Specific Features of Surface Morphology During Plasma Electrolytic Processing

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Abstract This article presents the features of the morphology of the surface layer of stainless, tool steels, copper in different types of electrolytic-plasma treatment. It is shown that the change in the surface layer of materials depends on the type of processing, the electrode-tool used, the initial parameter of the surface layer roughness, the electrolyte flow rate and the quality of surface preparation. The study uses different electrode tools to obtain a product with high precision and low surface roughness. The effect of plasma electrolytic treatment on the parameters of sample roughness and weight loss of samples made of stainless steels, tool steels and copper grade was studied. The minimum depth of material removal is fixed when using different technological modes. The reasons for the appearance of microcraters in the surface during electrolytic-plasma treatment are analyzed. The results of the work will make it possible to use the knowledge gained for finishing and roughing plasma electrolyte treatment.

Keywords Electrolytic jet · Electrolytic bath · Finishing · Roughing · Hollow cathode · Ganged current lead · Plasma electrolyte treatment

1 Introduction

Responsible mechanical engineering products, as a rule, have significant limitations in accuracy, the Ra parameter of the surface roughness, and the quality of the surface layer. These requirements are a tight tolerance corresponding to 5–6 grade of accuracy, a surface roughness parameter of less than $0.1 \leq$ Ra, the presence of defects in the surface layer of less than 10 μm. Obtaining products with these requirements is a complex and time-consuming technological task. Achievement of the specified

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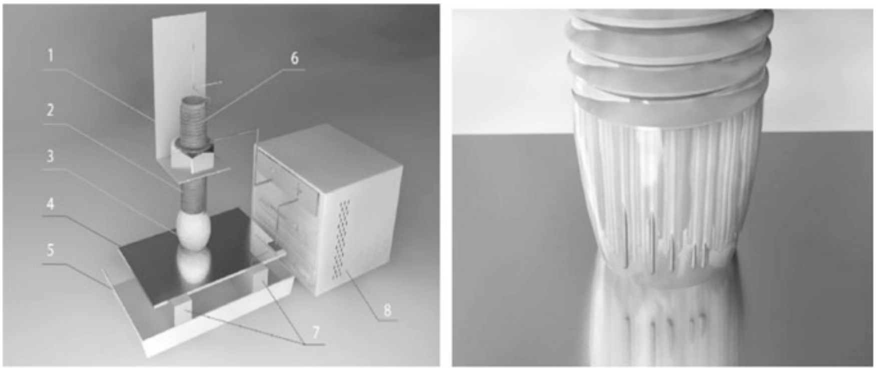
results is possible using the operation of finishing surface polishing using manual processing on polishing machines, using felt wheels using glued abrasive grains [1]. This method has a number of disadvantages associated with the unstable quality of grinding wheels, as well as insufficient stability of the dimensions performed using manual labor.

New surface finishing methods are replacing the traditional methods of surface finishing. These are methods of plasma electrolytic treatment by immersing the product in an electrolytic bath [2–4] or surface treatment with one or more electrolyte jets [5, 6]. The method of jet plasma electrolyte treatment includes processing the surface of a part (anode) with an electrolyte jet supplied from a nozzle connected to a negative potential [7]. The movement of the cathode is carried out using the program. It can have from two to five coordinate axes. The features of the method of jet plasma electrolyte treatment include low energy consumption, low processing temperatures, and a local processing zone [8, 9]. This method achieves high precision and low roughness of the processed surface. This method allows the polishing of complex surfaces such as dies, molds, turbine blades and other products made from various conductive materials. Undoubtedly, the method of jet plasma electrolytic treatment is applicable for accurate high-quality surface treatment. However, in the literature, the issues are insufficiently covered by issues related to the technological accuracy of the method, the minimum dimensions of the depth of the removed layer and the features of the formation of the morphology of the surface layer. Therefore, the purpose of our study is to study the effect of plasma electrolyte treatment on the accuracy, roughness and features of the formation of surface morphology. The tasks of our work are to study the parameter Ra of the surface roughness under various processing modes, to determine the amount of material loss, to establish the minimum value of the removed layer from the surface of the initial material, to study the features of the formation of surface morphology.

