrodes [6], particularly due to very small changes in the mass of the investigated sample, the eroded mass at one discharge being of about 10^{-6}-10^{-4} g.

Figures 1, a and b show the mass variations of cathodes made of steel and titanium, and respectively of the anodes made of copper, steel and graphite depending on the size of the gap at constant energy accumulated on the condenser bar of the current impulse generator. When the gap values are $S \leq 0.2 \div 0.3$ mm, there is an increase of the cathode mass (Figure 1,a) that may be explained on the basis of anode material drawing and transfer onto the cathode surface. When the gap values are $S = 0.3 \div 0.8$ mm, we can attest an erosion through cathode wear and for $S > 1.2 \div 1.5$ mm the cathode wear is very small.



a) b)

Fig. 1. Mass variation of cathodes (a) made of steel (1) and titanium (2) and mass variation of anodes (b) made of graphite (1), steel (2) and copper (3) depending on the size of the gap, Uc = 240V, f = 40 Hz, specific time of machining-1 min/cm^2

When the gap values grow, the erosion of anodes made of copper and steel decreases (Figure 1,b, Curves 2 and 3). The erosion of the graphite anode is different from that of anodes made of steel and copper (Figure 1,b, Curve 1) and is similar to that of the metal cathode (Figure 1,a).

The experimental findings presented above can be explained by the fact that more effects simultaneously concurrent in relatively small volumes in very short periods of time are produced. Thus it was noted in the papers [4-6] that when the gap dimensions grow, the following happens: redistribution of energy between electrode surfaces and the plasma canal in favor of the latter and the polycanal structure of plasma in the gap is made evident; the interaction of the plasma canal with electrode surfaces occurs through the "cold" and "hot" electrode spots which, in fact, determine the nature of erosion (vaporization, melting and drawing to the material or thermal interaction accompanied by erosion in solid state).

If we take into account what has been said above, it becomes clear that the state in which the erosion occurs is determined by the types of electrode spots. It has already been mentioned in the papers [4-6] that the "cold" electrode spots carry in themselves a thermal interaction, while the "hot" ones cause melting, vaporization and drawing to the material. At the same time, as it was mentioned in [4], electrode spots are both, heat sources and very strong electric field sources (if to create the machining conditions the voltage of the electric field on the gap constitutes 10^3V/m, electric fields with the voltage equal to 10^6 V/m appear under the influence of electrode spots), the drop of anodic and cathodic voltage is different from the point of view of the sign (the first is negative and the second is positive) and according to the absolute value (the anode value is several times higher than the cathode value and it is expressed by the ratio$\Delta\gamma_a/\Delta\gamma_k$), a fact which actually explains the amount of melted and drawn material from the surfaces of anode and under conditions of the same discharge.

Thus, for one and the same energy accumulated on the condenser battery, only by changing the gap size we can get to three distinct types of interactions: melting and vaporization, melting and drawing in a liquid state and thermal interaction, only thermal interaction.

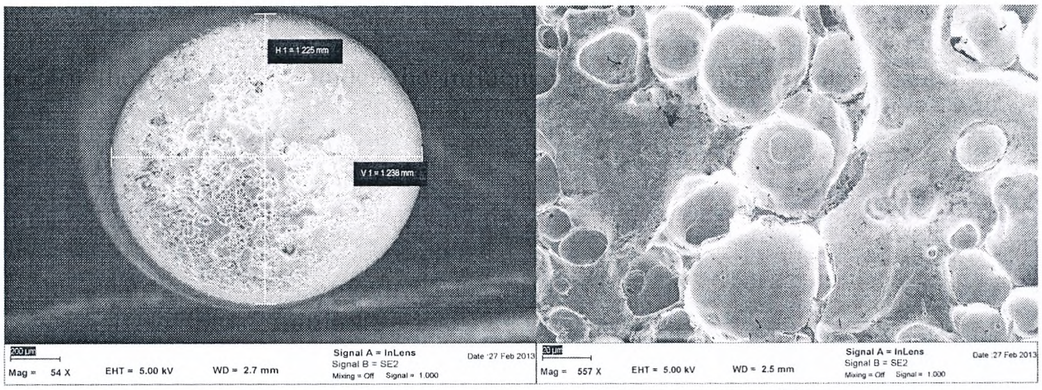
In accordance with the theory of electro-erosion, the material is taken from the anode surface under the form of ionized drops or positive ions; while the cathode surface emits mainly electrons. These findings are not valid for the electrode made of graphite used as cathode. If we analyse the character of the electrode made of graphite (Figure 1, b, Curve 1), we can clearly see that it is totally different in comparison with the mass erosion of metal materials. This can be explained based on the sample of electo-erosion of graphite developed in [6, 7]. Considering the fact that the electro- erosion process is an electro-chemical one that occurs at high temperatures, we may assume that recombinational and dissociative processes occur both at the surface of the anode and cathode electrodes and in the plasma canal.