2 Materials and Experimental Setup

Experiments on plasma jet electrolytic treatment of samples were carried out on a pilot plant (Fig. 1). The installation consists of a system for precise positioning of the electrolyte supply system and a DC power supply unit made according to Larionov's scheme.

The voltage between the electrodes was set equal to 20–500 V. The nozzle speed was determined by the ratio of the distance traveled over the time measured by the stopwatch .The morphology of the samples was analyzed using an LV-41 metallographic microscope (Lomo, Russia), a Solver P-47 Pro scanning probe microscope (Russia), and a Zeiss Supra 55/55VP analytical field emission electron microscope (Germany). The depth of removal of the processed material was measured with a digital electronic indicator "Micron" with a graduation of 1 μm. The weight of the samples was measured on a BM213M laboratory balance with a graduation of 0.001 mg. To reduce the average measurement error, each plate was weighed at



a) *b*)

Fig. 1 Schematic diagrams of plasma electrolyte surface treatment: **a** 1—current lead holder, 2—hollow current lead, 3—electrolytic cathode, 4—sample, 5—electrolyte receiving bath, 6—electrolyte supply pipeline, 7—insulated supports, 8—DC power supply current; **b** ganged current lead

least 7 times before and after processing. The studies used a hollow current lead and a type-setting current lead, a magnetron spray head and an electrolytic bath. The electrolytes used were solutions of ammonium sulfate ($(NH_4)\ 2SO_4$)—10 g and ammonium citrate ($(NH_4)\ 3C_6H_5O_7$)—10 g in tap water, ammonium sulfate ($(NH_4)\ 2SO_4$) and sodium sulfate (Na_2SO_4)—30 g in tap water. The electrolyte was fed in a stream through a copper tube with an inner diameter of 3 mm with a volume flow rate of 4.6–9.0 L/h. The measurement of the volumetric flow rate of the electrolyte was carried out by passing the electrolyte weighing 100 g with fixing the transit time using a stopwatch. The experiment was carried out at atmospheric pressure on marked 25 samples with dimensions 45 × 50 mm, 100 × 200 mm made of stainless steel 08Kh18N9T, AISI 304, corrosion-resistant high-temperature steel 20Kh13, alloy tool steel KhVG, chromium-silicon-manganese steel 30KhGSA and copper M1.

3 Experiment Results

3.1 Determination of Surface Roughness Parameters

To obtain the minimum values of the parameters Ra of the surface roughness of the samples in the range of operating voltages from 20 to 500 V, samples from different materials were used. In the experiment, a fixed ganged current lead was used. The minimum values of the parameter Ra of the surface roughness of the samples were obtained by polishing AISI 304 stainless steel (Fig. 2). It is shown that the value curve is not monotonic. In the voltage range from 220 to 380 V, a sharp decrease in the

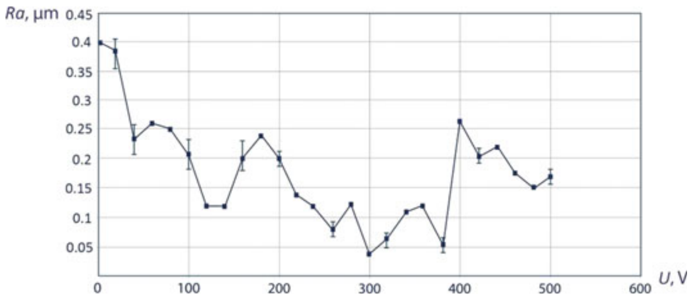


Fig. 2 Dependence of the roughness parameter on voltage during plasma electrolytic treatment of AISI 304 steel using a ganged current lead

roughness parameter to Ra 0.034 μm is observed. Obviously, this type of processing significantly affects the macro- and micro-reliefs of the surface.

With an increase in the operating voltage with a step of 20 V, a transition from a rough matte surface to a polished surface with a characteristic mirror-like shine is traced (Fig. 3). Different processing modes to varying degrees contribute to the removal of scratches and a decrease in the number and depth of depressions (holes) of the surface.

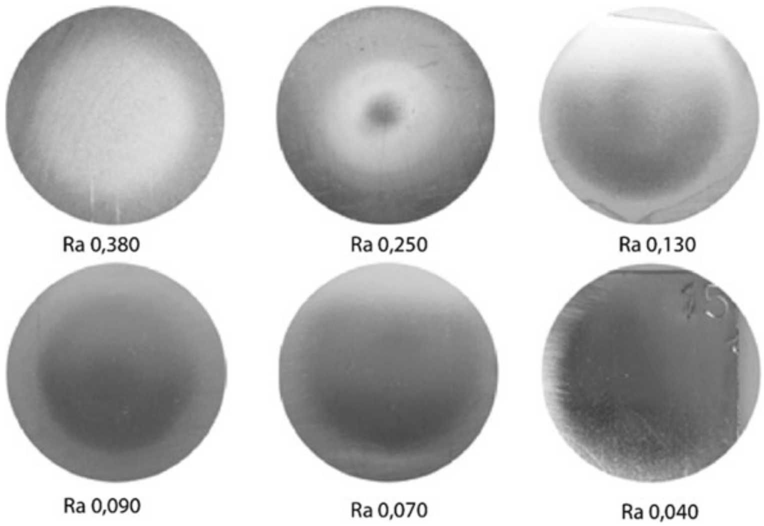


Fig. 3 Appearance of the surface of AISI 304 steel samples during plasma jet electrolytic treatment using a ganged current lead

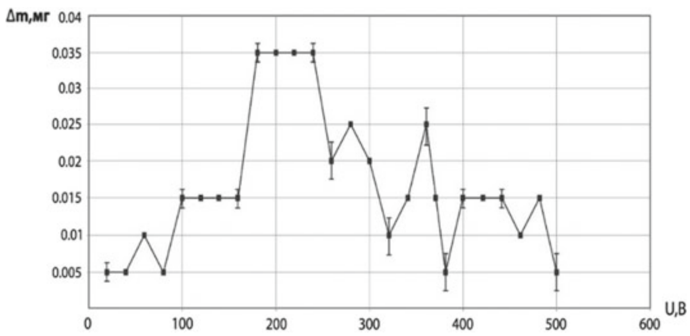


Fig. 4 Dependence of the sample weight loss on voltage during plasma electrolytic treatment of KhVG steel using a hollow current lead

3.2 Determination of Material Loss

The influence of jet electrolyte treatment on the value of the sample weight loss is most indicative for the KhVG steel when using a hollow current lead in the voltage range from 20 to 500 V (Fig. 4). Experiments show that the range from 160 to 300 V is characterized by increased metal removal in the electric discharge zone. This confirms the possibility of rough treatment with an electrolytic jet plasma in this voltage range. Also characteristic is the extreme value of material loss from 340 to 370 V. These extremes of material loss were also recorded for stainless steels at 340–460 V.

3.3 Formation of a Polished Surface with a Minimum Cut-Off Depth

However, for precision machining, a low Ra surface roughness is required. This is possible by removing the surface layer located between the maximum height of the tops and the minimum depth of the valleys of the microprofile. If this condition is met, a flat surface can be formed. Experiments show that the use of combined processing with the sequential use of ganged and hollow current leads allows you to effectively remove the tops of the micro-profile to a flat metal surface with subsequent polishing of the surface. The parameters of the electrolytic-plasma treatment of steel 20Kh13 using a hollow current lead are recorded in Table 1.

The parameters of the minimum depth of material removal using hollow and ganged current leads are fixed. The electrolyte solution in tap water contains ammonium sulfate and sodium sulfate. Research data are recorded in Table 2.

Based on the experimental results obtained, it can be concluded that the value of the minimum removal depth from the metal surface was 0.016 mm with a minimum surface roughness parameter Ra 0.083 μm.