Proceeding from the actual conditions (working environment air at atmospheric pressure), we could assume that, due to the fact that the plasma canal oxygen interacts more intensively with the cathode electrode surface, oxidation reactions occur with the release of carbon monoxide CO and possibly the formation of carbon dioxide CO_2. We can find the confirmation of the processes of graphite oxidation at the surface of the cathode in the results obtained by the authors of [9] concerning the process of oxide film formation on the surfaces of metal parts applying electric discharges in pulse. The carbon monoxide in the plasma of electric discharges in pulse gets negatively electrified by capturing an electron and it is subject to movement towards the surface of the piece anode.

Due to the fact that the energy released at the surface of the anode is higher than the energy released in the gap, the gas molecule dissociates into carbon and oxygen ions. The oxygen ions return to the plasma canal and perform the superficial oxidation of the cathode; the carbon ones recombine at the surface of the anode, forming the carbon film. Further, the graphite film formed on the surface of the work piece, under the influence of the heat at the plasma interface from the plasma canal, is subjected to the diffusion processes at the surface of the piece forming the hardened layer. However the erosion of some quantity of graphite from this surface is not excluded in the last phase.

When the polarity is changed, the graphite tool-electrode erodes less and under the influence of the energy from the plasma canal the graphite film diffuses in the piece and in this way the micro-hardening at the surface increases the functional properties of the pieces subjected to machining.

The SEM analysis of the electrode surface made of tungsten subjected to machining according to the regime parameters: S=0.3mm, U=240V, f=1 Hz, Wc=17,2 J, is presented in Figure 2. In this processing regime, one can notice a multitude of marks of melting and thermal character randomly distributed on the active surface of the tool. This confirms the hypothesis about the multiple canal of the plasma formation in the gap. The random distribution of the imprints also attests the fact that the discharge micro canals interact with the electrode surfaces through the electrode spots (which migrate on the asperity surface and on its impurities).



a) b)

Fig. 2. General view of the working surface of the tool-electrode made of W+Re(10%)
a) image of the tool-electrode obtained through the SEM method; b) the active surface has a developed micro geometry

After machining the work piece surface of the tool-electrode around the melting zone (or away from it), we can notice the formation of an oxide film. This oxide layer positively influences the process of machining because it causes the increase of electrical perforation resistance in the gap causing the intensification of the discharge power. As shown in Figure 2, b, the active surface has a developed micro-geometry as a result of a simultaneous or successive action of a number of discharge canals in the gap, thus increasing the productivity and machining quality. The formation of this micro-geometry can be explained on the basis of the electro-erosion physical model developed by the authors [4].

When the electric discharge ends, we may have two situations: if the extracted meniscus shaped material manages to crystallize before the drain in opposite direction then it keeps its shape and dimensions, if the material has not crystallized under the influence of the surface voltage force or under the influence of the weight force, it flows in the opposite direction, sliding on the hemispherical surface of the crater, it is ejected from it and crystallized as a concentric wave.

It has been noticed that practically all craters obtained at electric-erosion have an ideal spherical shape. This occurs due to the fact that at micro discharge (dimensional processing) the released surface energy depends on the electric field voltage vector and therefore the liquid metal bath copies the vector radius of the electric field. In this case, we confirm the hypothesis put forward in [4] according to which the electrode spot [5-8], which is the cause of different anode and cathode heating and melting (under the same conditions as those for solitary electric discharge), is a point-shaped heat source in which the force lines of the electric field, created by the anode and cathode drop of the potential fall, close.

Figure 3 presents frames of ultra rapid shooting of the process of electrode material drawing under conditions of electric discharges in pulse. We can observe the formation of the meniscus under the influence of the electric field, the melted metal drain on it accompanied by the formation of a drop (or simultaneously of more than one), the drawing of the drop from the meniscus and its transfer to the cathode surface. We can see that the drop (or the drops) in the gap (since the moment the narrow part is formed and drawn from the meniscus) becomes part of the discharge circuit and it interacts with the discharge canal through the electrode spots (Figure 3, the bright areola). The shifting track of electrode spots changes its shape simultaneously with the landing of particles and their shape transformation.

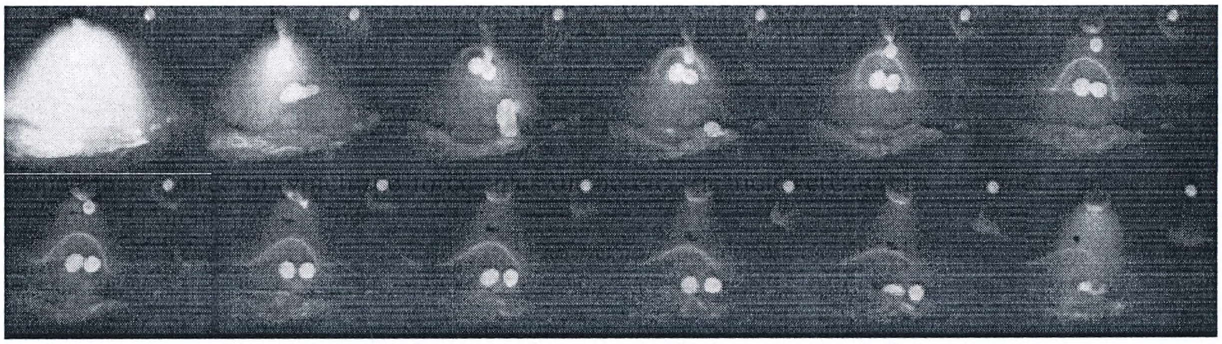
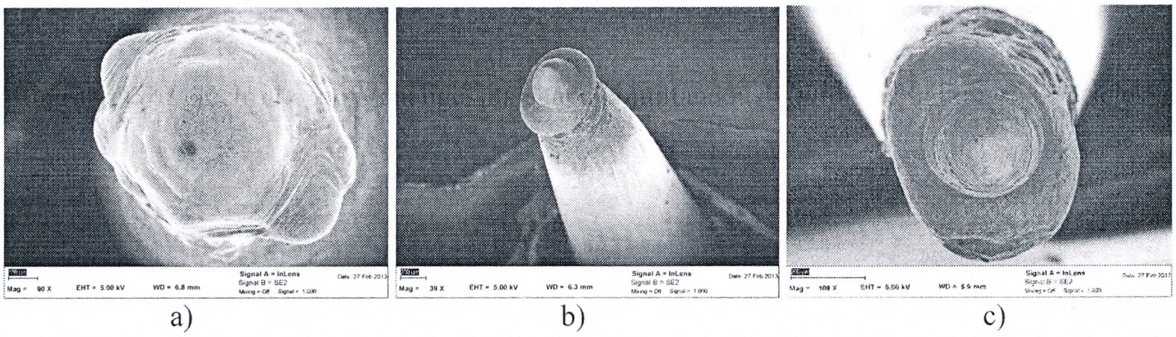


Fig. 3. The mechanism of mass transfer between tool-electrodes



a) b) c)

Fig. 4. Images obtained through SEM of cylindrical bar-shaped cathode electrodes made of stainless steel with a 1.3 mm diameter, pointed under an angle of 10 degrees after processing by electric discharges in pulse under different regimes (f=0.25-0.5 Hz, C=600 μF): a) S=0.3 mm U=100 V; b) S=0.4 mm, U=80 V; c) S=0.5 mm, U=80 V

If we analyze Figure 4, it is easy to see how the two competing phenomena are produced: the melted surface is extracted from the active surface under the form of Taylor cone roughness; simultaneously a metal wave concentric with the roughness is formed and crystallized around it. The first phenomenon has already been explained on the basis of the liquid metal interaction with the temperature and electric fields; the formation of the wave round the Taylor cone can be hypothetically explained based on the pressure caused by the electrical particles and by the drain of a part of the material under the influence of the surface voltage force (an important one if we take into account the capillary effects at the interaction between the liquid metal and the solid of very small portions). This phenomenon is observed both for the pointed tip electrodes and for those with a plane surface which proves that the hypothesis is viable.

The last statement plays an important role in the active geometry modification of the electrode and significantly influences the processing technology. It means that it is necessary to take into account the initial shape and dimensions of the tool when designing the geometry of the tool-electrode in the process of sizing.

Conclusions

The tool-electrode wear is due to the following factors and conditions: the physical-mechanical and thermal properties of the production material, the micro or macro geometric properties of the tool and work piece surfaces, the electrical and non-electrical parameters of the processing regime, the properties of the working environment and the processing procedure.

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