Table 1 Depth of material removal from the sample surface using a hollow current lead

Length of the processed surface l, mm	Current I, A	Voltage U, V	Feed rate S, mm/min	Volume flow rate of electrolyte, l/h	Number of nozzle passes n, pcs	Depth of material removal from the sample surface, mm
50	1.02	225	34.1	9.0	1	0.112
50	0.71	230	17.1	9.0	1	0.130
50	0.65	230	17.1	6.1	1	0.058
50	0.40	250	17.1	4.6	1	0.146
50	1.42	250	17.1	4.6	1	0.205
58	0.33	260	17.1	4.6	1	0.144
58	0.33	260	17.1	4.6	3	0.092

Table 2 Depth of material removal from the sample surface with sequential use of ganged and hollow current leads

Processing area, cm^2	Current I, A	Voltage U, V	Volume flow rate of electrolyte, l/h	Number of passes by ganged/hollow current lead n, pcs	Depth of material removal from the sample surface, mm	Parameter Ra of surface roughness, μm
36	1.2–1.5	250–260	4–6	2/1 (3)	0.020	0.062
12	0.8–1.1	270	5–6	3/1 (4)	0.031	0.068
4	1.1	260	5	2/1 (3)	0.035	0.067
4	1.1	260	5	3/2 (5)	0.045	0.036
48	1.1	260	5	1	0.016	0.083

3.4 Analysis of the Morphology of the Surface Layer

The morphology of the surface of the part during plasma electrolytic treatment is of great importance. It determines the quality of the surface layer of the working surfaces of parts, has a significant effect on the service life of units and elements of any mechanisms. Under cyclic loads, special requirements are imposed on the defectiveness of the surface layers of parts. The presence of stress concentrators leads to the development of microcracks and the subsequent destruction of parts.

Only in rare cases does a defective surface relief play a positive role, such as when honing the inner surface of “cylinders”. In most other cases, it leads to component failure.

We carried out research using a Solver P-47 Pro scanning probe microscope with a resolution of 5 nm. They showed that during plasma electrolytic treatment in a bath, not only the quantitative indicators of surface roughness change, but also the nature of the roughness changes. This combination defines the term "surface roughness". This means a change in the surface morphology of the treatment object. However, treatment in a bath is not always possible to completely smooth out the existing surface relief (Fig. 5). Depending on the size and shape of the part, significant surface defects can remain. They can be classified into three groups, traces of previous processing, areas of polishing, areas of selective explosive transfer of structural elements into the electrolyte.

The explosive nature of the transfer of structural elements into the electrolyte is also observed for the plasma jet electrolyte treatment.

This is due to several main factors, the initial level of surface roughness, the presence of surface defects, plastic deformation of the surface layers, and the presence of non-conductive surface contamination. The high initial roughness parameter of the surface layer Ra << 0.8 μm complicates the formation of a smooth surface with high reflectivity due to the comparable value of the plasma electrolyte layer, equal to 50–100 μm. Surface defects in the form of microcraters, deep scratches, areas of plastic deformation require long-term surface treatment or the use of additional technical solutions. Surface contamination leads to the formation of a non-conductive layer in the local area.

As a rule, these are areas in deep depressions of the surface contaminated with non-conductive oxide or grease films or products of material erosion. The presence of such areas leads to the accumulation of a surface charge of the opposite sign and the explosive development of a discharge in the form of spark discharges of higher

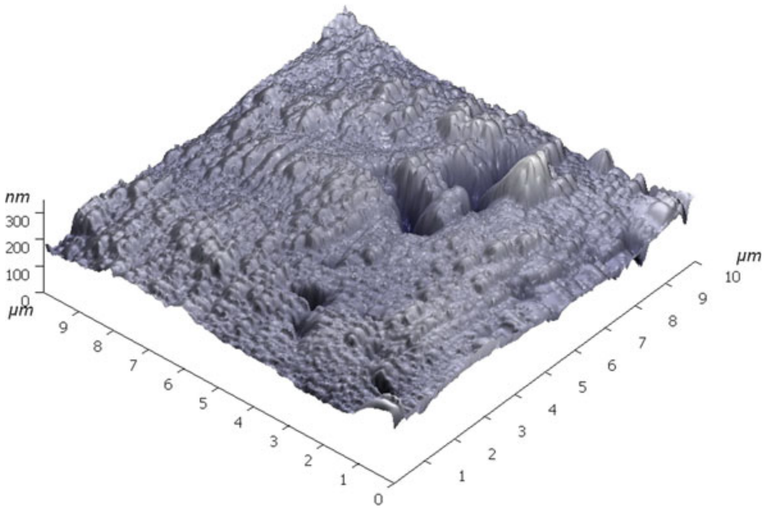


Fig. 5 Surface morphology of steel 30HGSA after plasma electrolytic treatment in a bath

power. This leads to the destruction of local surface zones mainly in the extended zone of deep grooves. In general, a change in the state of the surface layer occurs due to the intense formation of micro-discharges at the tops of microroughnesses.

In this case, when the electric field strength reaches, according to various estimates, 10^4–10^6 V/m, the discharge flows down to the top of the microroughness [10]. These microroughnesses can be formed as a group of grains, dislocations, or individual atoms. The removal of groups of atoms or individual atoms occurs, as a rule, already for an atomically aligned surface. Each type of current lead has its own peculiarity in the formation of the surface morphology. It is noted that during treatment with an electrolytic jet cathode using a hollow current lead, the formation of streamers is observed during the formation of a multichannel discharge. This may indicate the presence of uneven distribution of the electromagnetic field over the cross section of the electrolytic jet. Perhaps due to this, the localization of the maximum intensity of the electromagnetic field is present at the top of microroughnesses. The area of grooves on the surface has a lower potential, and in the presence of fatty films, zero or negative. This leads to the fact that when the charge of the opposite sign is accumulated, a discharge occurs between the non-conducting local zone and the zone with a high electric field strength. This leads to the erosion of microvolumes between the tops of microroughnesses (Fig. 6).

The ganged current lead has a higher uniformity of the field strength distribution in the area located directly under the current lead. Due to this, we have a field strength between the pointed peaks of microroughnesses and the opposite peaks of the ganged current lead. This facilitates the acceleration of the anodic processes of transfer of surface atoms into the solution and a higher rate of removal. The surface obtained with the use of a ganged current lead has a more uniform relief, the least roughness parameter and the minimum number of defects associated with the removal of microvolumes from the space between the vertices.

Mechanism of surface morphology change is well illustrated in Fig. 6. For the initial surface without processing, the tops of microroughnesses, blocks, foreign inclusions are clearly recorded. The presence of deep grooves (Fig. 6a) on the surface leads to additional formation of local depressions in them. Characteristic for the formation of surface morphology is the process of processing deep defects in the form of pits, obtained due to plastic deformation of the metal or having another origin. In the case of a shallow defect on the surface during processing, the radius also increases when passing to the main plane, with a smooth transition to the main surface and the complete disappearance of the microdefect. Another characteristic feature is the predominant influence of the chemical mechanism during the plasma electrolyte treatment. This is observed at high volumetric electrolyte flow rates $\geq$ 8 l/h and high salt concentration (Fig. 6i). In this case, the microrelief is removed with the identification of grain boundaries on the surface. The features of the magnetron spray head are as follows. This is the presence of a magnetic trap that traps electrons due to the magnetic field and makes them rotate due to the application of an electric field.

A significant number of collisions with atoms of the vapor–gas shell increases the percentage of ionization and increases the rate of processes on the surface. As

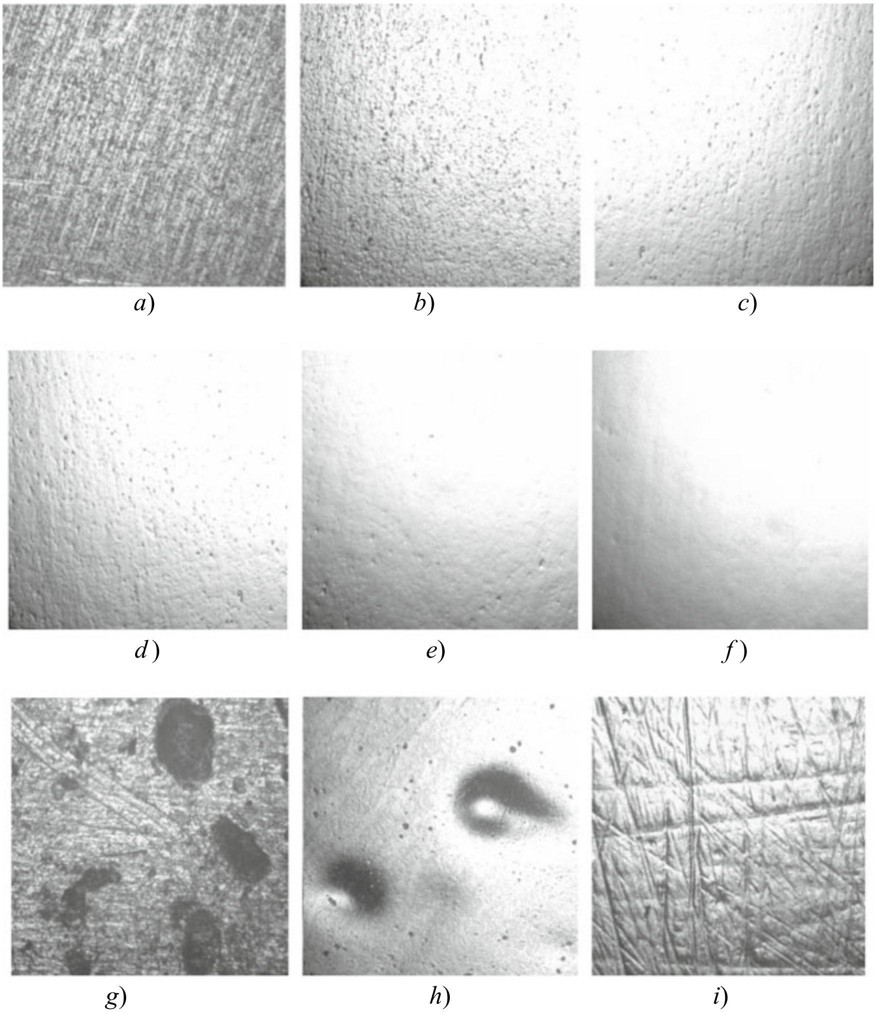


Fig. 6 Changes in the surface morphology of samples in the course of plasma electrolytic treatment when using sequentially ganged and hollow current leads: **a**–**f** AISI 304 steel; **g**, **h** steel 08Kh18N9T; **i** copper M1

a result, this type of processing has a higher reflectivity. The mechanism of surface morphology change when using a magnetron spray head when processing 20Kh13 steel after sawing with a band saw is shown (Fig. 7). Evaluation of the surface morphology using a magnetron spray head shows that in the process of removing microrelief, the tops of microroughnesses are smoothed out. The treatment is carried out evenly over the surface of the ring formed by the magnetic field of the magnetron spray head. In this case, the appearance of microdefects < 10 μm in size between the depressions of the microrelief is also recorded. Due to the fact that the initial

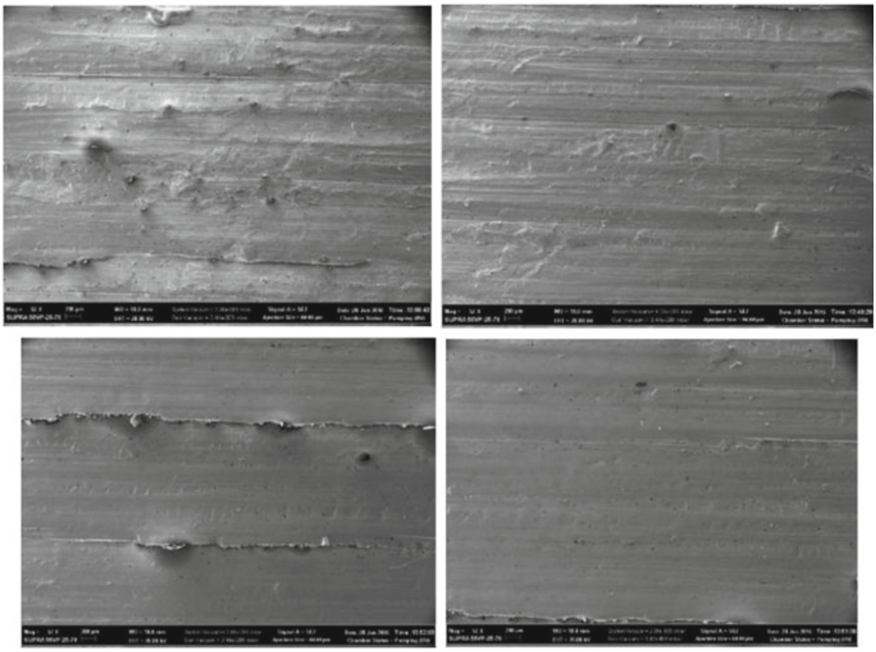


Fig. 7 Surface morphology of 20Kh13 steel specimens after treatment with a magnetron spray head

surface of the samples is very developed, a sufficient period is necessary for the final smoothing of the surface. In this case, a layer up to 0.6–0.8 mm thick is removed from the surface. The appearance of local zones of material discontinuity associated with the initial plastic flow of the material during sawing is noted.

4 Results and Discussion

As a result of numerous experiments carried out to study the formation of surface morphology, one can come to the following conclusions regarding the depth of plasma electrolyte action on the surface of samples from different materials. The minimum processing depth primarily depends on the tasks at hand. On the example of copper samples M1 it is shown that the effect of surface polishing with high reflective properties is manifested at a sufficiently developed surface roughness. This may indicate the removal of a thin layer from the surface with a thickness of less than 0.01 μm. For the depth of material removal from a developed surface with a roughness parameter Ra $\geq$ 0.8 μm, it is necessary to remove a technological allowance equal to 15–20 μm from the surface. In this case, we can obtain a surface without a defective layer with a roughness parameter Ra $\geq$ 0.1 μm. This is required in order to level the surface to the bottom of the depressions of the roughness, and then to the bottom of the microcraters formed during the initial surface treatment operations. An important point in the study of surface morphology is the physical essence of the phenomenon of removal of surface layers with a developed surface topography. It is significant that the removal of the surface layer occurs both at the tops of microroughnesses and in the depressions between two tops. Removal of metal from the surface of sharp tops of microroughnesses can be explained by a high level of electromagnetic field intensity. The processes occurring at sharp peaks are similar to physical phenomena observed in the form of spark discharges at pointed ends. The formation of microcraters between the tops of microroughnesses, shown above, is much more complex. Many authors have attempted to describe the polishing mechanism. However, there is still no understanding why there is the formation of numerous microcraters between the tops of microroughnesses and why this process stops after removing the vertices and smoothing the surface. Our hypothesis for this process is as follows. Numerous microdischarges are formed on the sample surface at the tops of microroughnesses and much less in the depressions between the tops. Smoothing of the tops of microroughnesses occurs with a smooth increase in the radii of their vertices. The formation of microcraters occurs simultaneously with the spraying of the volume of metal from the microcrater into the electrolyte. The surface of the depressions well retains various contaminants in the form of fatty films, oxide films, small dust grains, particles of the material of the tops, which are deposited during the plasma electrolyte treatment.

It is these elements of the system, being in the space between the vertices, are charged with respect to the treated surface with a negative electric charge. The growth of the potential at a local place of the surface determines the high intensity of the electric field between the non-conductive region and the main surface. The accumulation of charge in the local non-conductive region occurs by transfer of electric charge from the plasma electrolyte layer. When the threshold value of the breakdown voltage is reached, a spark discharge occurs between the main surface and the zone of opposite potential. This leads to erosion and the formation of microcraters in the space between the peaks. With a decrease in the conductivity of the electrolyte-plasma layer, an increase in the power and size of microcraters in the surface is also observed. In the general case, it can be assumed that an increase in the area and thickness of the zone contributes to the power of the spark discharge and its duration. It was revealed that after preliminary treatment with a type-setting current lead in the voltage range corresponding to the electrolysis mode, a surface is created containing a minimum number of non-conducting zones. This makes the plasma electrolytic polishing process more uniform. As a result, we have a higher quality surface with a lower Ra of the roughness and less machining time.

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